SemFeel: A User Interface with Semantic Tactile Feedback for Mobile Touch-screen Devices

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ABSTRACT

One of the challenges with using mobile touch-screen devices is that they do not provide tactile feedback to the user. Thus, the user is required to look at the screen to interact with these devices. In this paper, we present SemFeel, a tactile feedback system which informs the user about the presence of an object where she touches on the screen and can offer additional semantic information about that item. Through multiple vibration motors that we attached to the backside of a mobile touch-screen device, SemFeel can generate different patterns of vibration, such as ones that flow from right to left or from top to bottom, to help the user interact with a mobile device. Through two user studies, we show that users can distinguish ten different patterns, including linear patterns and a circular pattern, at approximately 90% accuracy, and that SemFeel supports accurate eyes-free interactions.

ACM Classification: H5.2 [Information interfaces and presentation]: User Interfaces. – Haptic I/O.

General terms: Design, Human Factors.

Keywords: Tactile feedback, mobile device, touch screen, multiple vibration motors.

INTRODUCTION

Mobile touch-screen devices have become increasingly more common in recent years. These devices typically do not need to include a large number of physical keys to support user input, and thus they can devote more of the surface area towards providing the user with a larger display screen. However, interactions with a completely flat touch-screen display surface lack the clear tactile feedback available when interacting with physical keys. This hampers the user's ability to perceive the object that she touches on the screen when not looking at it. Thus, the user must view the screen regardless of how long or short her interaction might be. This produces a significant challenge with using mobile touch-screen devices because it is often hard for the user to devote visual attention to the devices, particularly in a mobile setting [15].

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Auditory feedback is one way of conveying semantic information to the user about the object she is touching on the screen. For example, earPod [22] allows the user to traverse menus by telling the user which item she is selecting. However, auditory feedback is not always an appropriate form of output for mobile devices because the user may want to interact with applications in silence.

Haptic vibration has been used as an alternate way of providing tactile feedback on touch-screen devices [5, 7, 8, 10, 17]. When the user touches objects on the screen, such as a button, a webpage link, or an item on a linear list, a vibration motor embedded in the device activates. This helps the user perceive whether she is touching any object or not. Previous studies have shown that this enhancement can improve user performance of different tasks on mobile touch-screen devices [8, 17]. However, unlike auditory feedback, this basic form of haptic feedback does not help the user identify the object she is touching. Although different vibration patterns (*e.g.*, different rhythms or different strength levels) can be used to convey some semantic information [1], additional ways of conveying richer data that can be perceived and understood easily over the tactile channel remains to be explored.

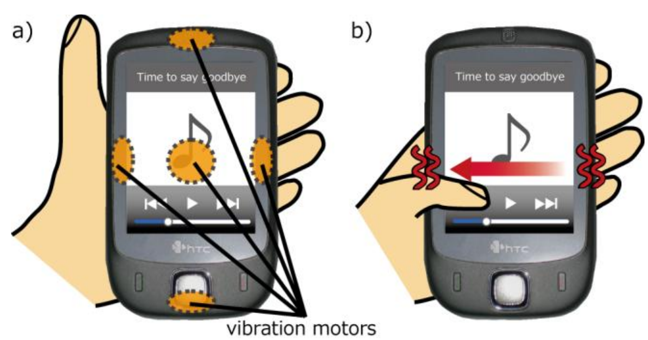

Figure 1: The SemFeel system concept: a) Multiple vibration motors are embedded in the backside of a mobile touch-screen device. b) The system generates vibration from right to left as feedback in response to when the user touches the "previous track" button.

We developed SemFeel, a tactile user interface for mobile touch-screen devices that informs the user about the presence of an object which she touches on the screen and provides additional semantic information about that item. Figure 1 a) shows the SemFeel system concept, which has five vibration motors embedded in different locations in the back of a mobile touch screen device, specifically the top, bottom, right, left, and center of the device. This placement allows the system to produce single-point vibration in specific locations as well as a "flow" of vibration (*e.g.*, a vibration moving from the top of the device to the bottom). These patterns are intended to be easy for the user to perceive and to associate with a specific meaning based on the current application context. Figure 1 b) presents an example use of SemFeel in a music player application. When the user touches the "previous track" button, she feels vibration flowing from the right of the device to the left in the palm and fingers of her hand.

In this paper, we first discuss the relevant research on tactile feedback for mobile touch-screen devices, and tactile feedback technologies to convey rich information. Next, we present our prototype SemFeel system, and eleven vibration patterns developed in this project. We then describe two experiments that we conducted to examine the accuracy with which users are able to distinguish the eleven different vibration patterns and the effect of SemFeel on the user's ability to perform eyes-free interactions with a mobile touch-screen device. Finally, we show some potential applications for the SemFeel system.

RELATED WORK

Tactile feedback has been recognized commonly as an important user interface feature for touch-screen devices [5, 8, 17]. In this section, we review previous tactile feedback technologies for mobile devices and focus on those aimed at conveying richer information than just a simple vibration.

Tactile Feedback Technologies for Mobile Devices

Touch screens are used in a variety of mobile devices today, such as cellphones, personal digital assistants, and portable music players. These devices often rely on vibrations to provide users with tactile feedback using the built-in vibration motor. Fukumoto and Sugimura were perhaps the first researchers to demonstrate that a vibrotactile actuator embedded in a mobile touch-screen device can be used to let a person know that she has registered a touch event on a screen in their Active Click system [5]. Because it allows users to know that they are touching an item on the screen, this form of tactile feedback helps users perform a variety of tasks, such as list item selection [7] and text entry [8].

Even with only one actuator, it is possible to produce different vibration patterns using different strength levels and frequencies. Poupyrev *et al.* showed that different vibration patterns can be used to convey information, such as the user's scrolling rate and position on the screen, and helps users to select items in a linear list 22% faster than when no tactile feedback was provided [17].

Alternatively, multiple actuators can be embedded in mobile devices to produce a richer set of vibration patterns that could be used to provide users with tactile feedback in a "background" channel. For example, Hoggan *et al*. demonstrated this concept by using tactile feedback to inform users about the progress of file downloads while they work on other tasks [10].

As a third option, mobile devices can provide users with tactile feedback through vibration motors that are attached to the user rather than the device itself. For example, Brown *et al.* explored the effectiveness of using multiple vibration motors attached to their participants' arm as a way of accessing calendar information [3]. They designed their calendar application to associate the rhythm, roughness, and spatial location of the vibrations with the type, priority and length of an event, respectively. Ghiani *et al.* developed a guide system which uses two strips with vibration motors worn by people with visual impairment on their index finger and the thumb of the hand holding the device [6]. They used vibration motors to present the direction to turn (*e.g.*, vibration from the right side means "turn right").

The projects described above have demonstrated that different vibration patterns can help users in performing a variety of tasks. The different vibration patterns can be generated by controlling the strength, frequency, and duration used by the actuator itself, but a richer set of patterns can be produced by using multiple actuators that can be strategically placed in the device or on the user's body. However, the addition of more actuators to mobile devices requires an understanding of how their specific placement impacts users' ability to perceive different vibration patterns that they would now be able to support. Sahami *et al*. examined how accurately users can distinguish vibration generated by six vibration motors located along the left and right edges of the back of a cellphone (without a touch screen) [18]. Their experiment showed that the participants could distinguish eight vibration patterns at 70 – 80 % accuracy, but they had difficulty identifying the location of the vibration source when their system activated only one of the vibration motors at a time (36% on average).

Tactile Feedback with Semantic Information

Semantic information can be provided over the tactile feedback channel using different vibration parameters such as frequency, rhythm, strength, and texture. For example, Brewster and Brown showed that their Tactons system could use different rhythms and frequencies to provide users with richer information than a simple vibration [1]. Hoggan *et al*. demonstrated that the texture of physical buttons could be mapped into parameters that are used later to be produced as tactile feedback for buttons on touch-screen devices [9]. Their study showed that different actuators and rhythms can be used to emulate different textures of physical buttons. Finally, Wall and Brewster illustrated that graph information can be conveyed through a mouse with tactile pin arrays [21]. The system uses tactile feedback to

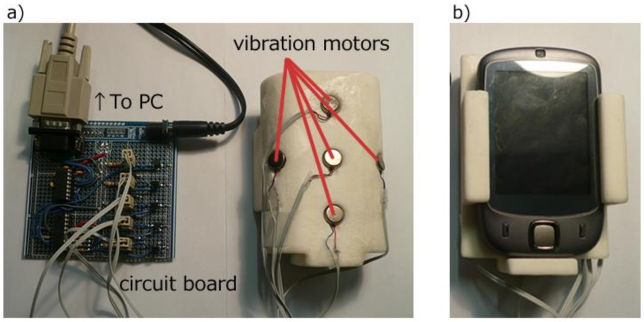

Figure 2: The SemFeel prototype: a) the circuit board and mobile touch-screen device with five vibration motors on the backside; b) the front side of the mobile device.

inform the user when she is touching bars in the graph, as well as how high that bar is by vertically moving the pin. Recently, Rantala *et al*. developed a method for presenting Braille characters on a mobile touch-screen device [18]. Their system uses different peaks of the pulses to generate raised and lowered dots. Their experiment with three different presentation methods of Braille tactile feedback revealed that experienced Braille users could recognize letters at 91 – 97 % accuracy.

As described in the previous section, another way of providing users with tactile feedback is through vibration motors that are attached to the user rather than the device itself. For example, ActiveBelt is a wearable device that includes eight vibration motors evenly spaced around the user's waist [20]. Combined with a GPS module, the device supports user navigation by activating the vibration motor in the direction of the user's destination. Luk *et al*. explored how different stimuli generated by layered piezoelectric benders could be mapped into applications on mobile devices [13]. In their system, different waveforms are used to convey information about the selected item in a browser application and the speed or direction of the tactile feedback could be used to provide the movement of the point of the user's focus. Finally, to explore how to use spatial movements as tactile feedback, Li *et al*. used a voice coil motor that moves back and forth horizontally along the user's palm to provide a different texture than the vibrations normally produced by tapping [11].

SYSTEM

One of the goals of this project is the development of a tactile user interface for mobile touch-screen devices that can provide the semantic information about the objects that the user touches on the screen. We first prototyped and informally tested a number of possible options before deciding to use small vibration motors, a similar approach to [5, 8, 10, 17, 18]. Because it is difficult with the current technologies to provide tactile feedback exactly at the contact point on the touch screen with vibration motors embedded inside the mobile device, our design instead looks to provide feedback on the palm and fingers of the hand holding the

Figure 3: The special sleeve for the SemFeel prototype allowing placement of the vibration motors as close to the palm and fingers of users as possible.

device. Although it is known that the palm is less sensitive than the finger tip (or "fingerpad"), Craig and Lyle's study showed that a level of performance similar to those on the fingerpad can be achieved by sufficiently enlarging the stimulus space [4]. In this section, we explain the design of our SemFeel prototype and the eleven vibration patterns developed in this project.

Hardware

Figure 2 shows our SemFeel hardware prototype. We attach five vibration motors (Samsung Disk Coin-Type Vibration Motor APB108) on the backside of a mobile touch-screen device. These vibration motors are connected to a circuit board, which contains two Integrated Circuit modules (PIC16F628 and MAX232A) for accepting signals from the computer and controlling each motor. The circuit board then communicates with a computer through a serial port connection.

In the study by Sahami *et al*. [18], their participants had difficulty distinguishing some of the vibration patterns produced by multiple vibration motors embedded along the left and right edges of backside of the cellphone. From our informal observations of how users hold mobile devices, we noticed that there is typically a small gap between a person's palm and the device. This gap potentially could be one of the causes for the difficulties experienced by the users in Sahami *et al.*'s study. As a result, we manufactured a special sleeve (Figure 3) that goes under a touch-screen device and curves to fit the shape of the user's hand when it holds the device. This sleeve allowed us to embed the vibration motors on the backside of the device while placing the motors as close to the palm and fingers as possible.

Each motor is controlled by a Pulse-Width Modulated (PWM) signal sent from PIC16F628. The signal is modulated at 10 kHz. With PWM, our hardware can change the total amount of power delivered to the vibration motors by changing the duty cycle. In this way, the hardware supports changes in the strength of the vibration, as well as turns the vibration motors on and off. Although the prototype can control the duty cycle nearly arbitrarily, our pilot study shows that users had difficulty perceiving the soft vibration generated by the system when the duty cycle is below 50%.

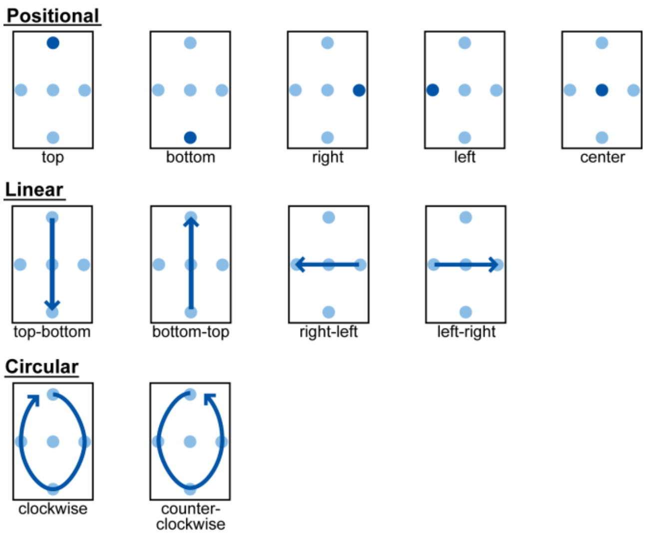

Figure 4: The eleven vibration patterns implemented on the prototype. For the linear and circular patterns, the vibration motors are activated sequentially, as the figure shows with the smoothing explained in Figure 5.

Additionally, more than 10% difference in the duty cycle is necessary for users to clearly distinguish between vibrations at two different strength levels. Therefore, we designed our prototype to operate with four pre-set levels of vibration strength: 0% (completely off), 60%, 80% and 100% of the duty cycle. We set the temporal resolution to 50 [msec] because we found that our hardware often could not activate the vibration motors completely in a shorter duration through our pilot experiment. We also set the maximum duration of the vibration to 1 [sec] because longer durations are not practical.

Vibration feedback patterns

Figure 4 presents the eleven vibration patterns that we designed for the current SemFeel prototype. There are three types of patterns: positional (top, bottom, right, left, and center), linear (top-bottom, bottom-top, right-left, and left-right), and circular (clockwise and counter-clockwise). For the linear and circular vibration patterns, different levels of vibration strength are used to produce a smoother transition of the vibration. Figure 6 shows how the vibration strength is controlled in the right-left vibration pattern. Our pilot study shows that participants preferred vibration with this smoothing over vibration without smoothing.

In the experiments described later, we use 100% strength for every vibration pattern except for the smoothing purpose because we wanted to focus on evaluating how accurately users can distinguish vibration patterns generated by multiple vibration motors attached to different locations rather than the strength or rhythm of the vibration, which have been studied previously [1]. However, future work should examine how accurately users can distinguish weak and strong linear vibration patterns, for example.

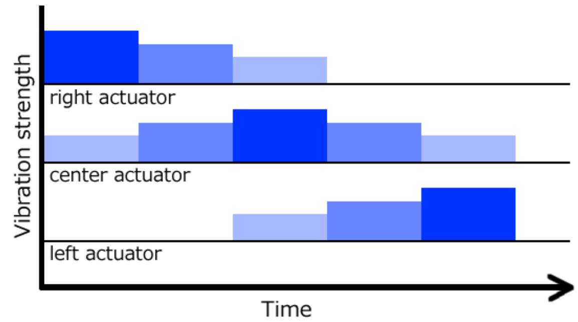

Figure 5: The smoothing of the vibration strength for the right-left vibration. The height of each square indicates the level of the vibration strength. The duration for each square is 200 [msec].

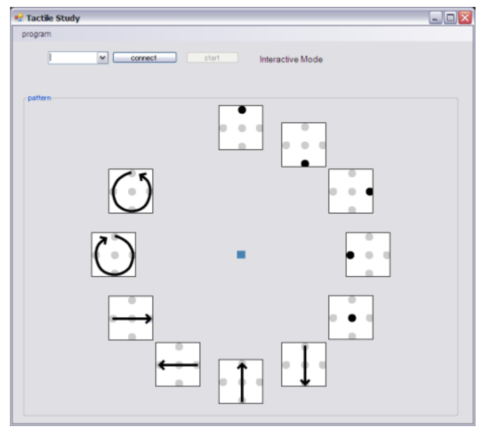

Figure 6: The screen shot of the application running on the Windows machine in the first experiment.

EXPERIMENT 1: DISTINGUISHABILITY OF PATTERNS

Tasks and Stimuli

In this experiment, we asked the participants to determine which of the eleven vibration patterns shown in Figure 4 was being generated by the system at a time (each time, the pattern was generated only once). After the system generated a pattern, the cursor appeared in the small blue square on a computer screen (Figure 6). The participants would then move the cursor to the diagram representing the vibration pattern they thought the system had generated and clicked on the diagram. Each diagram was a square (70 pixels x 70 pixels) placed the same distance (200 pixels) away from the initial cursor position. A dialogue would appear to show whether the response was correct. If the response was wrong, the correct answer would be provided. During the experiment, the participants were asked to perform the task as quickly and accurately as possible.

Variables

The independent variable that we controlled in this experiment was *Pattern* (five positional, four linear, and two circular patterns). In each block of the experiment, the order of the presentation of *Pattern* was randomized. Each vibration pattern was repeatedly presented three times in one

Table 1: The confusion matrix for *Pattern* in the first experiment. The numbers in bold font represent the number of occurrences of the user responses. The numbers with parentheses show the percentage of the occurrence of the user responses in each stimulus.

		User Response											
		top	bottom	right	left	center	top-bottom	bottom-top	right-left	left-right	clock-wise	counter-clockwise	total
Stimulus	top	**112** (93.3)		**4** (2.50)	**1** (0.83)	**1** (0.83)		**2** (1.67)					**120**
	bottom		**103** (85.8)	**8** (6.67)		**9** (7.50)							**120**
	right			**107** (89.2)		**13** (10.8)							**120**
	left	**2** (1.67)			**112** (93.3)	**6** (5.00)							**120**
	center	**1** (0.83)	**2** (1.67)	**3** (2.50)	**1** (0.83)	**109** (90.8)	**2** (1.67)	**2** (1.67)					**120**
	top-bottom						**110** (91.7)		**2** (1.67)	**3** (2.50)	**2** (1.67)	**3** (2.50)	**120**
	bottom-top	**4** (2.50)						**110** (91.7)	**1** (0.83)	**3** (2.50)	**1** (0.83)	**1** (0.83)	**120**
	right-left					**1** (0.83)	**3** (2.50)	**2** (1.67)	**107** (89.2)	**1** (0.83)	**6** (5.00)		**120**
	left-right					**2** (1.67)	**1** (0.83)	**1** (0.83)	**2** (1.67)	**106** (88.3)	**2** (1.67)	**6** (5.00)	**120**
	clockwise						**3** (2.50)		**1** (0.83)		**100** (83.3)	**16** (13.3)	**120**
	counter-clockwise										**41** (34.2)	**79** (65.8)	**120**
total		**119**	**105**	**122**	**114**	**141**	**119**	**117**	**113**	**113**	**152**	**105**	**1320**

block, and the experiment contained four blocks. Therefore, there were 4 *(Block*) * 11 (*Pattern*) * 3 (repetition) = 132 trials per participant.

We measured the reaction time as how long the participants took to click one of the diagrams shown in Figure 6 after a vibration pattern was presented completely. We also recorded the given vibration pattern and participants' response to calculate the error rate. The error rate for each pattern was calculated per block per participant (*i.e.*, 100 * [the number of the wrong responses] / 3).

Apparatus
We used the same prototype shown in Figure 2 in this experiment. A Windows Mobile 6 device (HTC Touch) was embedded in the custom sleeve. The application shown in Figure 6 was written in C# and ran on a Windows XP computer. The computer was connected to the circuit board. In this experiment, the durations of all the patterns were set to 1 [sec].

Procedure
The participants were given the explanation of the system and instructed to hold the prototype mobile device with their non-dominant hand and to use a mouse with their dominant hand to interact with the application on the computer. They were then asked to perform a practice set that used the same tasks as the test sessions. They could continue to practice until they felt comfortable with the tasks and system. On the average, the participants practiced for about five minutes. After each block, the participants were allowed to take a short break. In total, the entire experiment took about 45 minutes.

Participants
Ten people (five male and five female, aged 18 to 50) with different professional backgrounds (university students, law careers, business consultants, a physician, and a programmer) were recruited for this experiment. One male and one female were left-handed, and the others were right-handed. Three of the participants regularly used mobile touch-screen devices. All the participants were compensated for their time and effort with $20 CAD.

EXPERIMENT 1 RESULTS
Table 1 shows the confusion matrix for the eleven patterns. A one-way analysis of variance (ANOVA) test for the error rates against *Pattern* indicates the existence of statistically significant differences ($F_{10, 429}$=4.46, p<.001). The post-hoc Tukey multiple comparison revealed that statistically significant differences exist between counter-clockwise and the other patterns (p<.05 for the difference between clockwise and counter-clockwise, and p<.001 for all the other differences).

Figure 7 shows the mean reaction time for *Pattern*. For simplicity, we ran a one-way ANOVA test for performance time against the pattern categories (positional, linear, and circular). It shows the existence of statistically significant differences ($F_{2, 1317}$=65.2, p<.001). To accommodate the unbalanced sample sizes across the pattern categories, a Tukey-Kramer multiple comparison was used in the post-hoc test. It showed that the reaction time for the positional patterns (2.19 [sec]) was significantly faster than those for the linear patterns and circular patterns (2.43 [sec] and 2.95 [sec], respectively, p<.001), and the reaction time for the

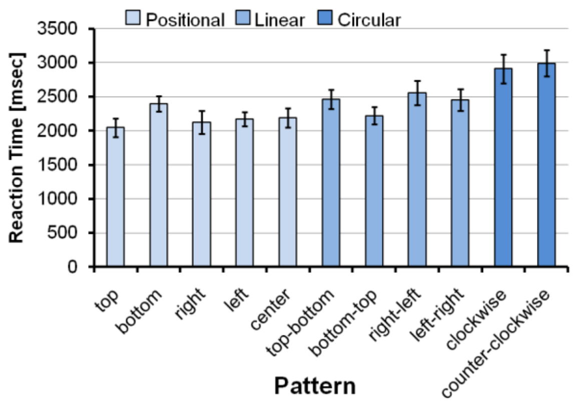

Figure 7: The reaction time across the categories of the vibration patterns in the first experiment. In this and all later charts, the error bars indicate the 95% confidence intervals.

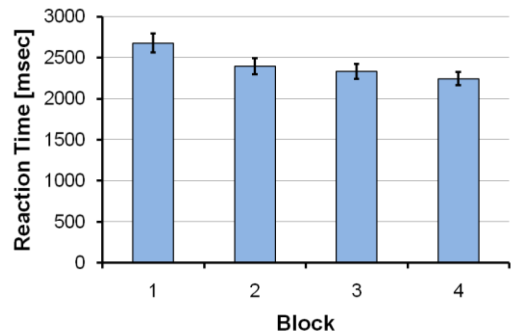

Figure 8: The reaction time across *Block* in the first experiment.

linear patterns was significantly faster than for the circular patterns (p<.001).

Figure 8 shows the reaction time across *Block*. A one-way repeated-measure ANOVA test for the reaction time against *Block* indicates the existence of statistically significant differences ($F_{3,\ 1280}$=17.6, p<.001). The post-hoc Tukey multiple comparison discovered significant differences between the first block and the other blocks (p<.001) and between the second block and the last block (p<.1). We did not find any statistical difference in the error rate across *Block* ($F_{3,\ 400}$=1.16, p=.32).

EXPERIMENT 1 DISCUSSION

The results of our experiment demonstrate that the participants could distinguish the eleven patterns except for counter-clockwise at 83.3 – 93.3 % accuracy (89.6 % on average) in spite of a short amount of practice. Although the results indicate that we need to modify the set of circular patterns (*i.e.*, use only one of the circular patterns, or start one of the circular patterns at a different location) to avoid user confusion, this is a significant improvement from the system studied by Sahami *et al* [19]. One possible reason is that the duration of the vibration in our experiment was 1 [sec] whereas the patterns they used were between 300 [msec] and 900 [msec]. Additionally, our specially-designed sleeve to fill the gap that normally exists between the user's hand and device might have helped the participants sense the vibrations better. We need to further investigate exactly why our prototype achieves higher accuracy, but this indicates that vibration generated by multiple vibration motors can be provided practically in mobile devices. Furthermore, we confirmed that there is a learning effect in terms of reaction time. These findings are promising for the efficacy of our system.

EXPERIMENT 2: USER PERFORMANCE ON INPUT TASKS

The first experiment shows that users can distinguish ten of the vibration patterns that our current SemFeel prototype can generate (five positional, four linear, and a clockwise circular vibration patterns) at about 90% accuracy. We designed the second experiment to examine user performance in a realistic application with the SemFeel technology. In particular, we wanted to compare the accuracy of user input when using the SemFeel prototype against user interfaces that offer no tactile feedback or tactile feedback using only a single vibration source.

Tasks and Stimuli

In this experiment, we asked participants to perform a number entering task. We chose this input task with the numeric keyboard because this is a commonly performed action on cellphones. Furthermore, this interaction can be extended to other applications (*e.g.*, text entry with the multitap method and menu selection). We conducted the experiment only with an eyes-free condition where we expected that a clear difference would be observed between SemFeel and the reference systems.

First, the system presented the participants with a 4-digit number in blue font on the computer screen (the right figure in Figure 9). Next, we asked the participants to type that number on a mobile touch-screen device using the numeric keyboard shown in the left part of Figure 9. Each key was a square (9.2 cm x 9.2 cm). This size was chosen to allow the participants to interact comfortably with their thumb based on the findings reported by Parhi *et al*. [16]. The participants could commit the typing by releasing the thumb from the screen, and then the entered number would appear on the computer screen (the right figure in Figure 9). The character "X" would be shown when the participant released the thumb outside any of the keys.

There were three tactile feedback conditions studied in this experiment: none (*No Tactile*), tactile feedback provided through a single vibration motor (*Single Tactile*), and tactile feedback provided through the SemFeel technology (or tactile feedback provided through multiple vibration motors, which we will refer to as *Multiple Tactile*). In the *Single Tactile* condition, the center vibration motor was used to provide tactile feedback when the participants were touching any of the keys on the keyboard. For the number '5' key,

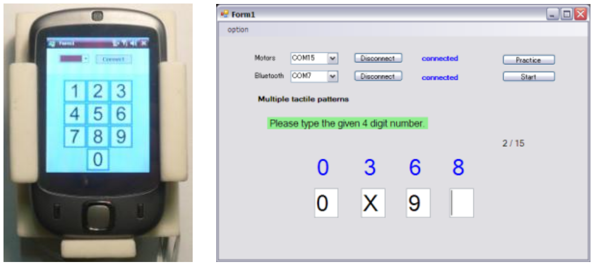

Figure 9: The applications used in the second experiment: left) the numeric keyboard on the prototype mobile device; right) a screen shot of the application running on a Windows computer.

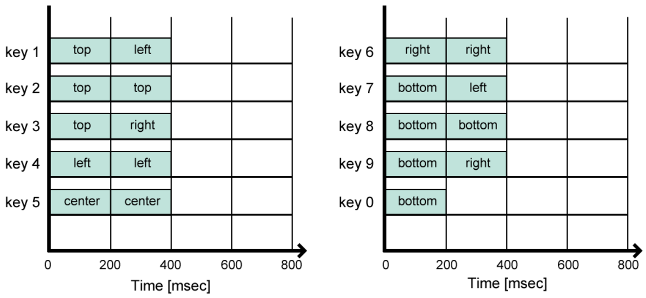

Figure 10: The mapping of the vibration patterns for the numeric keyboard used in the *Multiple Tactile* condition. Please note that the assignment of the vibration patterns is based on the spatial relationship of the keys (*e.g.*, the combination of top and left vibration is assigned to key 1).

the system turned the center vibration motor on for 400 [msec] and off for another 400 [msec]. For the other keys, the system turned on the center vibration motor for 200 [msec] and off for 600 [msec]. These patterns repeated while the participant's finger continued to touch the button. This implementation was designed to emulate a physical numeric keyboard (*i.e.*, every key except for the key for 5 has the same texture, and the number '5' key has a slightly different texture to indicate the home position).

In the *Multiple Tactile* condition, the vibration patterns were designed with simple combinations of the positional patterns, and assigned to match the spatial relationship as shown in Figure 10. Each pattern lasted 800 [msec], consisting of two 200 [msec] vibration generated by one of the vibration motors followed by 400 [msec] without any vibration. Only one of the motors was activated at a time. For instance, the system turns the left vibration motor on for 400 [msec] and off for another 400 [msec] when the user touched the number '4' key. It activated the top vibration motor for 200 [msec] first, and then the right vibration motor for the next 200 [msec], and stopped all the motors for the next 400 [msec] when the user touched the number '1' key. Similar to the *Single Tactile* condition, these vibration patterns were repeated while the participant's finger continued to touch a button. We confirmed that this design of the vibration patterns used was appropriate through an informal study.

Figure 11: The setup for the second experiment. The experimenters asked the participants to hold the prototype mobile device under the table in order to reproduce an eyes-free situation.

Variables

The independent variable that we controlled in this experiment was *Feedback* (*No Tactile*, *Single Tactile*, and *Multiple Tactile*). The order of the presentation of *Feedback* was counter-balanced across the participants. In each block, a 4-digit number was randomly generated, but it always satisfied the two following conditions: 1) each digit was different from the others, and 2) the frequency of each number was equal within the block. The experiment contained two blocks for each *Feedback* condition. Therefore, there were 3 (*Feedback*) * 2 *(Block*) * 15 (trial) = 90 trials per participant.

We measured the performance time as the time from after a 4-digit number was shown to when the participants released their thumb from the screen to enter the fourth digit. The error rate was calculated for each block (*i.e.*, 100 * [the number of the wrong entries] / [the number of the digits in one block = 60]).

Apparatus

We used the same devices used in the first experiment. The applications used in this experiment were written in C#. All the events on the numeric keyboard were sent to the computer via Bluetooth. The application on the computer then sent a signal to the circuit board to generate the pattern corresponding to the key the participant was touching.

Procedure

Before the experiment, participants were given the explanation of the system, and instructed to hold the prototype mobile device with their dominant hand and to use the thumb of that hand to interact with it. This instruction was included because it is highly likely that users would interact with a mobile device using only one hand in an eyes-free setting. However, due to the fairly large size and heavy weight of the prototype, we allowed the participants to support their dominant hand with their other hand. The partici-

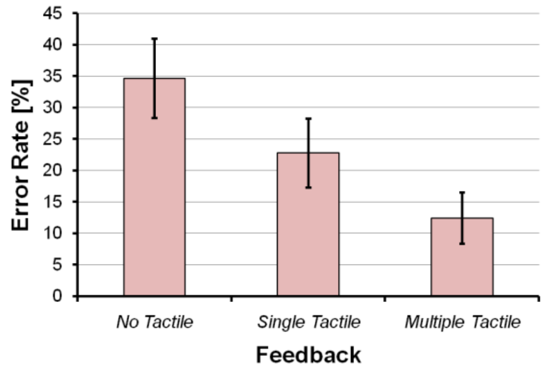

Figure 12: The error rate across *Feedback* in the second experiment.

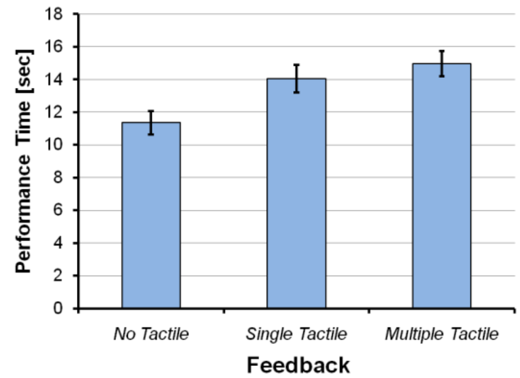

Figure 13: The performance time across *Feedback* in the second experiment.

pants were also instructed to touch the screen of the mobile device with their finger tip or nail due to the weak responsiveness of the screen. During the experiment, we asked the participants to hold the mobile device under the table (as shown in Figure 11) so that they could not see its screen. We asked them to perform the task as accurately as possible.

The participants were then asked to perform a practice set that used the same tasks as the test sessions to become comfortable with all the conditions at the beginning of the experiment. They could continue to practice until they felt comfortable with the tasks and system. On average, the participants practiced for about ten minutes. After each block, participants were allowed to take a short break. In total, the entire experiment took about 45 minutes.

Participants

Twelve right-handed people (eight male and four female, aged 18 to 50) with a variety of backgrounds (university students, accountants, a health worker, a technician, a car dealer, a waiter, and an executive assistant) were recruited for this experiment. Eight of the participants regularly used mobile touch-screen devices. All the participants were compensated for their time and effort with $20 CAD.

EXPERIMENT 2 RESULTS

Figure 12 shows the error rates for the *Feedback* conditions. A one-way ANOVA test for the error rates against *Feedback* reveals the existence of statistically significant differences ($F_{2,\ 69}=16.5$, $p<.001$). The post-hoc Tukey multiple comparison revealed that statistically significant differences exist between any of the two conditions ($p<.01$ for the difference between *No Tactile* and *Single Tactile*, $p<.001$ for the difference between *No Tactile* and *Multiple Tactile*, and $p<.05$ for the difference between *Single Tactile* and *Multiple Tactile*).

Figure 13 shows the mean performance time for *Feedback*. A one-way ANOVA test for performance time against *Feedback* indicates the existence of statistically significant differences ($F_{2,\ 1077}=22.3$, $p<.001$). The post-hoc Tukey multiple comparison indicated that there are statistically significant differences between *No Tactile* and *Single Tactile*, and between *No Tactile* and *Multiple Tactile* ($p<.001$ for both).

EXPERIMENT 2 DISCUSSION

Our second experiment shows that SemFeel can support significantly more accurate interactions with a numeric keyboard application in comparison to a user interface without any tactile feedback and one with tactile feedback using a single vibration source in an eyes-free setting. Furthermore, the participants could learn the vibration patterns in the *Multiple Tactile* condition within a short amount of time. We need to study further how SemFeel could improve user performance in other applications or other situations (*e.g.*, while users are walking), but the results gained from the second experiment indicate that SemFeel has the potential to help users accurately interact with mobile touch-screen devices without looking at the screen.

Our second study also shows that the user interfaces with tactile feedback were slower than the one without any tactile feedback. This is as we expected because the participants often adjusted their contact point on the screen based on the tactile feedback to hit the right key. However, without tactile feedback, participants were unable to make such adjustments. Due to the poor responsiveness of our prototype, the difference in the performance time between the *No Tactile* condition and the conditions with tactile feedback was large (about 3 [sec]). We believe that this difference could become much smaller if our system is manufactured better.

APPLICATIONS

There are other applications which also could leverage our technology to support a less visually-demanding or eyes-free interaction beyond the music player application (Figure 1) and a numeric keyboard that have already been discussed in this paper. Figure 14 a) shows one possible design of an alphabetic keyboard which has three large keys. The left, center, and right keys activate the left, center, and right vibration motors respectively. Each key contains nine alphabetical letters, and the user can enter one of those letters by touching the appropriate key and the makes a gesture to specify which letter she wants to input. For example, Figure

Figure 14: SemFeel applications: a) An alphabetic keyboard. The right, center and left vibration patterns are associated with three large keys which the user can touch and make a gesture to type a letter; b) A calendar application. The top, center, and bottom vibration motors are used for representing the morning, afternoon, and evening in a particular day, and the duration of the vibration generated by each vibration motor represents the availability of each time period (longer vibration means less available); c) A maze game. Users can interact by tilting the device, and when the ball hits the wall, the vibration is generated; and d) A web browser for people with visual impairment. Audio feedback is used for reading out the content of a webpage, and tactile feedback is used for providing information about the controls in the web browser application.

14 a) shows that a user is entering 'r'. In this case, she presses the center key first, and then moves the thumb towards the bottom-right direction. This keyboard is less visually-demanding than a normal mini-qwerty keyboard because the tactile feedback tells the user which key she is touching, and does not require fine-grained adjustment of the contact point to select the specific key for the desired letter. Thus, the user can focus visually on the text area rather than the keyboard.

SemFeel can also allow the user to use a calendar application and access its content without looking at the screen. Li *et al.* previously demonstrated an audio-based eyes-free interaction to access a calendar application through a cellphone [12]. The user can use this system even when they are talking over the phone. However, the audio feedback from the system could be a distraction to the phone conversation. With SemFeel, different time slots can be associated with vibration motors at different location. For instance, the top, center, and bottom vibration motors are associated with the morning, afternoon, and evening in a particular day, respectively. The duration of the vibration at each vibration motor can represent how busy the user is. Although the user will not know the details of the schedule, SemFeel still can provide the user with a general idea of her availability.

SemFeel could be used to enhance the current user interfaces on mobile touch-screen devices. For example, SemFeel can be incorporated into game applications to provide a more entertaining user interface. Figure 14 c) shows one example game application, a maze. The goal in this game is to move the ball to a target by tilting the device. When the ball hits a wall, the system generates a vibration in the direction of the obstacle.

SemFeel also could improve the design of user interfaces for people with visual impairment. McGookin *et al.* studied accessibility issues on mobile touch-screen devices [14]. One of their findings suggests that user interface designers should provide feedback for all the actions that have occurred on the screen. SemFeel could be used as an additional feedback channel for the user. Figure 14 d) shows a web browser application for people with visual impairment. The audio channel is used to read out the content of a webpage. Tactile feedback is used to provide information about the control that the user touches on the screen. Audio feedback can be used for this purpose, but it might be distracting because the read-out of the Web content function has to be stopped or users would have two different kinds of information delivered over the audio channel at the same time.

A navigation aid for people with visual impairment such as the system used in Ghiani *et al*.'s study [6] could also be enhanced by the SemFeel system. In our own, small study with people with visual impairment, we learned that these users rely heavily on their hearing to remain safe while navigating. Therefore, auditory feedback should not be used heavily in this type of system. Instead, SemFeel can be used to provide users with directions through the tactile channel (*e.g.*, when they have to turn right, SemFeel can generate the left-right vibration).

CONCLUSIONS AND FUTURE WORK

Lack of tactile feedback can hinder the effective use of mobile touch-screen devices, especially when users are unable to view the screen. We developed SemFeel, a tactile feedback technology for mobile touch-screen devices which provides the users with the semantic information about the object they are touching through multiple vibration motors embedded in the backside of the device. We conducted two experiments that demonstrate that users can distinguish ten vibration patterns, including linear patterns and a clockwise circular pattern, at around 90% accuracy, and that our system supports more accurate interactions in an eyes-free setting than systems that offer no tactile feedback or use only a single vibration motor.

We believe that SemFeel can offer users rich information through the tactile feedback channel. Although the results reported in this paper demonstrate the efficacy of SemFeel, further research should be conducted to determine additional sets of vibration patterns that can be distinguished by the users. Because SemFeel supports accurate eyes-free interactions, it would be interesting to study how SemFeel affects user performance of various tasks in a mobile setting, such as while users are walking.

In future work, we will develop mobile applications for people with visual impairment upon the SemFeel technology. In an informal user study with people with visual impairment, we learned that they can distinguish the vibration patterns used in our first experiment as successfully as the participants without visual impairment. We will further investigate how we can incorporate SemFeel into different applications for people with visual impairment, such as the web browser and navigation aids as discussed in this paper.

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