The Vibrotactile Experience of the HOME Button on Smartphones

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Abstract. The vibration of the virtual HOME button is very important for smartphone users. To understand the user experience of different vibration modes of the HOME button, we designed 2 experiments to study this issue. Study 1 compared 4 different HOME buttons that were experienced either in or out of visual sight. The results showed that the perceived intensity was the key factor related to the tactile experience of the HOME button regardless of the particular vibration mode. Study 2 explored the influence of vibration intensity on users' tactile experiences. The results showed that the frequency and amplitude of the vibration had a significant positive relationship with the overall evaluation of the tactile experience. More importantly, this effect was mediated by the perceived intensity. These results have implications for designing vibration modes that satisfy the needs of smartphone users.

Keywords: Perceived intensity · Frequency · Amplitude · HOME buttons

1 Introduction

Mobile phones are becoming part of everyday life, and their prevalence makes them ideal not only for communication but also for entertainment and games. As a means of communication, vibrotactile stimulation plays an important role in the use of mobile phones. For instance, mobile phone vibration engages people at different emotional levels and provides them with new ways of communicating and interacting (Liu 2010). Vibrations can be presented discretely to the user and can provide an alternative to auditory signals when interacting with a mobile handset in inhospitable environments (e.g., surrounded by the noise of traffic when walking on the street) (Qian et al. 2011). Fukumoto and Sugimura introduced Active Click using a vibrotactile signal, and their user evaluations showed that the tactile feedback reduced the touch panel operation time by approximately 5% in a silent environment and 15% in a noisy environment (Fukumoto and Sugimura 2001). Hoggan et al. demonstrated an improvement to not only onscreen typing but also button interactions by using different vibrotactile

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feedback for confirmation of different events (Hoggan et al. 2008). Brewster et al. used vibrotactile feedback to test users' performance, and they found text typing speed on a touchscreen to benefit significantly from tactile feedback in a quiet laboratory environment (Brewster et al. 2007). Therefore, vibrotactile stimulation has an invaluable role in the use of mobile phones.

With updates of mobile phones, the trend has been to replace the traditional physical button feedback with vibrotactile feedback. So what kind of vibrotactile stimulation can result in a better experience? Many studies have investigated the effect of vibrotactile stimulation on mobile phones. The most traditional and practical effect of vibrotactile stimulation for mobile phones has been improving their user interfaces. Nashel and Razzaque (2003) investigated different vibrotactile effects suitable for different contact events, such as pushing a button, crossing button edges, and lingering on a button (Nashel and Razzaque 2003). Hoggan et al. (2008) proved that vibrotactile feedback can boost accuracy and reduce completion time for text entry when the users were using a virtual keypad (Hall et al. 2008). Another use of vibrotactile stimulation is the delivery of information via vibrotactile signals in a mobile device. Li et al. (2008) developed a system called People-Tones, which can inform the user of the presence of friends nearby via vibrotactile cues from a mobile phone. A vibrotactile pattern was made by applying amplitude thresholding and bandpass filtering (Li et al. 2008). Kim and Kim (2007) proposed that users could be informed of the state of a car and the road by a vibrotactile signal in a mobile car racing game (Kim and Kim 2007). Brown and Kaaresoja (2006) developed tactons (tactile icons) to distinguish incoming calls, SMS and MMS by vibrotactile signals (Brown and Kaaresoja 2006). Kim and Tan used piezos to replace the dome structures of keys on a physical keyboard to simulate a flat, zero-travel keyboard with haptic feedback, and their study showed that users typed faster with local haptic keyclick feedback than with global feedback or no haptic feedback (Kim and Tan 2014). However, little research has explored the user experience of vibration. Koskinen et al. (2008) found that the rate of agreement of the keypad's vibra feedback with reality and comfort were higher than those of the keypad without tactile feedback (Koskinen et al. 2008). Therefore, it is necessary to explore users' vibrotactile experience on smart phones to improve the competitiveness of new phone designs.

The user experience of vibration is brought about by the motor, which is determined by its physical parameters. What factors could influence the user experience of vibrotactile stimulation? Some researchers have explored the effect of different physical parameters of vibration in many research fields. For example, the perceived intensity of vibration on a rigid steering wheel was determined using a method of magnitude estimation at seven frequencies (4 to 250 Hz) over a range of vibration magnitudes (0.1 to 1.58 m·s–2 r.m.s.). The comfort contours strongly depended on vibration magnitude, indicating that a frequency weighting for predicting sensation should be dependent on vibration magnitude (Griffin and Griffin 2017). Verrillo et al. (1969) studied the relationship between frequency and perceived intensity and found that it obeys a power law function (Verrillo et al. 1969). Terekhov and Hayward (2014) explored the relationship between the duration of a tactile stimulus and its perceived intensity. The results showed that in the case of a Gabor vibratory skin stimulation, the perceived intensity was negatively correlated with the temporal dimension of the envelope (Terekhov and Hayward 2014).

However, to the best of our knowledge, there has been no work investigating the key dimensions that influence the user experience of vibrotactile stimulation on the HOME button of mobile phones. In addition, there has been no work on the relationship between the users' tactile experience and the physical parameters of the HOME button of mobile phones. Therefore, to provide data relevant to the better design of the vibration characteristics of the HOME button, we designed the present experiment with two main aims. First, we wanted to find the key dimension that influences the users' tactile experience. Second, we investigated the relationship between the key dimension of tactile experience and the physical parameters.

2 Study 1

The aim of this study was to explore the effects of different vibration methods on user experience. Visual information was controlled in this experiment. Furthermore, we analyzed the impact of physical vibration parameters on the tactile experience.

2.1 Method

Participants. Twenty-six participants were recruited to complete this study. The average age was 23.3 years old (SD = 3.07), and there were 16 males and 10 females. All the participants were smartphone users, but they had never used test phones. The whole experiment lasted 90 min, and every participant received ¥60 as a reward after the experiment. The recruitment procedure and research protocol were approved by the Institutional Review Board of the Institute of Psychology, Chinese Academy of Science.

Design. A 2 (feedback method: tactile feedback with or without visual information) $\times$ 4 (vibration pattern: physical button, rotor motor, X-axis linear motor, Z-axis linear motor) within-subject experimental design was used in this study.

For the feedback method, in the condition with tactile feedback with visual information, participants executed tasks while looking at the test phone, whereas in the condition with tactile feedback without visual information, they executed tasks but could not see the test phone through an eye mask. To avoid an effect of the phone brand, the condition with tactile feedback without visual information was conducted in the first block. Then, the condition with visual information was conducted in the second block. In each block, users experienced 4 vibration patterns, which were incorporated into 4 different phones. The detailed parameters of the test phone are displayed in Table 1. The presentation order of these four vibration patterns in each block was randomly determined.

Table 1. Test phones used in the experiment

Phone	TM 1	TM 2	TM 3	TM 4
Vibration pattern	Physical button	Rotor motor	X-axis linear motor	Z-axis linear motor
Amplitude (g)	0.34	0.095	0.8	0.086
Frequency (Hz)	500	200	20	50
Duration (ms)	21.5	295	85	23

Materials. A Tactile Experience Questionnaire was designed to measure users' feelings when using the HOME button of mobile phones. The questionnaire contained 7 items that described the experience from different perspectives, including tactile authenticity, tactile comfort, perceived intensity, tactile timeliness, tactile duration, tactile location concentration, and tactile location proximity. The users needed to evaluate their experience on a 5-point Likert scale for each item. A higher score indicated a better experience. See Appendix for the detailed items. In addition, we set up a single 9-point item to assess the overall evaluation of the tactile experience. On this scale, 1 represented the worst feeling, 9 represented the best feeling, and every participant needed to choose one option that conformed to their feeling about the experience.

Procedure. First, all the participants signed confidentiality agreements before the experiment. Then, the instructions, including the experimental objective and experimental task, were explained by the experimenter. Third, all the participants executed the same experimental tasks on the test phones with different vibration patterns; each participant had two tasks. The first task was to press the test phone HOME button without constraint three times, and the second task was to press and hold the test phone HOME button for 2 s three times. Both of the tasks were performed using three hand positions, i.e., click by right hand thumb while the phone was in the right hand, click by right hand thumb while the phone was in the left hand, and click by right hand index finger while the phone was on the table. The three hand positions are displayed in Fig. 1. Finally, all the participants needed to evaluate their experience with the Tactile Experience Questionnaire and the additional item of overall evaluation of the tactile experience after two tasks. An open-ended question was provided to allow participants to evaluate the advantages and disadvantages of four kinds of vibration patterns.

Fig. 1. Hand gestures

Data Analysis. The data were analyzed using analysis of variance (ANOVAs) with repeated measures to examine the main effect of feedback method, vibration pattern, and the interaction effect of feedback method and vibration pattern. Then, linear regression was performed to investigate the influence of particular tactile experiences on the overall evaluation of the tactile experience. In the end, we used Spearman rank correlations to examine the relationships between tactile experience and vibration physical parameters. The physical button was not included in this part because the physical button did not use a vibration motor. The level of significance was set at $p < 0.05$ (two-tailed). All statistical analyses were performed using SPSS 21.0.

2.2 Results

1. Overall Evaluation of the Tactile Experience
The descriptive results of the overall evaluation of tactile experience in each condition are shown in Table 2. ANOVA with repeated measures showed that the main effect of feedback was significant. The mean overall evaluation of the tactile experience in the block with tactile feedback and visual information was 6.269 (SD = 0.218), which was higher than that in the block with tactile feedback and no visual information (mean = 5.702, SD = 0.241), $F = 14.783$, $p < 0.01$. In addition, the main effect of vibration pattern was also significant, $F = 5.555$, $p < 0.01$. The post hoc tests showed that the mean of the overall evaluation of the tactile experience of TM 2 was 6.615 (SD = 0.231), which was higher than that of TM 4 (mean = 5.096, SD = 0.365, $p < 0.01$) and TM 3 (mean = 5.769, SD = 0.399, $p < 0.05$). The mean of the overall evaluation of the tactile experience of TM 1 was 6.462 (SD = 0.327), which was higher than that of TM 4 (Mean = 5.096, SD = 0.365, $p < 0.01$). The interaction effect of feedback and vibration patterns was not significant.

Table 2. The descriptive statistics of the overall evaluation of tactile experience

Feedback method	Vibration pattern (M ± SD)			
	TM 1	TM 2	TM 3	TM 4
Tactile feedback without visual information	6.077 ± 1.719	6.423 ± 1.554	5.692 ± 2.035	4.615 ± 2.192
Tactile feedback with visual information	6.846 ± 1.782	6.808 ± 1.386	5.846 ± 2.185	5.577 ± 1.963

2. The Influential Factor on the Overall Evaluation of the Tactile Experience
To explore the effect of different dimensions of the tactile experience on the global user experience, linear regression was used to investigate the influence of each dimension. The results of the overall evaluation of the tactile experience showed that only perceived intensity had a significant effect on the overall evaluation of the tactile experience; the standardized regression coefficient was 0.688, $t = 4.641^{**}$, $F = 21.541^{**}$, $adj\ R^2 = 0.451$.

3. The Relationship Between the Tactile Experience and Vibration Physical Parameters
To investigate the relationship between the tactile experience and vibration physical parameters, we converted the vibration physical parameters into ordinal data for this analysis as the data did not conform to a normal distribution. Spearman rank correlations were used to explore the relationship between the tactile experience and vibration physical parameters. The correlation results showed that there was a significant positive correlation between perceived intensity and duration, $r = 0.266$, $p < 0.05$.

3 Study 2

Vibratory sensation is assumed to be a function of amplitude and vibration frequency, and the experience of intensity depends on vibration frequency, amplitude and energy of the vibration (Joel 1935). Additionally, study 1 found that perceived intensity had a significant positive correlation with vibration duration. However, we did not find a significant correlation between other subjective experiences and the objective parameters. One possible explanation was that the motor type was not the same in the four smartphones used in study 1. Thus, we controlled the motor type and adjust the vibration intensity through vibration physical parameters to investigate the relationship between tactile experience and vibration physical parameters in experiment 2.

3.1 Method

Participants. Twelve participants were recruited to complete this study. The average age was 24.2 years (SD = 2.47), and there were 4 males and 8 females. All participants were smartphone users, but they had never used test phones. The whole experiment lasted 30 min, and every participant received ¥25 as a reward after the experiment. The recruitment procedure and research protocol were approved by the Institutional Review Board of the Institute of Psychology, Chinese Academy of Science.

Design. A single factor completely randomized design was used in this study. The independent variable was vibration intensity with three levels: low, medium and high. The dependent variable was overall evaluation of the tactile experience. Twelve participants were randomly assigned to the three levels. The detailed parameters of the test phones are displayed in Table 3.

Table 3. Test phones used in the experiment

Vibration physical parameters	Vibration intensity		
	Low	Medium	High
Amplitude (g)	0.086	0.092	0.165
Frequency (Hz)	50	200	250
Duration (ms)	23	18.5	24.25

Materials. The questionnaire was the same as that used in study 1. To increase the ecological validity of the experiment, we used three vibration intensities of the same test phone to represent the three levels of intensity. The test phone was the TM 4, and the motor was the Z-axis linear motor.

Procedure. The procedure included only the condition of tactile feedback without visual information to avoid the impact of visual information. The users needed to operate the HOME button at three different vibration intensities. The order of these 3 conditions was counterbalanced using a Latin Square across participants.

Data Analysis. The data were analyzed using Pearson correlations to examine the relationship between the tactile experience and vibration physical parameters. One participant's data were excluded from the analysis as an outlier. The level of significance was set at $p < 0.05$ (two-tailed). All statistical analyses were performed using SPSS 21.0.

3.2 Results

1. The Relationship Between the Tactile Experience and Vibration Physical Parameters

Perceived intensity had a significant positive correlation with amplitude ($r = 0.726$, $p < 0.05$) and frequency ($r = 0.780$, $p < 0.05$). The overall evaluation of the tactile experience had a significant positive correlation with frequency ($r = 0.793$, $p < 0.05$) (Table 4).

Table 4. Correlations

	Amplitude	Frequency	Duration
Overall evaluation of the tactile experience	.495	.793**	−.233
Perceived intensity	.726*	.780**	.106

*$p < 0.05$ **$p < 0.01$ ***$p < 0.001$

2. Mediation Analysis

To investigate the relationship among the physical parameters, perceived intensity, and overall evaluation of the tactile experience, we adopted a mediation analysis to explore the mediating effect of perceived intensity between amplitude, vibration frequency and duration and the overall evaluation of the tactile experience.

This research adopted a bootstrap method to examine the mediation effect. First, a * b was tested to determine whether it was significant, where a was the regression coefficient of the independent variable to the mediator variable, b was the regression coefficient of the mediator variable to the dependent variable. Second, if the result of a * b was significant, then c' should be tested to determine whether c' was significant; if c' was significant, it was implied that there was some other mediator or that c' was the regression coefficient of the independent variable to the dependent variable when the mediator variable was added. Third, if c' was significant, it was then necessary to judge the direction of a * b * c'; if a * b * c' > 0, it was implied that the direction of the missed mediator was the same as that in our model, and the missed mediator was called s complementary mediator. If a * b * c' < 0, it was implied that the direction of the missed mediator was contrary to the direction of the mediator in our model, and the missed mediator was called a competitive mediator (Chen 2010). The results were as follows (Table 5).

Table 5. Mediation effect table

	Effect	Boot SE	BootLLCI	BootULCI
Amplitude	40.8594	43.1832	17.9387	219.5323
Frequency	0.01	0.01	0.0006	0.0368
Duration	0.0702	0.4155	−0.3228	0.6568

Perceived intensity had a mediation effect between the amplitude and overall evaluation of the tactile experience (BootLLCI = 17.9387, BootULCI = 219.5323). Perceived intensity had a mediating effect between the frequency and overall evaluation of the tactile experience (BootLLCI = 0.0006, BootULCI = 0.0368). Then, c' was investigated as follows (Table 6):

Table 6. Regression coefficients

	Coefficient	SE	t	p	LLCI	ULCI
Amplitude	−13.879	14.0153	−0.9903	0.351	−46.2132	18.4553
Frequency	0.0073	0.006	1.2244	0.2556	−0.0065	0.0212
Duration	−0.2455	0.1114	−2.1941	0.0595	−0.5016	0.0126

The effect of amplitude on the overall evaluation of the tactile experience was not significant (LLCI = −46.2132, ULCI = 18.4553), and the effect of frequency on the overall evaluation of the tactile experience was not significant (LLCI = −0.0065, ULCI = 0.0212), implying that there were no other mediators in our model.

4 Discussion

The current study investigated the key dimension that influenced the user's experience of vibrotactile stimulation and explored the relationship between the subjective vibrotactile experience and the objective physical parameters of the HOME button on mobile phones. The results showed that the perceived intensity had a significant effect on the overall evaluation of tactile experience and that perceived intensity had a significant positive correlation with vibration duration on the HOME button. Moreover, perceived intensity had a mediation effect between the vibration amplitude and frequency and overall evaluation of the tactile experience.

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 (Ryu et al. 2010). The regression analysis revealed that perceived intensity was a linear function of tactile experience. In other words, when the perceived intensity was higher, the tactile experience was better. To the best of our knowledge, this is the first study to investigate the key dimension that influences tactile experience on the HOME button of mobile phones. In addition, we found a relationship between amplitude/frequency and perceived intensity in our study, which was in line with previous research conclusions (Verrillo and Gescheider 1992; Verrillo 1974; Verrillo and Capraro 1975). Nevertheless, Ryu et al. found that perceived intensity increased with amplitude depending on frequency. These exponents exhibited a U-shaped relation against frequency, with a minimum between 150 and 250 Hz for mobile devices (Ryu et al. 2010), and a chart can be defined the relates the frequency and amplitude of a vibration to its perceived intensity. These values can also be transformed to construct equal sensation contours, each of which represents a set of vibration frequencies and amplitudes that result in the same perceived intensity. These data are useful for the design of effective vibrotactile actuators. Unfortunately, we did not find a significant relationship between vibration duration and perceived intensity, which was the opposite of a previous study (Verrillo and Smith 1976). The reason for this discrepancy may be that the task was too simple. The participants were only required to push the HOME button three times in our study, so the response of the HOME button was rapid and transient, which led to this result.

Moreover, we found that there was a significant positive relationship between vibration frequency and overall evaluation of the tactile experience, which suggested that modification of the vibration frequency could improve users' experience. This was the first attempt to explore the relationship between the physical parameters and tactile experience as far as we know. Meanwhile, we found the mediation effect of perceived intensity between the physical parameters and user experience. This suggested that perceived intensity can be improved by increasing the amplitude and frequency, resulting in an improved user experience. We further explored the mechanism between these factors.

This study had some limitations. First, the participants were all young adults aged from 19 to 31 years. Previous studies have suggested that the user experience of vibrotactile stimulation in the elderly was different from that in young adults (Gescheider and Valetutti 1989; Cholewiak and Collins 1993). Studies with larger sample sizes and range of ages are needed to generalize the findings to a broader population. Second, we only tested the vibration of the HOME button in this study. Vibration can be used in many parts of the smartphone. In future studies, we can explore the vibrotactile experience of users' experience on other parts of the smartphone, for example, the vibrotactile experience of "SMS". Third, we investigated the relationship between three vibration physical parameters and perceived intensity. In fact, perceived intensity is related to many factors of vibration, such as amplitude, frequency, duration, contact area, contact force, contact site and so on (Verrillo and Gescheider 1992). Specifically, for vibration direction, there has been some evidence implicating the dependence of vibrotactile perceived intensity on vibration direction, but the quantitative effect of vibration direction has not yet been measured in terms of absolute measures, which is necessary for the optimal design of vibrotactile actuators and stimuli for mobile applications (Hwang et al. 2013). In this study, the kinds of parameters were limited, and we need to explore more physical parameters in future studies.

In summary, the findings of this paper can be used for many purposes in designing a vibrotactile HOME button for smartphones. For example, the designer of vibration actuators for smartphones often lacks information on the influential factors that are related to the vibrotactile experience. The present results indicated that the designers of vibration actuators should pay more attention to perceived intensity. Perceived intensity can be key to designing a satisfactory vibrotactile interface. In addition, the results of the mediation analysis showed that both amplitude and frequency had an indirect effect on the overall evaluation of the tactile experience through perceived intensity. This finding implies that amplitude and frequency may be adjusted to obtain a highly satisfactory vibration of the HOME button for smartphones. In future work, we are planning a series of follow-up studies to explore the psychophysical magnitude function between vibration physical parameters and user experience across all ages, and the experience should be extended to other operational scenarios on smart phones.

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Appendix

Tactile Experience Questionnaire					
Vibration is very real	1	2	3	4	5
Vibration is very comfortable	1	2	3	4	5
Vibration intensity is very suitable	1	2	3	4	5
Vibration is very timely	1	2	3	4	5
Vibration location is centralized	1	2	3	4	5
Vibration duration is very suitable	1	2	3	4	5
Vibration location is close to touch location	1	2	3	4	5

1 = disagree completely, 2 = disagree, 3 = agree, 4 = very agree, 5 = agree completely

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