Psychophysical Model for Vibrotactile Rendering in Mobile Devices

Abstract

Vibrotactile rendering is one of the most popular means for improving the user interface of a mobile device, but the availability of related perceptual data that can aid vibrotactile effect design is not currently sufficient. The present paper reports data from a series of psychophysical studies designed to fill this gap. In Experiment I, we measured the absolute detection thresholds of sinusoidal vibrotactile stimuli transmitted to the hand through a mobile phone. Stimuli were generated by a mechanical shaker system that can produce vibrations over a broad frequency and amplitude range. The detection thresholds reported here are a new addition to the literature, and can serve as a baseline for vibrotactile stimulus design. In Experiment II, we estimated the perceived intensities of mobile device vibrations for various frequencies and amplitudes using the same shaker system. We also determined a form of parametric nonlinear function based on Stevens' power law and fit the function to the measured data. This psychophysical magnitude function, which maps vibration frequency and amplitude to a resulting perceived intensity, can be used to predict the perceived intensity of a mobile device vibration from its physical parameter values. In Experiment III, we measured another set of perceived intensities using two commercial miniature vibration actuators (vibration motor and voice-coil actuator) in place of the mechanical shaker. The purpose of this experiment was to evaluate the utility of the psychophysical magnitude function obtained in Experiment II, as vibrotactile stimuli produced by miniature actuators may have different physical characteristics, such as vibration direction and ground condition. Comparison of the results of Experiments II and III confirmed that the psychophysical magnitude function can reliably predict changing trends in the perceived intensity of mobile device vibration. We also discuss further research issues encountered during the investigation. The results presented in this paper may be instrumental in the design of effective vibrotactile actuators and perceptually-salient rendering algorithms for mobile devices.

1 Introduction

The advent of personal mobile devices, such as cellular phones, PDAs (personal digital assistants), and portable gaming devices, has dramatically impacted our daily lives. Related technology and UIs (user interfaces),
including the use of vibrotactile rendering for information delivery, have been rapidly evolving. Vibrotactile rendering is generally regarded as an effective means of improving the limited interaction capacity of a mobile device. In the past 10 years, a great number of vibrotactile rendering applications have been developed for diverse purposes, for example, alternative ring tones, special effects for game controllers, vibratory rhythms that accompany music, interactions on a touch screen, and tactile messages for abstract meaning delivery (see Section 2.1 for a review). In contrast, research into the underlying perception of mobile device vibration has not kept up with the application needs. Despite the considerable knowledge available on human vibrotactile perception (see Section 2.2), comprehensive psychophysical data that can be directly applied to mobile devices are scarce. This deficiency motivated the present series of psychophysical studies.

In this paper, we provide basic psychophysical data that can contribute to vibrotactile stimulus design for mobile devices. First, we report absolute detection thresholds of sinusoidal vibrations transmitted through a mobile phone held in the hand (Experiment I; Section 3). The detection threshold is a basic psychophysical measure of the minimum stimulus intensity that can be reliably perceived by a human observer. In general, the detection thresholds of vibrotactile stimuli are a function of vibration frequency, and depend on various factors such as contact area, contact force, contact site, skin temperature, stimulus duration, use of a rigid surround, probe-surround gap, age, and even the psychophysical method used for measurement (Jones & Lederman, 2006). When a mobile device is grasped in the hand, a vibrating medium, the mobile device itself, stimulates all five fingers and the palm with a large contact area. Detection thresholds measured under this situation are not yet available in the literature. Using a mechanical shaker of wide bandwidth, we measured the detection thresholds for seven frequencies from 10 to 500 Hz. In addition, the measured thresholds were compared to previously published detection thresholds for vibrotactile stimuli perceived via other types of handheld tools (Morioka & Griffin, 2005; Israr, Choi, & Tan, 2006, 2007).

Second, we present a psychophysical magnitude function for mobile device vibration, which maps the amplitude and frequency of vibration to its resulting perceived intensity (Experiment II; Section 4). Perceived intensity is the strength of a stimulus that a human user feels, and is one of the most important properties to be taken into account in interface design. The perceived intensity of a vibratory stimulus depends on many factors, including frequency, contact area, contact force, contact site, stimulus duration, and age of the perceiver (Verrillo & Gescheider, 1992). Using the same shaker system, we measured perceived vibrotactile intensities over a broad parameter range (frequencies of 20–320 Hz and amplitudes of 6–45 dB SL1) via absolute magnitude estimation. We then designed, based on the power law, a 2D nonlinear regression model with two independent variables of frequency and amplitude, and fit the model to the measured perceived intensity data. This procedure led to a psychophysical magnitude function that can predict the perceived intensity of mobile device vibration from its physical parameters. To our knowledge, this psychophysical magnitude function is the first of its kind for mobile devices.

Third, we examine the extent to which the psychophysical magnitude function can explain the perceived intensities of mobile device vibrations produced by miniature vibration actuators that are currently used in commercial mobile devices (Experiment III; Sections 5 and 6). Two popular actuators, the vibration motor and the voice-coil actuator, were used in this experiment. The physical characteristics of vibration stimuli produced by these actuators are different from those produced by the mini-shaker in aspects such as vibration direction, mechanical ground, and device weight. These differences are presented as physical stimulus measurements and explored in subsequent analysis in Section 5. We also measured the perceived vibration magnitudes resulting from the two miniature actuators using absolute magnitude estimation, and compared these with the psychophysical magnitude function obtained in Experiment II (Section 6). This last step illustrated the utility of the

1. Sensation level in dB SL = 20 log10(A/AL), where A is the signal amplitude and AL is the corresponding absolute threshold (limen).
psychophysical magnitude function for vibrotactile effect design.

Finally, we conclude this paper in Section 7, along with a discussion of the potential uses and limitations of our results for vibrotactile rendering in mobile devices.

2 Related Work

2.1 Vibrotactile Rendering in Mobile Devices

In the past decade, a multitude of studies have investigated the use of vibrotactile rendering for various purposes (for recent reviews, see Gallace, Tan, & Spence, 2007; MacLean, 2008). We briefly review the studies related to mobile devices in this section.

One of the most traditional and practical goals of vibrotactile rendering for mobile devices has been improving their UIs, especially virtual buttons displayed on a touch screen. This has become more important with the recent advent of display-only phones that lack physical keypads. For instance, Fukumoto and Sugimura (2001) showed that character input speed using soft buttons on a touch screen can be improved with vibrotactile feedback, especially in noisy environments. Nashel and Razzaque (2003) presented diverse vibrotactile effects suitable for different contact events, such as pushing a button, crossing button edges, and lingering on a button. Recently, a usability study by Hoggan, Brewster, and Johnston (2008) demonstrated that vibrotactile feedback enhances accuracy and completion time for text entry using a virtual keypad, with a significantly reduced subjective workload.

Research for the use of vibrotactile rendering along with other GUIs (graphical user interfaces) has also been active. Poupyrev, Maruyama, and Rekimoto (2002) developed a miniature vibrotactile actuator, called the TouchEngine, which stacked piezoelectric bending motors in multiple layers to increase vibration strength. They proposed to use vibrotactile feedback as ambient sensory cues to assist user interaction, and demonstrated a 22% reduction in task completion time for a 1D text scroll task where the user controlled the scroll speed by tilting a mobile phone with vibrotactile feedback. This work was extended to the design of vibrotactile signals appropriate for several finger movements interacting on a touch screen, such as touching down, holding, dragging, and lifting off (Poupyrev & Maruyama, 2003). Rekimoto and Schwesig (2006) added another input dimension by sensing the pressing force of a finger and used this information to change the degree of GUI response, for example, scaling the screen scroll speed with pressure. In addition, Hall, Hoggan, and Brewster (2008) suggested the need for GUIs designed solely for mobile devices, instead of using those adapted from desktop GUIs. They conceptualized and evaluated one such GUI, T-Bar, which can prevent the user’s finger from occluding visual icons displayed on a touch screen by guiding finger movements for menu selection via vibrotactile feedback.

Another topic to which significant research efforts have been devoted is abstract information delivery via vibrotactile messages in a mobile device. For instance, Brown and Kaaresoja (2006) designed tactile icons (tactons) for three alert types and three alert priorities, thus a total of nine tactons, and demonstrated an acceptable recognition rate. Töyssy, Raisamo, and Raisamo (2008) proposed a coding scheme for time using simple sequences of vibrotactile pulses. The recognition rate was as high as 80% without training. Recently, Li, Sohn, Huang, and Griswold (2008) developed an interesting system, PeopleTones, which notifies the presence of friends in the vicinity via musical and vibrotactile cues played by a mobile phone. A vibrotactile pattern was made by applying amplitude thresholding and band-pass filtering to the wave file of a song. Ghiani, Leporini, and Paternò (2008) installed two vibration motors in a PDA to deliver directional information to the visually impaired. We note that in a more general context beyond mobile devices, designing effective tactons, or haptic icons, with high discriminability and learnability has received great attention from the haptics community, and direct the reader to MacLean (2008) for a recent review.

Even though most mobile devices have only one vibration actuator due to the compact form factor, research using multiple actuators to provide richer vibrotactile sensations has also surfaced. For example,
Sahami, Holleis, Schmidt, and Häkkilä (2008) developed a prototype phone with six vibration motors. The identification rate of a stimulation site was 75% for the motors in the corners, but only 36% for the motors located in between. When the motors were activated in groups, the identification rate was higher, at 64–76%. Hoggan, Anwar, and Brewster (2007) designed 2D tactons by varying the stimulation site and rhythm of tactile progress bars. Faster task completion was observed when three actuators were placed on the sides of a mobile phone. Kim, Yang, Han, and Kwon (2008) installed two different vibration actuators for texture rendering. A solenoid actuator with a larger vibration output rendered large-scale textures, while a piezoelectric actuator with a faster response time was responsible for detailed textures.

Multimodal rendering using two or more sensory channels also has great potential for improving mobile device UIs. Hoggan and Brewster (2006) proposed crossmodal icons that combine earcons and tactons. Each stimulus pair shared the same properties, such as rhythm, roughness, intensity, and spatial location. Simultaneous playback of sound and tactile vibration also was a topic of interest (Chang & O'Sullivan, 2005). From a sound file, they made vibrotactile patterns for beat information by amplifying the sound signals in a low frequency band or by synthesizing one if such low frequency components were absent. Playing vibrotactile patterns together with sound was reported to enhance the perception of sound quality.

Vibrotactile rendering has also been used with gesture recognition. Brown and Williamson (2007) developed a multimodal messenger, Shake2Talk, which integrated inertial sensing, gesture recognition, and vibrotactile feedback. In Williamson, Murray-Smith, and Hughes (2007), a ball-bouncing application for a mobile phone was presented by combining device motion sensing, vibrotactile feedback, and realistic impact sound.

### 2.2 Human Perception of Vibrotactile Stimuli

Human perception of vibrotactile stimuli is a complex process. In this section, we introduce earlier psychophysical studies and their findings related to the absolute thresholds and the perceived intensities of vibrotactile stimuli. A more thorough review can be found in Jones and Lederman (2006).

A number of psychophysical studies have presented absolute detection threshold curves for vibrotactile stimuli as a function of vibration frequency. A detection threshold curve usually consists of two main segments. A low-frequency segment is associated with the NP (non-Pacinian) I channel, and is essentially flat, regardless of stimulation frequency. This segment may or may not appear, depending on experimental conditions. A high-frequency segment, mediated by the PC (Pacinian) channel, forms a V-shaped curve in a log-log scale; thresholds decrease rapidly with frequency, reaching the most sensitive frequency between 200 and 300 Hz, and then increase again. Vibrotactile detection thresholds are affected by many factors including contact area, contact force, contact site, skin temperature, stimulus duration, use of a rigid surround, probe-surround gap, age, and even the psychophysical method. See Verrillo and Gescheider (1992) for a summary of factor effects.

Since the present study uses a vibrating rigid object (a mobile device) grasped in the hand, detection thresholds measured under similar setups are relevant. Previously, Reynolds, Standlee, and Angevine (1977) reported detection thresholds for a 1.905-cm diameter aluminum handle measured using the method of adjustment. Two grips were used: in a finger grip, the handle was touched only with the palmar sides of the fingers, while in a palm grip, the handle was also enclosed by the palm. Using an adaptive up-down tracking procedure, Brisben, Hsiao, and Johnson (1999) measured detection thresholds for a 3.2-cm diameter cylindrical tool that was held in a power grip. Recently, Morioka and Griffin (2005), investigating the effects of contact area and contact location, published vibrotactile detection thresholds using a 3-cm diameter cylindrical handle. Detection thresholds for tools that are common in force-feedback haptic interfaces have also been published, for example, for a stylus (Israr et al., 2006) and a ball (Israr et al., 2007). Compared with these studies, however, a mobile device
has a significantly larger contact area, and its vibration stimulates all five fingers and the palm. To our knowledge, detection thresholds measured under the exact same conditions have not yet been documented.

The sensation magnitudes of vibrotactile stimuli at suprathreshold levels have also received considerable attention in haptic perception research. Since Stevens (1959) first showed that vibrotactile perceived intensity follows the power law, a series of studies have appeared that aim to elucidate factor effects and give an understanding of the associated perceptual processes. For example, Verrillo and colleagues made comprehensive perceived intensity measurements for vibrations applied on the thenar eminence in the hand, and published equal sensation curves (Verrillo, Fraiolo, & Smith, 1969). Thereafter, they investigated the effects of various factors on vibrotactile perceived intensity, including stimulation site (Verrillo, 1974), vibration frequency (Verrillo & Capraro, 1975), stimulus duration (Verrillo & Smith, 1976), and participant’s age (Verrillo, 1982). A comprehensive review on this topic can be found in Verrillo (1991).

In contrast, research on vibrotactile perceived intensity that is directly applicable to mobile devices has been rare. Previously, our group published preliminary data for the case of a vibration motor attached on the thenar eminence (Jung & Choi, 2007) and presented a short poster for the perceived intensity of mobile device vibration (Ryu, Jung, & Choi, 2008). Very recently, Yao, Grant, and Cruz (2010) demonstrated that perceived vibration strength increases with increased mobile device weight and with decreased vibration frequency when the vibration amplitude represented in an acceleration unit remains constant. In the present article, we extend our previous work by reporting the detection thresholds and the perceived intensities for three kinds of vibration actuators.

2. The power law explains a relation between stimulus intensity and its sensation magnitude using a power function (Stevens, 1957). That is, $\psi = k\phi^a$, where $\psi$ is sensation magnitude and $\phi$ is stimulus intensity.

3 Experiment I: Absolute Detection Thresholds

In this section, we describe the design and results of Experiment I that measured the absolute thresholds of sinusoidal vibrations delivered to the hand through a mobile device.

3.1 Methods

3.1.1 Apparatus. The apparatus used in this experiment is shown in Figure 1. The key component was a commercial mini-shaker (Brüel & Kjær; model 4810) that has high precision and repeatability in a wide bandwidth (18 kHz in the unloaded condition). The shaker was placed inside a heavy metal enclosure to prevent interference by ambient vibration. A cellular phone (LG Electronics; model KH-1000; size = $51.6 \times 98 \times 22.15$ mm; weight = 120 g) was connected to the shaker through a rigid adapter. The phone protruded through a hole in the top plate of the enclosure, so that it could be grasped by the hand. The
phone was taken from a repair kit, and was missing a few parts, including an LCD panel. The weight difference from the regular phone was compensated for by adding plastic weights around the LCD opening inside the case. A high-precision accelerometer (Kistler; model 8630C) was also fastened to the adapter. The total weight of the vibrator assembly, including the dynamic mass of the shaker, was 201.7 g.

The shaker system was controlled by a computer using a data acquisition board under an open-loop control scheme. An analog signal generated from the board passed through a high-bandwidth linear power amplifier (Brüel & Kjær; model 2718), and the amplifier output excited the shaker vertically (along the length direction of the cellular phone). The accelerometer output was captured by a 16-bit analog-to-digital converter at a sampling rate of 10 kHz using the data acquisition board.

Since the shaker has frequency-dependent gains, we identified the relationship between input (voltage command in a program) and output (vibration measured by the accelerometer) in the unloaded condition. For each test frequency, the following procedure was repeated. First, the shaker was driven with sinusoidal voltage waveforms of 10 amplitudes. The resulting vibration amplitudes were retrieved from the power spectral densities of acceleration measurements. These vibration amplitudes in acceleration, $A_{acc}$, were converted to equivalent amplitudes in position, $A_{pos}$, by

$$A_{pos} = \frac{A_{acc}}{(2\pi F)^2},$$

where $F$ is the signal frequency. This is equivalent to finding the amplitude of a sinusoidal waveform in position by double-integrating the sinusoidal waveform in acceleration, and is more robust to noise. A straight line was then fitted to the data using the least-square estimation, which usually showed very high accuracy ($R^2 = 0.99$). The inverse of the I/O relationship was used to determine input voltage amplitude for the desired amplitude of output vibration.

The cellular phone on the shaker system vibrated along the length direction, and was mechanically grounded. On the other hand, other portable vibration actuators used in mobile devices, such as the vibration motor or the voice-coil actuator, may have different vibration directions (see Section 5). Their vibrations are also ungrounded; the device weight is entirely supported by the hand. These types of actuators, however, were not appropriate for use in Experiments I and II, which required vibrotactile stimuli in a broad parameter range with high precision and repeatability. Therefore, our strategy was to use the shaker system in Experiments I and II, and then conduct further tests with miniature actuators in Experiment III to analyze the differences.

### 3.1.2 Participants

Ten volunteers (five males and five females; 19–26 years old, average age 22.5 years) participated in this experiment. Nine participants were right-handed, and the other one was left-handed, as determined by self-reports. All participants were everyday users of a mobile device, and reported no known sensorimotor abnormalities. They were paid after the experiment.

### 3.1.3 Stimuli

In the experiment, the participants were presented with sinusoidal vibrations generated by the shaker system. The vibrations had seven frequencies, 10, 20, 40, 80, 160, 320, and 500 Hz. We selected a frequency set that was identical to the frequencies used in Israr et al. (2006, 2007), to allow direct comparisons of results. These two previous studies reported detection thresholds of vibrations transmitted to the hand through common haptic tools (stylus and sphere, respectively).

Each vibration stimulus was 1 s long. This duration was sufficient to obtain stable threshold estimates, since the temporal summation of the PC channel saturates within 1 s (Verrillo, 1965). The same stimulus duration was used previously in other related studies (Brisben et al., 1999; Morioka & Griffin, 2005; Israr et al., 2006, 2007).

### 3.1.4 Procedures

The experiment consisted of seven experimental conditions for the seven frequencies. The order of frequencies (and thus the experimental conditions) was randomized for each participant.

In each experimental condition, we used a one-up three-down adaptive staircase procedure (Levitt, 1971; Leck, 2001). In this method, three consecutive correct responses decrement the stimulus intensity, and one incorrect response increments the intensity, both by a
predefined step size. This combination yields the 79.4 percentile point on a psychometric function as a detection threshold. Each trial had three time intervals; the participant was presented with three 1-s long stimuli separated by 250-ms interstimulus intervals. One randomly selected interval contained a test stimulus, and the other two contained no signal. The participant’s task was to answer in which of the three intervals a vibration was perceived by pressing a corresponding key (1, 2, or 3) on a keyboard. The participant was instructed to make a best guess when he or she was uncertain of the stimulus-presented interval (forced choice). A new trial started immediately after the participant’s response. An initial stimulus amplitude was set much higher than an approximate threshold found in pilot experiments. The step size was initially 4 dB (for faster convergence), and this was then reduced to 1 dB (for finer resolution) after the first three reversals (a reversal occurred if the stimulus amplitude changed from increasing to decreasing, or vice versa). A test series was terminated after 12 reversals at the 1-dB step size.

The participant sat in front of a computer monitor and grasped the cellular phone on the shaker with the right hand, as shown in Figure 2. When vibration is tangential to the skin surface as in Experiment I, the skin is always in contact with a vibrator (as opposed to vibration perpendicular to the skin surface). In this case, absolute thresholds for vibration perception remain independent of grip force, unless the force is so large as to transmit vibration into bones and tendons (Brisben et al., 1999). The grip force with which ordinary users hold the mobile phone on the shaker was about 1.79 N, with a standard deviation of 1.13 N (see Appendix A.1). This small grip force level is unlikely to affect detection thresholds (Brisben et al., 1999). Thus, we did not explicitly control the participant’s grip force. Instead, we asked the participant to grasp the mobile phone comfortably, as he or she usually did. The participant was also instructed to rest the right elbow on an armrest and to use the left hand to enter responses using the keyboard. The participant wore headphones that played white noise to block the faint sound emanating from the shaker. Visual instructions were displayed on the monitor to notify the start and end of each interval, along with audio beeps played through the headphones. No correct-answer feedback was provided during the experiment.

Each participant completed all seven experimental conditions. Prior to beginning each condition, the participant experienced some vibrations of the corresponding frequency. Each experimental condition took about 5–7 min. After finishing each condition, the participant was required to take a break of 5 min to prevent fatigue and sensory adaptation. The entire experiment took about 90 min on average.

After the experiment, a contact area between the participant’s hand and the cellular phone was estimated. The participant’s hand was colored with washable paint, and a sheet of paper was wrapped around the cellular phone. The participant then grasped the phone with the colored hand for a few seconds. The paper was scanned at 1200 DPI, and the number of inked pixels was counted to estimate a contact area using a custom-made program.

3.1.5 Data Analysis. During each experimental condition, we measured vibration accelerations in the trials where the last 12 reversals (six peaks and six valleys) occurred, and saved the data in a computer file. The data were postprocessed after the experiment as follows. We first calculated position amplitudes from each of the 12 sets of acceleration data. The 12 position amplitudes were averaged pairwise, resulting in
six estimates of a detection threshold. The six estimates were averaged for a final threshold, and a standard deviation was also calculated. This procedure of using measured stimulus amplitudes, instead of commanded stimulus amplitudes, compensated for the loading effect of the participant’s hand, and allowed precise measurements of very small detection thresholds.

3.2 Results and Discussion

3.2.1 Contact Area. The common hand posture with which the participants grasped the cellular phone is shown in Figure 3. The phone was usually placed on the palm with the four fingers, not including the thumb, enclosing the phone body. The participants were apt to keep the thumb stretched out. This seems to be a habit that develops to allow pressing of buttons on a cellular phone with the thumb while supporting the phone with the other fingers and palm. Figure 4 shows an example of contact region imprints between the palmar side of the hand and the cellular phone. The imprint confirms that the thumb was not in contact with the cellular phone. Overall, the male participants showed larger contact areas (30.5–56.6 cm²; average 45.0 cm²) than the female participants (26.1–48.3 cm²; average 37.1 cm²). The average contact area of all participants was 41.7 cm² with a standard deviation of 10.3 cm².

3.2.2 Detection Thresholds. The measured detection thresholds for vibrotactile stimuli transmitted to the hand grasping the cellular phone are presented in Figure 5 as filled squares. The average standard deviation across all frequencies was 0.1755 μm, but individual standard deviations are not shown for greater clarity. The detection thresholds followed a conventional V-shaped curve with the minimum located at 320 Hz. Also shown for comparison are five kinds of vibrotactile detection thresholds taken from the literature. The detection thresholds for the uses of stylus- and ball-shaped interfaces are represented by the upward open triangles (Israr et al., 2006) and by the open circles.
Figure 6. Detection thresholds in acceleration converted from Figure 5.

(Israr et al., 2007), respectively. From Morioka and Griffin (2005), the detection thresholds for the fingertip, the whole palm, and a cylinder grasped by the hand were reproduced, and are plotted with the downward open triangles, open diamonds, and open hexagons, respectively. Another set of vibrotactile detection thresholds for a cylindrical tool is also available in Brisben et al. (1999), but these thresholds are not included in Figure 5 because of their similarity to the cylinder data from Morioka and Griffin (2005) represented by the open hexagons, except for very high frequencies.

Whereas the academic literature usually specifies vibrotactile detection thresholds in terms of displacement amplitude, using acceleration amplitude is more standard in the industry (personal communication with LG Electronics). Thus, we converted the detection thresholds in Figure 5 to the equivalent detection thresholds in acceleration, and showed the results in Figure 6. The acceleration detection thresholds were nearly constant at 10–40 Hz, began to decrease at 40 Hz, reached a minimum at 160 Hz, and then increased abruptly at 160–500 Hz.

The detection thresholds resulting from Experiment I were lower than those for the fingertip and the stylus-and ball-like tools. This is to be expected because the contact area of the mobile phone (41.7 cm² on average) was much larger than for the other three cases and other experimental conditions were either very similar or the same. Larger contact area improves the sensitivity of vibration perception due to the spatial summation of the PC channel (Verrillo & Gescheider, 1992). The average contact areas for the stylus and ball interfaces were 5.5 (Israr et al., 2006) and 11.0 cm² (Israr et al., 2007), respectively. In contrast, the detection thresholds for the mobile phone were larger than those for the whole palm and the cylinder grip reported in Morioka and Griffin (2005), in spite of very similar experimental conditions including contact area. The only notable difference was the contact force (grip force) between the hand and a tool. In Experiment I, the participants were instructed to grasp the cellular phone comfortably, and this type of grip resulted in contact forces around 1.79 N (see Appendix A.1). In Morioka and Griffin (2005), however, the contact force was controlled to be 10 N. According to Brisben et al. (1999), controversial evidence exists on the effect of contact force on vibrotactile detection thresholds, but contact forces larger than 1–2 N may enhance vibrotactile sensitivity by transmitting vibrations further to bones and tendons. The present results, although the comparison is indirect, are in favor of this conjecture of Brisben et al.

4 Experiment II: Psychophysical Magnitude Function

Experiment II aimed at obtaining a psychophysical magnitude function that can be used for vibrotactile stimulus design in mobile devices. We measured the perceived intensities of mobile device vibrations at various frequencies (20–320 Hz) and amplitudes (6–45 dB SL) using absolute magnitude estimation. We then regressed a mathematical function to the measured perceived intensities using vibration frequency and amplitude as independent variables. The function form was selected based on the power law. This psychophysical magnitude function can be used to estimate the perceived intensity of mobile device vibration from its frequency and amplitude.

4.1 Methods

Methods that were common to Experiment I are not repeated for conciseness.
4.1.1 Participants. Eleven university students (eight males and three females; 23–27 years old, average age of 25.1 years old; all right-handed and native Koreans) took part in this experiment. All participants reported that they were everyday users of a mobile device and that they had no known sensorimotor impairments. The participants were compensated after the experiment.

4.1.2 Procedures. We measured the perceived intensities of sinusoidal vibrations generated by the shaker system shown in Figure 1. Five frequencies (20, 40, 80, 160, and 320 Hz) and six amplitudes (6, 10, 20, 30, 40, and 45 dB SL) were combined, resulting in a total of 30 experimental conditions. Two frequencies, 10 and 500 Hz, which were included in Experiment I for absolute threshold measurements, were excluded in this experiment. The shaker system was unable to reliably produce vibrations of very large amplitudes at these two frequencies. Note that vibrotactile signals at such low or high frequencies are seldom used in actual mobile device applications. We also removed the plastic weights that had been added to the mock-up phone to make it lighter. The phone weight without the plastic weights was 101.6 g, and the total weight of the moving assembly was 183.3 g.

In order to estimate the perceived intensity, we used the absolute magnitude estimation paradigm (Zwislocki & Goodman, 1980). Each participant finished three sessions. In each session, the 30 vibrations were presented in a random order. The first session was for training, and its results were discarded. In each trial, the participant held the cellular phone in the right hand, perceived a vibration for 1 s, and answered its perceived intensity in free scales without a modulus (standard stimulus) by entering a positive number on a keyboard with the left hand. The next trial began 1 s after the participant’s response. After each session, the participant was required to take a break of 3 min. Prior to the experiment, the participant was given the standard instructions of absolute magnitude estimation, which were taken from Gescheider (1997, p. 254) and translated into Korean. The experiment lasted for approximately 30 min per participant.

We used a more careful shaker calibration procedure in this experiment. The loading effect of the participant’s hand was greater when the vibration stimulation level was high, presumably due to the grip force increase for high magnitude vibration. This loading effect was compensated for by calibrating the shaker I/O relation at each frequency for each participant while the participant’s hand held the mobile phone on the shaker. This individually-tuned I/O relation was used, together with the absolute thresholds measured in Experiment I, to compute input voltage amplitudes to the shaker in terms of the sensation level. We also recorded acceleration readings during the experiment, and computed errors between the desired and measured displacements to assess the loading effect of the participant’s hand.

4.1.3 Data Analysis. The results were normalized following Murray, Klatzky, and Khosla (2003). From the data of each participant, we first computed the geometric mean of the 60 responses from the last two sessions, \( M_p \). The grand geometric mean of all responses made by all participants, \( M_g \), was also calculated. A normalization constant for the participant was then computed by \( M_n = M_g / M_p \). This normalization constant was multiplied by the responses of the participant to obtain normalized perceived intensities.

4.2 Results and Discussion

We first computed the absolute errors between commanded and captured vibration amplitudes caused by the loading effect of the participant’s hand. The absolute errors were very small (0.98 dB on average), and did not exhibit noticeable patterns, except that they were relatively larger at low frequencies (20 and 40 Hz). In Experiment I, we took into account such small errors for accurate estimation of the detection thresholds. In Experiment II, however, the errors were rather insignificant compared to the greater stimulation levels, thus were ignored in the subsequent analysis.

4.2.1 Psychophysical Magnitude Function.

Figures 7(a–e) show the average perceived intensities for each frequency as a function of vibration amplitude.
Figure 7. Vibration amplitude versus perceived intensity (a–e), and frequency versus perceived intensity (f). The circles represent measured values, and the triangles represent those taken from the fitted model in Figure 8.
In each plot, the circles represent the perceived intensities, with the error bars indicating standard deviations. At each frequency, the measured perceived intensity linearly increased with the logarithm of vibration amplitude (note that the amplitude is in dB SL). In Figure 7(f), the same data are redrawn as a function of frequency for each amplitude.

In all the plots, the triangles represent points taken from a best-fitting surface shown in Figure 8, which was obtained using the following nonlinear regression model:

$$\log_{10} I = A \sum_{i=0}^{4} \alpha_i (\log_{10} F)^i + \sum_{i=0}^{4} \beta_i (\log_{10} F)^i,$$

where $I$ is the perceived intensity, $A$ is the vibration amplitude in dB SL, and $F$ is the vibration frequency in Hz. Given frequency $F$, this regression model is linear to $A$ following Steven's power law (note that $A$ is already logarithmic in sensation level). In order to consider the dependence of perceived intensity on $F$, we modeled the exponent and scaling constant of the power function as fourth-order polynomials of $\log_{10} F$. Among other various models tested, this model in Equation 1 yielded the best fit. The best-fitting values of $\alpha_i$ and $\beta_i$ are given in Table 1. The value of $R^2$ was 0.7622, but a few large standard deviations are shown in Figures 7(b) and 7(c), which were caused by a few individual outliers, and thus did not allow further improvement of $R^2$. It can also be confirmed visually that the fitted surface accounts well for the measured perceived intensities. Therefore, the model in Equation 1 with the coefficients in Table 1 can be regarded as an adequate psychophysical magnitude function of mobile device vibration.

Figure 7(f) shows that, for each of low vibration amplitudes (6, 10, and 20 dB SL), the perceived intensities initially increased with frequency, then decreased to a minimum at 160 Hz, and then increased again until 320 Hz. For an amplitude of 30 dB SL, the perceived intensities were nearly constant regardless of frequency. For each of the higher amplitudes (40 and 50 dB SL), the perceived intensities formed a V-shaped curve with a minimum at 160 Hz. In addition, the ranges of the perceived intensities of the same amplitudes differed by frequency. For example, the ranges were 0.91–1.36 at an amplitude of 6 dB SL, and 9.81–28.15 at 45 dB SL. This indicates that the growth rate of perceived intensity was contingent upon vibration frequency.

The perceived intensities in Figure 8 are redrawn in Figure 9 where vibration amplitudes are specified in acceleration. Given frequency, the perceived intensity increased monotonically with amplitude. Given amplitude, the perceived intensity tended to decrease with frequency, which is consistent with the findings of Yao, Grant, and Cruz (2010).

### 4.2.2 Growth Rate of Perceived Intensity

Whether a growth rate of perceived intensity with vibration amplitude depends on frequency has been a controversial issue (Jones & Lederman, 2006), with the rate represented by an exponent in the power law. For instance, Verrillo and Capraro (1975) showed that when the thenar eminence was stimulated by a contactor of 0.28-cm² area without a surround, the exponents of two different frequencies (60 and 250 Hz) were very similar. This is in contrast with a recent study of Morioka and Griffin (2006), which demonstrated clear frequency dependence for a cylindrical handle of 30-mm diameter grasped in the hand with a much larger contact area. Both studies used magnitude estimation to measure perceived intensity.
Table 1. Coefficients of the Psychophysical Magnitude Function

<table>
<thead>
<tr>
<th>Coefficient index (i)</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha_i )</td>
<td>-0.8592</td>
<td>1.9688</td>
<td>-1.5739</td>
<td>0.5419</td>
<td>-0.0682</td>
</tr>
<tr>
<td>( \beta_i )</td>
<td>39.6979</td>
<td>-90.4316</td>
<td>75.0109</td>
<td>-27.0254</td>
<td>3.5759</td>
</tr>
</tbody>
</table>

Figure 9. Another 3D representation of the perceived intensities (solid lines). Vibration amplitudes are specified in acceleration.

Motivated by these findings, we ran linear regressions to find the average slopes of perceived intensity increases, which correspond to the exponents of the power functions, for the five frequencies tested in Experiment II. The results are shown in Figure 10 with standard errors. With increasing frequency, the exponents initially decreased from 0.036 at 20 Hz to 0.027 at 160 Hz, and then increased to 0.029 at 320 Hz, in a U-shape. ANOVA verified that frequency was statistically significant for the exponent, \( F(4, 40) = 3.67, p = .0122 \). Therefore, our data also indicate that vibration frequency affects the rate of sensation growth.

In order to compare our results in Figure 10 with the previous results in Verrillo and Capraro (1975) and Morioka and Griffin (2006), we converted the exponents in Figure 10 in sensation level \( (a_{sl}) \) to those in acceleration \( (a_{acc}) \) by \( a_{acc} = 20a_{sl} \) (this can be easily derived from the power law and the definition of sensation level). The results are summarized in Table 2, where values not measured in the studies are interpolated from neighbor exponents. Compared to Verrillo and Capraro (1975) and Morioka and Griffin (2006), the exponents measured in Experiment II were apt to be larger at the same frequencies, ranging from 0.55 to 0.72. As the experimental methods used in the three studies were not identical, exact causes for the larger exponents are not clear. However, the most pronounced difference seems to be contact area; the mobile phone used in the present study stimulated a much larger skin area on the fingers and palm. The exponent differences may be related to the spatial summation of the PC channel.

5 Experiment III-I: Stimulus Characteristics of Miniature Vibration Actuators

In Experiments I and II, we used the shaker system to produce vibrotactile stimuli in a wide frequency and amplitude range. However, the physical vibration
Table 2. Exponents of Stevens’ Power Law Representing the Rate of Sensation Growth*  

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>20</th>
<th>40</th>
<th>60</th>
<th>80</th>
<th>160</th>
<th>250</th>
<th>320</th>
</tr>
</thead>
<tbody>
<tr>
<td>Verrillo and Capraro (1975)</td>
<td>—</td>
<td>—</td>
<td>0.40</td>
<td>—</td>
<td>—</td>
<td>0.35</td>
<td>—</td>
</tr>
<tr>
<td>Morioka and Griffin (2006)**</td>
<td>0.81</td>
<td>0.52</td>
<td>0.44†</td>
<td>0.46</td>
<td>0.41</td>
<td>0.44</td>
<td>0.32†</td>
</tr>
<tr>
<td>Experiment II</td>
<td>0.72</td>
<td>0.68</td>
<td>0.61†</td>
<td>0.55</td>
<td>0.54</td>
<td>0.55†</td>
<td>0.58</td>
</tr>
</tbody>
</table>

*Vibration intensities are in acceleration (μm/s²).

**Vibrations were along the lateral direction (y direction in Figure 3).

†Interpolated values.

characteristics of miniature actuators used in commercial mobile devices differ in several respects. The aim of Experiment III was to quantify the extent to which the psychophysical magnitude function obtained in Experiment II can account for perceived intensity distributions resulting from the use of miniature actuators. We analyze the proximal stimulus characteristics of two common miniature actuators (a vibration motor and a voice-coil actuator) in this section, and compare the perceived intensity data produced by the shaker and the miniature actuators in the next section.

5.1 Methods

5.1.1 Apparatus. In this experiment, either a coin-type vibration motor (LG Innotek; model MVMF-A345A; diameter = 10 mm) or a voice-coil actuator (Audiological Engineering Corp.; model Tactaid VBW-32; weight = 10.0 g with an adapter) vibrated the mobile phone used in Experiments I and II. As shown in Figure 11, the vibration motor was included in the phone. The voice-coil actuator was installed on the bottom of the phone using a custom-made adapter because of its large size. A smaller LRA (linear resonant actuator), which is used in commercial display-only phones, was an alternative, but we preferred the Tactaid voice-coil actuator since the frequency bandwidth of LRA is very narrow (only several Hz wide). In addition, the Tactaid actuator has been frequently used in haptics research. A triaxial high-precision miniature accelerometer (Kistler; model 8765A; weight = 6.4 g) was rigidly attached to the phone using adhesive wax to capture vibration acceleration. Neither the voice-coil actuator nor the accelerometer was in contact with the participant’s hand during the experiment. The total weight of the mobile phone with the vibration motor was 120 g (with the plastic weights inside the phone), and that with the voice-coil actuator was 111.6 g (without the plastic weights to compensate for the adapter weight). The actuators and accelerometer were controlled by a PC using a data acquisition board (National Instruments; model PCI-6229).
The coin-type vibration motor was placed horizontally, parallel to the plane spanned by the width and height directions of the phone (i.e., $xy$ plane in Figure 11). In this case, the rotor with eccentric mass distribution within the motor rotated in the $xy$ plane, and its vibration energy was evenly distributed on the plane (see Appendix A.2). We thus aligned the $x$ and $y$ axes of the accelerometer to be in the width and height directions of the phone, respectively. Vibration in the $z$ direction was substantially weaker (about 1/10 of the amplitude). On the other hand, the voice-coil actuator vibrated along one direction (the length direction of the phone; $y$ axis in Figure 11), similar to the shaker.

5.1.2 Procedure. Ten university students (five for each actuator) participated in this experiment. Their task was simply to grab the mobile phone comfortably. This was to average individual differences in the skin impedance and the grip force on the measurements of vibration stimuli.

In order to drive the vibration motor, ten constant voltages in the range of 1–5.5 V with 0.5 V step size were used. The angular velocity of a rotor is proportional to the input voltage to a vibration motor. Thus, a DC input produces a sinusoidal vibration in a vibration motor. In a voice-coil actuator, a sinusoidal voltage waveform needs to be applied to obtain a sinusoidal vibration output. We prepared 168 sinusoidal waveforms by combining 14 frequencies in the 50–500 Hz range (50, 100, 150, 200, 220, 250, 260, 280, 300, 320, 350, 400, 450, and 500 Hz) and 12 amplitudes in the 0.1–3.0 V range (0.1, 0.3, 0.5, 0.55, 0.6, 0.8, 1.0, 1.2, 1.5, 2.0, 2.5, and 3.0 V). In pilot experiments, the voice-coil actuator exhibited better performance at 200–350 Hz and 0.5–0.8 V. Therefore, we subsequently used finer resolution in this region for more detailed data.

In each trial, a vibration actuator was excited for 1 s, and the resulting vibration acceleration was measured at a sampling rate of 10 kHz. The average grip force for an ungrounded mobile device was measured as 1.75 N with a standard deviation of 1.42 N (see Appendix A.1). These values were similar to those of the grounded case. The accelerations collected in this way represent the physical intensities of vibrotactile proximal stimuli delivered to the skin of the hand during ordinary usage of a mobile device. For the vibration motor, we recorded accelerations in the $x$ axis (vibrations along the $x$ and $y$ axes were almost the same). For the voice-coil actuator, accelerations along the $y$ axis were measured. After each trial, a break was enforced so that the skin impedance was fully restored.

5.2 Results and Discussion

The physical characteristics of vibrations generated by the vibration motor are summarized in Figure 12 as a function of applied voltage. The error bars represent standard deviations. Figure 12(a) presents average principal frequencies taken from the power spectral densities of acceleration measurements. As applied voltage increased from $v = 1.0$ to 5.5 V, the average principal frequency increased from 65 Hz to 284 Hz, but the rate of frequency increase was reduced at high voltages. The principal frequencies were very consistent with very small standard deviations, except for the highest applied voltages of 5 and 5.5 V.

Acceleration amplitudes of vibration at the principal frequencies were also found from the power spectral densities and were averaged for each applied voltage. The results are plotted in Figure 12(b). The average acceleration amplitude of vibration increased from 0.14 G at $v = 1.0$ V to 2.61 G at $v = 5.5$ V, and the increase rate diminished after $v \geq 4$ V. The variability of acceleration amplitude of vibration was also much larger for $v \geq 4$ V, indicating that the vibration motor operation was not very reliable in the high voltage range.

Position amplitudes of vibration calculated using the principal frequencies and the acceleration amplitudes were also averaged, and are shown in Figure 12(c). These varied in a range of 7.5–8.1 $\mu$m, with consistent standard deviations, creating a nearly flat line. This was to be expected, since the movement of a mobile device driven by a vibration motor is circular and its movement radius should be constant in the steady state (see Appendix A.2).

Figure 13 presents the physical characteristics of vibrations produced by the Tactaid voice-coil actuator. In Figure 13(a), the average principal frequencies of
vibration outputs are shown for each input frequency, with the error bars indicating standard deviations. Only vibrations with input frequencies higher than 200 Hz preserved the input frequencies. The operation of the voice-coil actuator for input signals with lower frequencies was rather erratic, with very large standard deviations. This is partly due to the operating principle of a voice-coil actuator. A voice-coil actuator contains mass and spring elements, and makes use of their mechanical resonance to produce high-amplitude vibration. The nominal resonance frequency of the voice-coil actuator was 250 Hz.
Position amplitudes of vibration induced by the voice-coil actuator are shown in Figure 13(b). Out of 12 input amplitudes used in the experiment, the results of only five input amplitudes are included for visibility. The data indicate that the magnitude gains of the voice-coil actuator were not linear. The gains were relatively low for input amplitudes in the range of 0.1–0.5 V, and increased abruptly in the range of 0.5–0.6 V. Further increases of input amplitude did not noticeably increase the output. Distinct peaks were also observed at 250 Hz, which is the resonance frequency of the actuator.

6 Experiment III-2: Perceived Intensities of Miniature Vibration Actuators

The purpose of this experiment was to measure the perceived intensities of mobile device vibrations produced by the two miniature actuators (a vibration motor and a voice-coil actuator), the physical characteristics of which were examined in Experiment III-1. The results were compared with the psychophysical magnitude function obtained in Experiment II in order to assess the applicability of the function.

6.1 Methods

6.1.1 Apparatus. The hardware setup of this experiment was identical to that of Experiment III-1.

6.1.2 Participants. Ten participants (22–31 years old, average age 25.4 years) participated in the experiment for the vibration motor, and another ten participants (23–31 years old, average age 25.2 years) participated in the experiment for the voice-coil actuator. All participants were everyday users of a mobile device, and reported no known sensorimotor abnormalities. They were compensated after the experiment.

6.1.3 Procedure. Input signals for the vibration motor were 10 DC voltages in the range of 1–5.5 V with 0.5 V step size. Those for the voice-coil actuator were 24 sinusoidal waveforms, and their parameters were the combinations of six frequencies (220, 250, 260, 280, 300, and 320 Hz) and four amplitudes (0.6, 0.8, 1.0, and 1.2 V). We used 250 Hz instead of 240 Hz since 250 Hz was the nominal resonance frequency of the voice-coil actuator. The selected parameter range included the usable response range of the voice-coil actuator found in Experiment III-1.

6.2 Results and Discussion

6.2.1 Perceived Intensity. The perceived intensities of mobile device vibrations produced by the vibration motor were averaged across all participants, and the results are shown in Figure 14(a). The error bars represent standard deviations. Overall, the average perceived intensity tended to increase with applied voltage, but its increase rate was slowed after $v \geq 3.5$ V. Indeed, Tukey’s HSD test confirmed that the perceived intensities for $v \geq 3.5$ V were not statistically different, $q(0.95; 9, 190) = 4.53$; minimum significant difference = 2.72. This suggests that driving the vibration motor with voltages higher than 3.5 V is not beneficial for perceived vibration strength while using more electric power.

Average perceived intensities for the voice-coil actuator are provided in Figure 14(b) for each input frequency. Standard deviations were 1.06, 2.78, 2.38, 1.03, 0.58, and 0.73 for the vibrations of 220, 250, 260, 280, 300, and 320 Hz, respectively, but are not shown for visibility. Given an input amplitude, the perceived intensities formed an inverted V-shaped curve as a function of frequency, with a distinct peak at 250 Hz. The perceived intensities of 250 Hz vibrations were much larger than those of the other frequencies for all input amplitudes. This was because the voice-coil actuator had the largest magnitude gain at 250 Hz (Figure 13[b]) and the detection threshold at 250 Hz was among the smallest (Figure 5). Other frequency vibrations, except for 250 and 260 Hz, resulted in significantly lower perceived intensities, less than 5 (the maximum is about 12). These results suggest that the voice-coil actuator should be driven with a 250-Hz input signal in order to
deliver high perceived intensity. Other input frequencies around 250 Hz can still be used to make diverse vibration effects, but their discriminability from 250 Hz vibration is in question due to the relatively poor human vibrotactile discriminability of frequency.

### 6.2.2 Comparisons of Perceived Intensity

The psychophysical magnitude function for mobile device vibrations attained in Experiment II was measured using the shaker in the grounded condition, while the perceived intensities reported in Experiment III resulted from the two miniature actuators in the ungrounded condition. In order to evaluate the applicability of the psychophysical magnitude function, we compared the two data sets. First, from the shaker data, we computed equal sensation contours, which represent vibration frequencies and amplitudes resulting in the same perceived intensity. The equal sensation contours are shown in Figure 15, where each intensity value is specified on the corresponding contour. We then mapped the perceived intensities of the miniature actuators into the contours. The results appeared primarily in the upper right-hand side of Figure 15. The parameter range covered by the shaker was clearly broader than those of the two miniature actuators.

For direct comparison, we interpolated the perceived intensities obtained with the shaker so that they matched the vibration frequencies and amplitudes used for the two miniature actuators. The results are presented in Figure 16, where the predicted perceived intensities from the shaker data are represented by triangles, and the perceived intensities measured using the miniature actuators are indicated by circles. In Figure 16(a), the changing trends of perceived intensities were almost identical between the shaker and the vibration motor.

![Figure 14. Average perceived intensities of mobile device vibrations produced by the miniature actuators.](image1)

![Figure 15. Equal sensation contours.](image2)
The predicted and actual perceived intensities were highly correlated, with a correlation coefficient of 0.99. The same can be seen in Figure 16(b) between the shaker and the voice-coil actuator. The correlation was also very high, with a coefficient of 0.97.

On the other hand, the perceived intensities resulting from the shaker were consistently higher than those from the miniature actuators by a large amount. In general, the perceived intensity of vibrotactile stimulus is affected by many factors, such as vibration direction (Morioka & Griffin, 2006), grip force (Morioka & Griffin, 2007), and weight (Yao et al., 2010). The factor values relevant to the present study are summarized in Table 3. The table suggests that a main reason was the device weight difference; the total weights for the shaker, vibration motor, and voice-coil actuators were 183.3, 120.0, and 111.6 g, respectively. Yao et al. recently showed that mobile device weight is an important factor that increases the perceived intensity of the vibrotactile stimulus.

The average ratio of perceived intensities between the shaker and the vibration motor was 138%, and that between the shaker and the voice-coil actuator was 240%, even though the total weight difference between the vibration motor and the voice-coil actuator was very small (8.4 g). Vibrations produced by the vibration motor were two-dimensional in the $xy$ plane, stimulating the hand in both the fore-aft and lateral directions (corresponding to the $x$ and $y$ axes in our notation), whereas those by the voice-coil actuator stimulated the hand only along the lateral direction. The multidimensional stimulation of the vibration motor may have contributed to its larger perceived intensity for the same frequency and amplitude.

In addition, the current data do not clearly exhibit the effects of phone-supporting condition (grounded/ungrounded). Even the grip forces were similar (see Appendix A.1).

The above comparisons allow us to draw two conclusions. First, the psychophysical magnitude function measured in Experiment II can be reliably used for predicting the changing trends in the perceived intensities

| Table 3. Comparison of Experimental Setups Between the Three Vibration Actuators |
|-----------------------------------|----------------|----------------|
| Actuator                          | Shaker         | Vibration motor | Voice-coil actuator |
| Vibration direction               | $y$ axis       | $x$ and $y$ axes | $y$ axis |
| Phone holding                     | Grounded       | Ungrounded      | Ungrounded |
| Grip force                        | 1.79 N         | 1.75 N          | 1.75 N       |
| Total weight                      | 183.3 g        | 120.0 g         | 111.6 g      |
of mobile device vibrations produced by miniature vibration actuators. Second, the absolute values of the psychophysical magnitude function needs to be scaled up or down depending on the weight of a mobile device and the vibration direction. Exact formulas for this scaling are not yet known.

7 Conclusions and General Discussion

In this paper, we explored the human perception of mobile device vibration in terms of the absolute detection threshold and the subjective perceived intensity when vibrations are transmitted to the hand through a mobile device held in the hand. Three psychophysical experiments were conducted. Experiment I presented the detection thresholds of sinusoidal vibrotactile stimuli at frequencies in the range of 10–500 Hz, measured using a mechanical shaker. The thresholds were also compared with previously published detection thresholds under tool uses. Our thresholds were generally smaller than those of the tools that were held with smaller contact area and small grip force (stylus and ball interfaces). A handle that was grasped with a much higher grip force was also demonstrated to have improved sensitivity.

Experiments II and III were concerned with the perceived intensity of mobile device vibration. In Experiment II, the perceived intensities were measured for various vibration frequencies (20–320 Hz) and amplitudes (6–45 dB SL) using absolute magnitude estimation. The vibration stimuli were produced by the shaker. From the measured data, we constructed a psychophysical magnitude function based on the power law. The magnitude function maps vibration frequency and amplitude to perceived intensity. In order to validate the utility of the magnitude function, we performed Experiment III, which estimated the vibratory perceived intensities resulting from two common miniature actuators (a vibration motor and a voice-coil actuator). Comparisons between the results of Experiments II and III led to the conclusion that the psychophysical magnitude function can faithfully account for the changing patterns of perceived intensity with respect to vibration frequency and amplitude. This is an important benefit because most vibrotactile effects are designed by varying their parameter values over time. The comparison results also indicated that in order to use the magnitude function for predicting the absolute level of perceived intensity, additional scaling laws that take mobile device weight and vibration direction into account are necessary. To our knowledge, the data for perceived intensity for mobile device vibration in a wide parameter range (Experiment II) and those for commercially used actuators (Experiment III) are the first of their kind.

The findings of this paper can be used for many purposes in designing vibrotactile applications for handheld devices. For instance, the developers of vibration actuators for mobile devices often suffer from a lack of the perceptual data necessary to define specifications (personal communication with LG Electronics). The psychophysical magnitude function presented in this study can serve as a quick reference for actuator design. In addition, adequate understanding of perceived intensity can be critical in designing effective vibrotactile effects. For example, tactile icons that are evenly separated along perceived intensity have been shown to have significantly improved discriminability (Ryu & Choi, 2008) and absolute identifiability (Ryu, Lee, & Choi, 2010), even in the presence of other dominant factors such as rhythm (Ryu, 2010). The magnitude function can provide an exact basis for this purpose.

In future work, we are planning a series of follow-up studies to investigate the effects of device weight and vibration direction on the perceived intensity of mobile device vibration. Comprehensive data for vibrotactile perceived intensity in relation to the user’s age would also be valuable, given the needs of the mobile device industry.

Acknowledgments

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References


Appendix A

A.1 Grip Force Measurement

Eight participants (25–30 years old, average age 27.1 years) participated in this experiment to measure grip force while holding the mock-up cellular phone. A thin aluminum 10-mm diameter plate was fastened to the side of the phone that was pressed by the thenar eminence of the hand. A film-type pressure sensor (Tekscan Inc.; model FlexiForce A201) was placed between the phone and the aluminum plate. This was necessary for reliable grip force sensing due to the small sensing area of the pressure sensor. The attachment position of the aluminum plate was manually determined for each participant to accommodate individual differences in hand size and grip posture. The pressure sensor was calibrated using standard weights prior to the experiment.

The participants were instructed to hold the phone with a comfortable grip force in two conditions: grounded and ungrounded. In the grounded condition, the phone was attached to the shaker. In the ungrounded condition, the participants held the phone in the air without any mechanical support. For each condition, 10 trials were repeated, and the grip forces were measured in each trial. The participants were asked to release and grasp the phone again between trials.

On average, the grip forces were 1.79 N for the grounded condition and 1.75 N for the ungrounded condition. Standard deviations were relatively large, 1.13 N and 1.42 N, respectively, due to large individual differences. We confirmed via ANOVA that the phone-supporting condition was not statistically significant for the grip force, \( F(1, 6) = 0.03, p = .8605. \)

A.2 Vibration Amplitude Induced by Vibration Motor

A vibration motor is a common DC motor consisting of a permanent magnet and a rotor of eccentric mass distribution. The angular velocity of the rotor is proportional to the voltage applied to the armature windings. The rotor, once rotated, produces large centrifugal force due to its unbalanced inertia. This induces a rotational vibration of a mobile device containing the motor. Thus, vibration frequency generated from a vibration motor is proportional to applied voltage.

The magnitude of mobile device movement actuated by a vibration motor can be derived as follows. As defined in Figure 17, let \( c_r \) be the position of the center of mass of a rotor within a vibration motor, \( c_o \) be that of the other parts of a mobile device except the rotor, and \( c_m \) be that of the mobile device. Their masses are denoted by \( m_r, m_o, \) and \( m_m (= m_r + m_o) \), respectively. The center of rotation of the rotor is at \( p_r \), and that of

![Figure 17. Coordinate definitions for a mobile device with a vibration motor.](image-url)
the mobile device is at $p_m$. When voltage is applied to the motor, these two points rotate with a radius of $r_c$ and $r_m$, respectively, whereas $c_o$ remains fixed at $p_o$. If we denote the unit vectors in the $x$ and $y$ directions by $u_x$ and $u_y$, respectively, then:

$$c_r(t) = p_r + r_r\{\sin(2\pi F_t)u_x + \cos(2\pi F_t)u_y\}$$

$$c_o = p_o,$$

$$c_m(t) = \frac{m_r c_r(t) + m_o c_o}{m_m}.$$

Substituting Equation 4 with Equations 2 and 3 results in:

$$c_m(t) = \frac{m_r p_r + m_o p_o}{m_m}$$

$$+ \frac{m_r}{m_m} r_r\{\sin(2\pi F_t)u_x + \cos(2\pi F_t)u_y\}.$$  (5)

On the right-hand side of Equation 5, the left term is the center of rotation of the mobile device, and the right term expresses its rotational motion. Therefore, the rotation radius of the mobile device, $r_m$, is:

$$r_m = \frac{m_r}{m_m} r_r.$$  (6)

This indicates that, in the steady state, vibration amplitude in position remains constant, regardless of vibration frequency in the mobile device.