Doctoral Dissertation

Perceptual and Affective Characteristics of Complex Multimodal Tactile Stimuli

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by

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ABSTRACT

Tactile stimuli are widely used in recent human-computer interaction (HCI) applications, but their roles generally have been limited to delivering simple information. Recent advances of vibrotactile actuator and rendering enable us to generate more diverse and complex vibrotactile stimuli, which can help to expand roles of tactile stimuli. However, such complex stimuli could not have chances to show their potential in interactions yet, since we have lack of understandings of the perceptual characteristics of them. Moreover, large extents of their emotional characteristics have not been unveiled, although touch is the most affective and empathetic sense among the five senses of the human. Therefore, in this research, we investigate the perceptual and affective characteristics of complex tactile stimuli, as well as suggest some applications of them.

As perceptual characteristics, we investigated the perceived intensity of su-

perimposed vibrations, which is the most fundamental property. Using the stimulus power absorbed by the skin as a metric, we found a simple way to estimate the perceived intensities of superimposed vibrations and verified it through a user study. Then we focused on the qualitative characteristics. Based on the concept of musical chords, we evaluated the degree of consonance (perceived harmony) for superimposed vibrations. Experimental results showed a well-structured relationship between the degree of consonance and two frequencies. We also conducted a large-scale survey that sought appropriate verbal expressions to describe the subjective quality of vibrotactile sensations. Expressions of heaviness and thickness were frequently chosen to describe single frequency vibrations' sensations, and dual-frequency superimposed vibrations were described by fastness, denseness, and bumpiness, bearing a more physical meaning. The low-frequency components such as the beat of superimposed vibrations were described by roughness and bumpiness. Based on these findings, we conducted magnitude estimation experiments for perceived heaviness, roughness, and bumpiness to confirm their appropriateness to express the subjective quality of sensations. The results showed clear relationships between the physical parameters of stimuli and the perceived degree of the subjective quality of sensations. The degree of heaviness is correlated with the frequency components, while those of bumpiness and roughness are highly dependent on the superposition ratio.

In addition to perceptual characteristics, we investigated the emotional properties of complex tactile stimuli. Using the valence-arousal space (VA space), we measured the valence and arousal of various vibrotactile stimuli in user experiments. The results indicated that four parameters—amplitude, carrier frequency, duration, and envelope frequency—showed clear relationships to the valence and arousal of tactile stimuli. Then, we measured emotional responses of multimodal vibrotactile-thermal stimuli. The results indicated that constant temperature stimuli generally shift and intensify the emotional responses of vibrotactile stimuli while preserving the effects of the vibrotactile parameters. However, responses of vibrotactile stimuli with varying temperatures showed a different tendency. Vibrotactile parameters such as frequency and amplitude have considerable effects on arousal, while less on valence. Thermal parameters such as direction (cooling/warming) and extent of temperature change are closely related to valence rating, but rarely related arousal.

Finally, to explore the applicability of the complex tactile stimuli, we suggested two applications. First, we made an adjective-based authoring tool, provide an easier design of superimposed vibrations on an adjectival space. The adjectival space is a 1D or a 2D Cartesian space with adjectival axes that represent the perceived degrees of subjective quality of sensation corresponding to the expressions. We utilized the experimental results abovementioned to build them. The results of user experiment showed the adjective-based authoring is useful and intuitive for composing complex vibrations. Second, we suggested a concept called *emotional augmentation*, means adding haptic stimuli to convert or enhance the existing emotional contents. We validated this by a user experiment with some emojis which have strong emotional meanings. Experimental results indicate that 1) high-frequency vibrations increased arousal, while low-frequency vibrations decreased valence, 2) warming stimuli increased arousal and decreased valence for both positive and negative emojis while cooling stimuli intensify valence ratings. In the post-hoc survey, a considerable number of participants mentioned that sometimes they felt different emotional meanings from the original ones by adding tactile stimuli. Some of them pointed out that adding vibrations which have similar emotional responses (*emotionally congruent stimuli*) generally enhance the original emotional meaning elicited by emojis and vice versa; supports the valence-arousal rating results.

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Part I

Introduction

1. Introduction

1.1 Motivations and Goal of The Research

Tactile stimuli are widely applied to various areas such as information communication [2], multimedia [3], and virtual or augmented environment [4] to enrich users' experience. Although visual and auditory senses are main displays of information, tactile stimuli, or haptic stimuli in a broad sense, have been considered to be a meaningful feature in applications [5]. Commercialized products including mobile devices, automobiles, and wearable devices also started adopting haptic features. Wide-band vibrotactile actuators with a large output power have been developed to meet the needs of the applications. Piezoelectric actuators [6], voice-coils, electrovibration panels [7], and electroactive polymers (EAP) [8] are developed and widely used for researches and applications. The perceptual and affective characteristics also have been studied to help understandings of tactile stimuli. Researchers have investigated the characteristics such as perceived intensity [9, 10], adjectival ratings [11], and emotional responses [12, 13, 14].

However, in most cases, the roles of tactile stimuli were still focused and limited to delivering simple information or providing feedback. In our perspective, the reasons for such phenomenon are twofold. First, we are still lack of perceptual backgrounds of tactile stimuli. This problem is even worse for the perception of complex stimuli such as superimposed vibrations. Second, we have lack of verbal expressions *to express* the sensations of tactile stimuli. There exist only a few words to describe them, as compared to those of the visual or auditory sensations. In the haptic designer's perspective, that also means it is difficult to express the difference between stimuli. Therefore, the advantages of the current rendering and actuator technology have not been applied yet to the design of interactions.

Haptic stimuli have an inherent appealing virtue for enhancing the emotional aspects of interaction. Touch is the most empathetic, affective, and private among the five senses [15]. Not only interpersonal touch, e.g., a handshake, a hug, a kiss, but also touch with objects can convey emotions [16]. The physical properties of objects, for example, texture, temperature, and shape, also affect the elicited emotions [17, 18].

Thermal sensations are another key components in emotional aspects of interactions. Temperature is related to interpersonal relationships such as social warmth [16, 19]. We can also convey emotions directly and effectively through touch, especially in human-human interaction. Beyond this, synthetic thermal stimuli have effects on people's emotions. Earlier studies showed the feasibility of this [20, 21]. However, still, a large extent of the emotional aspects of thermal stimuli are veiled.

In this thesis, we pursue a better understanding of the perceptual and affective characteristics of tactile stimuli and their applicability. To this end, we first investigate the perception of superimposed vibrotactile stimuli in a systematic way with wide ranges of physical parameters. Second, we study the affective characteristics of tactile stimuli in the same way. We combined thermal stimuli and superimposed vibrations to compose complex tactile stimuli. Then we explore the effects of the physical parameters such as the direction and the extent of temperature change, vibrotactile frequency and superposition ratio, amplitude, and duration. Third, we suggest adjective-based authoring and the emotion augmentation framework as applications.

1.2 Contributions

The contributions of this research are summarized as follows:

- Investigated the perceptual characteristics of superimposed vibrations, in terms of perceived intensity and perceived consonance (harmony).
- Proposed an estimation function of the perceived intensities of dual-frequency superimposed vibrations, based on skin-absorbed power.
- Sought the adjectival expressions to express vibrotactile sensations and then quantified the subjective quality of vibrotactile sensations using adjectival measures.
- Explored the emotional responses of vibrotactile and thermal stimuli using a wide range of physical parameters.
- Analyzed the effects of physical parameters of thermal and vibrotactile stimuli on emotional responses.
- Suggested an adjective-based vibrotactile authoring method and a content augmentation method using the complex tactile stimuli as applications.

1.3 Organization

The thesis consists of four parts. First, the introduction part contains the motivations, goals, contributions of this paper with the background of this study in part I. In part II, we present the investigations on the perceptual characteristics of complex vibrotactile stimuli. We investigated the perceived intensity, consonance perception, and adjectival expressions of dual-frequency superimposed vibrations. Part III contains the study on affective characteristics of complex tactile stimuli that include thermal (temperature variations) and superimposed vibration. Lastly, part IV introduces some applications such as an authoring tool and an emotion augmentation framework, which utilizes the perceptual and affective characteristics investigated in this thesis. The conclusion chapter follows the part IV.

2. Background

2.1 Perceptual Characteristics of Tactile Stimuli

2.1.1 Perceived Intensity

The strength humans feel from a single-frequency vibrotactile stimulus has long been studied. Vibrotactile intensity perception depends on many factors including vibratory amplitude, frequency, duration, direction, stimulated body site, contact area, stimulator's weight, and age [22, 23, 24, 9]. Among them, frequency and amplitude are the most elementary variables. The perceived intensity of a single-frequency vibration increases with an increase in its amplitude, following Stevens' power law [25]. The exponent of the power function, which determines the increase rate of perceived intensity, forms a U-shaped curve as a function of frequency [23, 24, 9].

A psychophysical magnitude function for single-frequency vibrations can be defined as a mapping from the frequency and amplitude of a vibration to its perceived intensity. Such a magnitude function can also be transformed to equal sensation contours, which represent a set of vibration frequencies and amplitudes that result in the same perceived intensity [26]. These are analogous to the auditory loudness and the equal loudness contours [27] and can serve as references for vibrotactile stimulus design in a variety of applications. Our group published two psychophysical magnitude functions of vibrotactile stimuli transmitted to a hand through a mobile device [24, 9]; the effect of vibration direction was also modeled in [9].

However, to our knowledge, none of previous studied addressed the intensity perception of superimposed vibrations yet. Instead, we review the perception of superimposed vibration in the followings section.

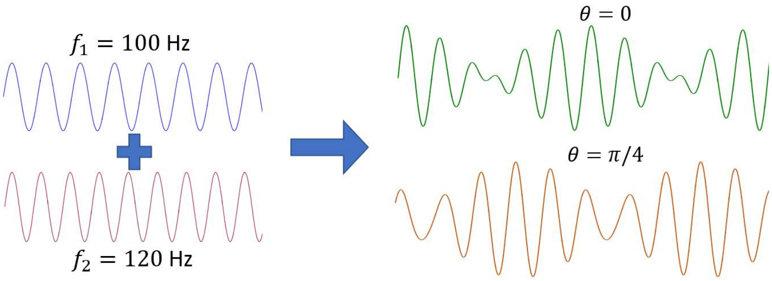
2.1.2 Complex Vibrations

A vibration signal $x(t)$ in which two sinusoidal vibrations $x_1(t)$ and $x_2(t)$ are superimposed can be written as

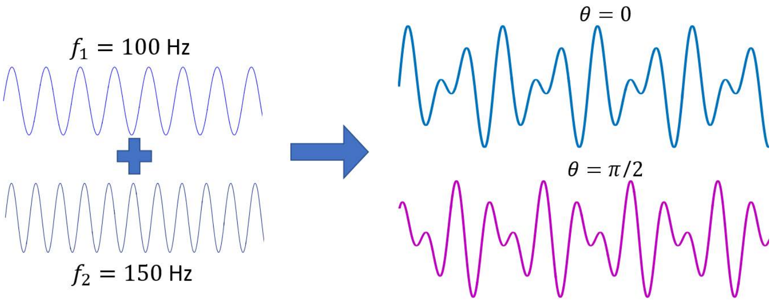
$$x(t) = a_1 \sin(2\pi f_1 t) + a_2 \sin(2\pi f_2 (t - \theta)), \tag{2.1}$$

where a_1 and a_2 are the amplitudes, f_1 and f_2 are the frequencies ($f_1 < f_2$), and θ is the phase offset. $x(t)$ represents the acceleration of the vibration signal in this paper unless specified otherwise. $x(t)$ can express a wide variety of waveforms depending on the values of the five parameters (Figure 2.1).

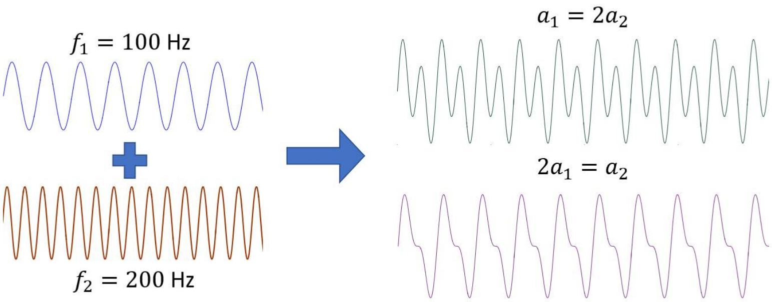
Here, we review the effects of the five variables in (2.1) on the general perception of dual-frequency superimposed vibrations. The two frequencies f_1 and f_2 can be rewritten with the base frequency $f_b = f_1$ and the frequency ratio $f_r = f_2/f_1 (f_r > 1)$, which play a key role in the perception of $x(t)$ [28]. The effect of f_b is similar to that of frequency for single-frequency vibrations: a low-frequency stimulus with frequency below 80 Hz–100 Hz feels like a rough, fluttering oscillation (mediated by the rapidly adapting (RA) channel), whereas a stimulus with a higher frequency is perceived as a smooth vibration (mediated by the Pacinian (PC) channel) [11]. This basic sensation determined by f_b is modulated



(a) $a_1 = a_2$, $f_1 = 100\,\text{Hz}$, $f_2 = 120\,\text{Hz}$, and $\theta = 0$ and $\frac{\pi}{4}$



(b) $a_1 = a_2$, $f_1 = 100\,\text{Hz}$, $f_2 = 150\,\text{Hz}$, and $\theta = 0$ and $\frac{\pi}{2}$



(c) $a_1 = 2a_2$ and $2a_1 = a_2$, $f_1 = 100\,\text{Hz}$, $f_2 = 200\,\text{Hz}$, $\theta = 0$

Figure 2.1: Examples of superimposed vibrations.

by f_r. A low f_r close to 1 generates a clear beat, and this produces low-frequency fluctuation-like sensations. For a high f_r, the beat has a higher frequency, and the overall sensation becomes smoother. For example, both of (50 Hz+ 60 Hz) superimposed vibration and (150 Hz+ 180 Hz) vibration ($f_r = 1.2$) feel rough and intrusive, while the (70 Hz+ 140 Hz) and (150 Hz+ 300 Hz) vibrations ($f_r = 2.0$) feel comfortable and pleasant. The effects of a_1 and a_2 are relatively straightforward. If $a_1 \gg a_2$, the perceptual identify of $x(t)$ is determined by $x_1(t)$, and vice versa. If $a_1 \simeq a_2$, the frequency difference matters as described above. The phase offset θ was shown to have little effect on the discriminability of superimposed vibrations [29]. In [30], the analysis of perceptual relationships between superimposed vibrations made using perceptual spaces were conducted.

Superimposed vibrations often exhibit easily perceptible beats (Figure 2.1a and 2.1b). The frequency of beat is $|f_2 - f_1|$ for the superimposed vibration in (2.1). Thus, the beat frequency is generally lower than the individual frequencies. This is an important perceptual feature distinguishing superimposed vibrations from single-component sinusoidal vibrations [31, 32, 28]. For these reasons, superimposed vibrotactile signals can be perceived to be disparate from single-frequency vibrations.

The discrimination of the different frequency components also have been investigated. An early work of Makous et al. showed the independency of low- and high-frequency bands in vibrotactile masking, named the critical bands of Pacinian channel [33]. In their experiment, participants perceived and discriminated 25 Hz and 200 Hz vibration without interferences. Bensmaïa et al. investigated the intensity perception of superimposed vibrations in terms of discriminability [31]. The results showed that human subjects can discriminate the superimposed vibrations robustly (sensitivity index d' ranged from 1.13 to 5.23).

The results showed that the lower frequency component, as well as the frequency ratio between two components, showed dominant effects on the dissimilarity.

The perception of amplitude-modulated vibrotactile stimuli are also investigated. Amplitude-modulated vibrations are a special case of superposition, and the amplitude of the two frequency components are same. Our group investigated the perceptual space amplitude-modulated vibrations with a carrier frequency of 150 Hz and modulation frequencies in the range 0–80 Hz [34]. The results revealed that perceptual distance (e.g., perceived difference) increased when the modulation frequency was below 5 Hz, but the distance was decreased as the modulation frequency increased from 10 Hz. Modulation with 40 Hz or 80 Hz resulted in a small perceptual distance with the carrier frequency (150 Hz) itself.

2.1.3 Expressions for Subjective Quality of Sensations

Owing to the previous researches, we could understand of the basic perceptual characteristics such as absolute and differential thresholds [31], effects of masking and adaptation [35, 36, 37], discriminability [29], and information transfer [38] of vibrotactile stimuli. However, they have been used vibrotactile stimuli without knowing how to express. This problem undermines the advantages of the current vibrotactile rendering that enables providing diverse and rich vibrotactile stimuli.

Therefore, since Katz's illustration of tactile perception [39], researchers have been investigated how to describe and express the perception of vibrotactile stimuli. Van Erp and Spapé evaluated the suitability of 16 words for expressing the sensations of 59 vibrotactile melodies that were extracted from diverse music pieces [40]. Kyung and Kwon looked at the vibrotactile perceived roughness as a function of the frequency and the amplitude using a vibrotactile pin array [41]. MacLean's group investigated perceptual dimensions underlying the perception using a large number of vibration set consists of various rhythms and amplitudes. They found evenness and duration as two prominent dimensions [42]. Our group also investigated adjectival representations of sinusoidal vibrations in the context of mobile applications [11]. The evaluation of consonance (perceived degree of harmony) of dual-frequency superimposed vibrations [28]. The vibrotactile consonance showed a similar tendency to that of auditory consonance; superposition with adjacent frequency generates a dissonant sensation. Several adjectives including roughness, pleasantness, and evenness were associated to the consonance.

Though the previous studies unveiled some expressions for vibrotactile stimuli, it is still difficult to express the sensations using objective and standard terms unlike other sensory modalities. Expressions representing visual colors, textures, and brightness, for example, have long been established and are used in daily life. The 12-semitone octave scale is the standard for the description of auditory pitch perception.

There are some known factors that affect the subjective quality of sensations. The sensation of vibrotactile stimuli can be varied by the physical parameters such as the frequency and the amplitude. A frequency of 100 Hz is widely used to discriminate the sensation of lower and higher frequency of vibrotactile stimuli, based on the four-channel theory of vibrotactile perception [43]. Tan classified the vibrotactile perception into the four categories by frequency: 1–3 Hz of vibrations as a slow kinesthetic motion, and 10–70 Hz as fluttering and 100–300 Hz as smooth vibrations [38]. In a previous study of our group, we observed that two perceptual dimensions that spanned a low-frequency range (40–100 Hz) and a high-frequency range (100–250 Hz) were close to being orthogonal in a perceptual space of vibrations [11]. Such difference of the sensation is originated from the different channels and mechanoreceptors' activation levels (RA1 and PC, Meissner corpuscle and Pacinian corpuscle). Roy and Hollins introduced the *ratio code* of vibrotactile pitch, which described and quantified vibrotactile pitch (perceived highness) using the ratio of two mechanoreceptors' activation levels [44].

Recently, researchers have been tried to use various adjectives to describe vibrotactile stimuli for intuitive representation. MacLean's group found that two principal dimensions of 'even-uneven' and 'short-long,' using a large number (84) of tactile icons [42, 45]. Our group selected 13 adjective pairs, each consists of antonyms to rate the subjective quality of sinusoidal vibrations [11]. Then the scores were regressed and mapped into a 2D perceptual space of sinusoidal vibrations. As results, the adjectival pairs of 'bumpy–even' and 'rough–smooth' were associated with the frequency of vibrations. The adjectives of 'dark-bright' and 'dull-clear' also can express the vibrotactile sensations in a wide frequency range (40–250 Hz). The pairs of 'slow-fast' and 'bumpy-smooth' are associated to the sensation of low- frequency (40–100 Hz), while pairs of ‘deep–shallow’ and ‘hard–soft’ are related to that of high- frequency (100–250 Hz) vibrations.

2.1.4 Perceptual Metrics

Some perceptual qualities such as *vibrotactile pitch* and *vibrotactile roughness* are frequently investigated.

An early study of von Bèkèsy [46] showed that vibrotactile pitch increases with vibration frequency, but under the influence of other factors such as duration and amplitude. In his experiment that used a 100 Hz vibrotactile stimulus, longer duration increased the perceived pitch in a logarithmic form, whereas higher amplitude decreased the perceived pitch. He also suggested the possibility of the existence of a few separate neural channels associated with vibrotactile pitch perception.

Later studies attempted to relate vibrotactile pitch to the activation levels of associated mechanoreceptive channels. Using 30- and 150-Hz vibrations, Morley and Rowe showed that vibrotactile pitch is correlated with the activation levels of the RA and PC channels [47]. Based on this, they suggested that temporal coding in the impulse activity of the RA and PC channels could be responsible for pitch perception. Unlike this study, Roy and Hollins presented evidence that a ratio code can be a better candidate [44]. They demonstrated that the loudness of the PC channel normalized by the sum of the loudness values of the PC, RA, and SA-I channels can be an appropriate descriptor of vibrotactile pitch in a power function form.

The perceived roughness was frequently investigated as a metric. Lederman et al. investigated the vibrotactile perceived roughness of vibrotactile stimuli using six levels of intensities and two (20 and 250 Hz) frequencies [48]. Klatzky et al. evaluated the roughness of vibrotactile stimuli transmitted from a rigid bar between the skin and a bumpy surface [49]. Their results indicated that perceived roughness is high when the amplitude was high, and the frequency transmitted to the hand was low.

Hollins and Risner suggested that two types of sensory cues, spatial and temporal cues, enable texture perception [50]. The spatial cues, mediated by the SA-I channel, result from spatial features on the surface and are dominant when the features are relatively coarse (feature size larger than 100 μm [51]). The temporal cues are the vibratory cues that occur when the skin is moved against the surface and thus mediated by the RA and PC channels. They are responsible for the perception of fine features (feature size smaller than 100 μm [51]). Hence, it is accepted that vibratory cues alone can elicit rough sensations, and this has been a subject of recent research. In particular, Bensmaïa and Hollins investigated the viability of temporal and intensive codes for vibrotactile roughness perception [52]. Using a set of surfaces with fine features (spatial periods from 16 to 416 μm), they demonstrated that the Pacinian-weighted power of a stimulus is highly correlated with the subjective judgment of roughness, supporting the intensive code than the frequency code.

2.1.5 Measures of Subjective Qualities

How to represent the sensory stimuli is an essential research problem in the human perception. Such representations are mostly describes visual and auditory sensations, which occupy most of the sensory stimuli. For example of visual stimuli, we can find and download an enormous number of a PC background wallpapers with verbal descriptions, such as 'comfort,' 'mysterious,' 'neat,' and so on. Web-based color picker applications such as Adobe Kuler (Color CC[1]) have been developed, and they suggest color combinations to users with descriptions such as monotone, complementary color, and mixed. Words like red, blue or green describe the perception of color, which is determined by the wavelength of light rays which reflected by a surface. Similarly, dim, glare or bright describes the perception of light, which indicates the amount of light accepted by human eyes.

A number of sensory words regarding the five senses were frequently used in daily life. Delicate qualities such as scent or taste often uses adjectival representations and measures. For example, the terms of 'fruity,' 'thick,' 'sweet,' and 'fresh' are often used to express the fragrance of perfume or taste of liquors. Using this, perfumers mix the scents to create a desired fragrance for the customers. Sommeliers also describe the tastes of wine to users using those representations.

Color Systems

In addition, systematical ways to present sensory perception were investigated based on the physical characteristics of stimuli. For example, in color perception, Munsell classified colors systematically using three basic dimensions of hue, value (lightness) and chroma (color purity), and we called it as Munsell's color system [53] in the early 20th century. It was the first systematic repre-

[1]https://color.adobe.com/

sentation of color that separates three perceptually independent dimensions. A standard color system RGB (red-green-blue) [54, 55] was developed from the synthesis of light based on its spectrum. Another standard of the LAB (L*a*b*) color space [56] that parameterizes the activation levels of the cone cells in human eyes. They are commonly used in computer graphics area.

Psychoacoustic Measures

For auditory stimuli, researchers also have been investigated such ways. Psychoacoustic measures such as booming, sharpness, and roughness were already developed and used for audio engineering applications [57]. Booming indicates the portion of the low-frequency sounds, while sharpness does the portion of the high-frequency sounds. Example sounds of large sharpness are screaming, friction sound of metals, whereas those of large booming are engine sound and woofer speaker's sound.

One of the most well-structured system is the octave system and chord notations. In Western music, chords are commonly classed by their root note. For instance, the chord C major can be described as a chord of major quality built upon the note C, and it can be either a two-note chord (called an interval or dyad) or a three-note chord (called a triad). An octave consists of 12 (semi-)tones, so 12 different intervals belong to an octave. Each semitone is separated by one key on a piano, and the frequency ratio of two adjacent semitones is always $2^{\frac{1}{12}} : 1$ (about 1.059 : 1) in the standard tuning. Thus, the frequency of an octave-higher pitch is always twice higher than that of the original pitch.

The perception of musical chords has been extensively studied since the late

19th century. Established theories pertaining to consonance in sound include Helmholtz's theory [58]. Helmholtz argued that consonance and dissonance in sound are determined by the level of acoustic *beat*[2] [58]. Two simultaneously played sound waves interfere with each other, and the human auditory system perceives them as a single combinational tone. When two pure tones are mixed, their frequency difference creates beats. In Helmholtz's theory, if the beats between the frequency components are so intense that humans hear them as rough and unpleasant, then the chords are regarded as dissonant. Otherwise, they are considered as consonant. This theory can account for the perception of consonance in music to a large extent. However, it is not suitable for a very low or high frequency band where the frequency differences between semitones are too small or large. There have been several attempts to describe auditory consonance with pairs of adjectives such as beautiful–ugly, euphonious–cacophonous, and pleasant–unpleasant [59, 60]. Smoothness was also frequently used to describe consonance [61, 62].

Textures

Regarding tactile stimuli, only a few characteristics were investigated. A standard sandpaper numbering system can be a good example [63], which originally designed for finding a suitable sandpaper to grind materials with different hardness. This system also can present perceived roughness of surface; the number indicates the grit size (average particle diameters), and that can provide

[2]A pulsation caused by the coincidence of the amplitudes of two oscillations of unequal frequencies, which has a frequency equal to the difference between the frequencies of the two oscillations (dictionary.com).

different degrees of rough sensations.

2.2 Affective Characteristics of Tactile Stimuli

Among the five major human senses, touch is the most affective, private, empathetic, and emotional with important roles in emotional communication [15]. Not only interpersonal touch, e.g., handshake, hug, and kiss, but also touch with objects can convey emotions [16]. Such emotional states can be expressed visually using emoticons, images, and even colors [64] and aurally using rhythms, melodies, and timbres [65]. Such representations of emotion are widespread, especially in computer-based personal communications such as e-mails, text messages, and social networking services. The physical properties of real and virtual objects being touched, e.g., texture, temperature, and shape, also affect the elicited emotions [17, 18].

2.2.1 Affective Space

There are a few dimensional models to express emotional experiences with appropriate, quantitative parameters. The circumplex model of emotion [1] (also called a valence-arousal (V-A) space) is a quantitative representation of emotion using a mathematical space. The model uses two parameters of valence and arousal which indicate positiveness and intensity of emotion, respectively. PAD (pleasantness-arousal-dominance) model [66] uses the third parameter of dominant-submissive parameter, as well as pleasantness (similar parameter to valence) and arousal.

The circumplex model is typically illustrated with valence along the horizontal axis and arousal along the vertical axis. The emotions are placed in a circle, centered at a state of neutral valence and middle arousal, with emotions close to each other are similar. The four quadrants in circumplex model categorize emotions.

Researchers have been investigated the mapping of emotional responses of sensory stimuli on the circumplex model. For example, a large standardized database, called International Affective Picture Set (IAPS), is available for affective visual images [67]. It includes 956 photographs tagged with their affective ratings, ranging from everyday objects to rare or arousing scenes. A similar database was constructed for 167 natural sounds (International Affective Digital Sounds; IADS) [68]. Affective responses to various multimedia contents, such as movie and music clips, have been studied similarly [69, 70]. Though it has been argued that the circumplex is sometimes not appropriate to present emotions, as well as the type of stimuli would used affect the emotional responses [71], the metric of valence and arousal were used in common. In this thesis, we used the same metrics to evaluate the emotional responses of vibrotactile-thermal multimodal tactile stimuli.

2.2.2 Vibrotactile Stimuli

There has been increasing interest in understanding the emotional responses that synthetic tactile stimuli elicit. For example, six emoticons used in instant messaging were matched to intuitively-designed tactile icons to enrich user experience [72]. It was demonstrated that four distinctive emotions can be communicated using a simple haptic knob [73]. Using a rotating cylinder that stimulated the user's finger, Salminen et al. assessed the effects of several physical parameters on emotional responses in terms of pleasantness, arousal, approachability, and dominance [12]. The same group also evaluated three emotional variables of pleasantness, arousal, and continuity for tactile sensations of movement, e.g., saltation [74]. We also investigated the emotional responses of vibrotactile stimuli using a two-dimensional model consists of valence (perceived pleasantness) and arousal (perceived intensity of emotion) [13].

In [75], we presented a framework that allows for the design of congruent crossmodal icons by matching emotionally similar visual and tactile icons using their V-A responses. This work included one experiment that measured the V-A responses of 24 tactile icons (2 frequencies$\times$2 amplitudes$\times$ 6 envelopes). Their V-A scores generally showed negative correlation, and no tactile icons appeared in the high valence–high arousal or the low valence–low arousal region. The latter indicates that the tactile icons were not associated with very positive and arousing emotions (e.g., excited [1]) or very negative and relaxing emotions (e.g., depressed [1]). Therefore, the emotions that the 24 tactile icons could invoke were rather limited.

Seifi et al. evaluated the affective responses of vibrotactile stimuli with different frequencies and rhythms [76]. They used affective ratings of intensity, roughness, pleasantness, rhythmic–nonrhythmic, and alarming–calm. Rhythm had a statistically significant effect in all the measures, but frequency was significant for only alarming–calm. The effects of four physical parameters (frequency, amplitude, envelope, and duration) on the emotional responses in the V-A space were investigated using a large number of vibrotactile stimuli [13]. Frequency and envelope were generally correlated to valence while amplitude and duration were to arousal. Stimuli with high-frequency, even envelopes were evaluated to be positive, while those with low-frequency, uneven envelopes considered negative. Intense and long stimuli resulted in high arousal scores, while weak and short ones low scores. The range of valence given an arousal score spanned by the vibrotactile stimuli was increased with arousal, forming an inverted triangle in the V-A space. Recently, Seifi et al. introduced a framework to design vibrations with desired affective properties [77]. They first investigated the emotional characteristics of vibrations with a large-scale experiment (10,080 ratings), and then they found expressions that can attribute vibrotactile emotional properties such as agitation, liveness, and strangeness. Lastly they suggested application scenarios using the results, including a vibrotactile authoring tool with predetermined emotion filters which automatically tunes the physical parameters of vibrations.

2.2.3 Thermal Stimuli

Thermal sensation is often considered as a key component for emotional experiences. Temperature is especially related to interpersonal relationships such as social warmth [16, 19]. Several studies investigated the affective characteristics of thermal stimuli. Salminen et al. collected affective ratings of pleasantness, approachability, arousal, and dominance for many profiles of temperature including constant temperatures [20, 21]. Stimuli changing in a warm interval were perceived more dominant and arousing than those varying in a cold interval. However, the temperature changes did not affect pleasantness and approachability. Wilson et al. mapped the emotional responses of various temperature changes into a V-A space [78]. The responses were distributed in a linear region straddling the second and fourth quadrants of the space. Intense changes of temperature were evaluated to negative valence and high arousal scores, while mild changes were to weakly positive valence and low arousal scores. Lee et al. gathered users' interpretations of temperature changes by associating emotions with either warmness or coolness and the extent of temperature change with the degree of emotion [79]. Results suggested that warmness was associated with negative feelings, while coolness was with positive ones (but somewhat obscured by ambient temperature and humidity [80]).

2.2.4 Multimodal Stimuli

Approaches using multimodal stimuli was done to provide stronger emotional experiences. Obrist et al. matched tactile gestures rendered using ultrasonic waves focused on the hand to affective pictures sampled from IAPS [81]. Results showed that the ultrasonic touch stimuli could induce changes in arousal, but with large differences in individual interpretations. The feasibility of the method was demonstrated by collecting the emotional responses of visual and tactile icons and then comparing them to the congruence scores of the combined multimodal icons. Akshita et al. assessed the emotional responses of visual-vibrotactile stimuli [82]. The visual stimuli dominated the valence of the multimodal stimuli, and adding a vibrotactile stimulus to a visual stimulus increased arousal.

2.3 Applications

2.3.1 Tactile Icons and Their Authoring

One of the most simple but widespread applications of the characteristics are designing tactile icons. Tactile icons, also called tactons [83], refer to short tactile stimuli that are associated with abstract meanings. Tactile icons are valuable to users with visual impairments, as well as in many applications where users' visual attention is unavailable or sound stimuli are inappropriate. Studies regarding tactile icon design explored various design variables, such as amplitude, frequency, duration, waveform, envelope, rhythm, and body site [40, 84, 42, 85, 34], to establish effective design guidelines. The main performance measures used were the discriminability, identifiability, and memorability of tactile icons [86].

Tactile icons are actively used in applications. For example, improved key entry on a touchscreen [87], eyes-free navigation [88], and haptic warnings during driving [89], providing a realistic feedback for virtual button [34], presenting graphical user interface haptically [90], and many other applications (see [5].) Use cases of tactile icons are expected to further expand with the recent advent of commercial wearable devices.

The authoring tools also have been investigated to facilitate the design and evaluation of vibrotactile patterns. Outcomes of early-stage intuitive haptic authoring tools, such as Hapticon Editor [91], Haptic Icon Prototyper, and Viv-iTouch Studio [92, 93], and Immersion's Haptic Studio [3] provide intuitive and easy-to-use graphical user interface (GUI) with some unique features. The Hap-

[3] www.immersion.com

ticon Editor and its upgraded version, the Haptic Icon Prototyper, were developed for designing haptic icons to be played via one degree-of-freedom (DOF) haptic device (e.g., a haptic knob). Although the target attribute was a force profile, the two editors may be adapted to designing vibrotactile patterns. In particular, Haptic Studio (Immersion Corp.) has been used for years in the industry. It offers a simple pattern element and a timeline interface on which the elements can be combined for a more complex vibrotactile pattern. Our research group released the posVibEditor, a graphical vibrotactile pattern editor with several advanced functionalities [94]. It supports pattern design and test for multiple vibration motors, which is common in VR and HCI applications, using a multi-channel timeline interface. posVibEditor also suggests a design mode for perceptually transparent rendering that can minimize distortion in the user's percept from intended vibrotactile effect [95].

Various methods were suggested to provide intuitive and easy interfaces for end-users who have no knowledge of the underlying dynamics of vibration generations. Our research group proposed a vibrotactile score that uses musical symbols for vibrotactile pattern design and demonstrated its improved performance and user preference for several representative design tasks [96]. This method adopted graphical user interfaces of a music composing program and customized to represent physical parameters of vibrotactile signals. In the touchscreen environment, the recently released iOS5 includes a notable feature that allows users to design their own vibrotactile patterns by simply tapping on a touchscreen [97]. It is extremely simple, intuitive, and easy to learn, but this customization function of iOS5 allows the user to control only vibration duration. Hence, the user cannot design diverse and complex vibrotactile patterns, that is the current mainstream trend of vibrotactile applications. To this end, our research group proposed a demonstration-based authoring tool [98], to overcome this lack of supportability of the iOS authoring method.

Recently, a web-based vibrotactile authoring library named VibViz, supports faceted library search and browsing [99]. It uses the Infoviz scheme to present subjective characteristics of vibrations, to help to find appropriate vibrotactile icons for a certain event of effect. The same research group conducted a user study of a web-based authoring tool named Macaron, provides an easy user interface based on click and drag [100]. This process is intuitive and easy to learn, allowing the efficient design of vibrotactile patterns even for non-experts. However, it has a limitation on customization; means each vibration in the library are generally immutable and non-editable.

2.3.2 Multimedia and HCI Applications

Tactile icons have been used widely in many applications, such as human-computer interaction (HCI) [5]. A number of studies have investigated its utility in many applications including delivery information, assistive technologies, and even affective interactions [2, 101, 102, 103, 104]. Commercialized libraries such as Immersion's HD haptics[4] already support a diverse vibrotactile patterns to the application developers. Such Vibrotactile rendering can enhance the user's immersion in multimedia contents and entertainment activities. A number of

[4]www.immersion.com

applications and games utilized such function to enrich user experiences.

The author's group suggested several multimedia applications. First, Hwang et al., implemented a real-time dual-band haptic music player [105], using a dual-mode actuator that have two resonant frequencies (175 and 210 Hz). Superposing the two frequencies generates low-frequency beats, which are used to present the lower-frequency bass contents of music, while two high frequencies renders the high-frequency treble components. The algorithm calculated the auditory saliency of frequency ranges of the music to select the range to render, and the signals in that range were rendered haptically. In [106], the author's group also suggested a perception-level translation scheme of auditory signal into haptic signal. Utilizing the auditory roughness [107] and loudness [27], the audio signals in multimedia contents such as movie, music, or game sound, were translated to perceptually-congruent haptic stimuli in real-time.

Recently, its growing demands of novel interactions on the entertainment industry, vibrotactile interaction has been adopted in various applications such as theme park attraction, 4D movies and virtual reality (VR). Lemmens et al., suggested a haptic jacket to enhance the experience of a movie [108]. The jacket uses 64 vibration motors to produce tactile patterns on the user's torso. In [109], 4D motion effects were translated to vibrotactile stimuli using the vibration metaphors of the motion chair movements.

Emotional communications using tactile sensation were investigated. Rovers and van Essen designed and tested tactile icons for six emoticons popular in instant messaging to enrich user interaction [72]. Smith and MacLean used a simple motorized knob to communicate four distinctive emotions of angry, delighted, relaxed, and unhappy [73]. Yohanan and MacLean presented a small robotic creature, which could inform its emotional state through haptic responses, better in valence than in arousal [110]. Rèhman et al. developed a rendering algorithm of human facial expression (i.e., emoticons) on a mobile phone for visually impaired people [111]. Combining all of the visual, audio, vibrotactile, and thermal stimuli, Wilson et al., suggested multimodal emoticons called Multi-moji [112]. They investigated the effects of the parameters of each modality on emotional responses and explored the feasible range of emotional states in the V-A space.

In addition, VR social interaction applications used haptic feedback to provide emotional experiences to the users. Tsetserukou et al., suggested an integrated system named "iFeel IM!" that consists of HaptiHeart, HaptiButterfly, HaptiShiver, HaptiTemper, HaptiTickler and HaptiHug [113, 114]. HaptiHeart mimics the heartbeat patterns according to emotion to be conveyed, and HaptiHug renders the motion of hugging using vibrations. HaptiButterfly and HaptiTickler produce a fluttering and a tickling sensation on a user's abdomen, and HaptiShiver and HaptiTemper produces the shivering and warming sensation to the user's spine. For example, sadness is associated with slightly intense heartbeat and coldness, anger with violent heartbeat and hotness. The system recognizes the emotions from the text messages, and provide the corresponding haptic sensations to them.

Part II

Perception of Complex Vibrotactile Stimuli

3. Perceived Intensity of Dual-frequency Superimposed Vibrations

The perceived intensity is one of the most salient perceptual characteristics of vibrotactile stimuli. Investigations on vibrotactile perceived intensity were conducted, but they are focused on sinusoidal vibrations with single frequency. To our knowledge, intensity of complex vibrations were not investigated yet. Therefore, in this chapter, we address a novel model as to the perceived intensity of superimposed vibration that estimates the perceived intensity of superimposed vibrations, using the intensities of individual frequency components. Based on the previous findings of the literature, here, two hypotheses of perceived intensity of vibrations we would suggest:

1. The perceived intensity of a vibration can be estimated using the skin-absorbed power on the stimulated body site.

2. The perceived intensity of a superimposed vibration can be estimated using the orthogonal sum (Pythagorean sum) of a two-component vibration, that is, $I_1^2 + I_2^2 = I_S^2$, where I_1 and I_2 are the perceived intensities of two component vibrations and I_S is the perceived intensity of their superposition.

To verify the hypotheses, two absolute magnitude estimation experiments were conducted. We first conducted Experiment I to gather perceived intensities of single-frequency, and derived the psychophysical model using the methods of previous studies [24, 9]. Then we conducted Experiment II to compare the measured and estimated (by Pythagorean sum) the perceived intensities of dual-frequency superimposed vibrations. The following sections describe the two experiments, analyze of results, and discussions.

3.1 Theoretical Backgrounds: Skin-absorbed Power and Its Summation

Perceived intensity of a vibrotactile stimulus could be presented as a function of its physical parameters such as amplitude and frequency. Our group have been investigated the the perceived intensity of vibrations transmitted to human hands. We formulated a magnitude function of vibrotactile perceived intensity using parameters of frequency and amplitude [24]. We also investigated the effect of weight of the vibrating object, direction of vibration [9], and grounding [115].

Attempts that associate the physical metrics and the perceived intensity have been conducted. In [116], Bensmaïa and Hollins calculated the Pacinian-weighted power P_p. For a sinusoidal vibration $x(t) = A\sin(2\pi f_s t)$, where A is the amplitude, and f_s is the carrier frequency, the Pacinian-weighted power P_p can be represented by the spectral power of the sinusoid weighted by the detection threshold $T(f_s)$.

$$P_p = (\frac{A}{T(f_s)})^2 \tag{3.1}$$

The metric is useful for estimating the perceived intensity of superimposed vibrations. However, it considered the energy transmitted to the Pacinian channel only, hence the intensities of low-frequency vibrations that mediated by the RA1

(Rapid Adaptation 1, Meissner corpuscle mechanoreceptor) channel could not be appropriately estimated.

To tackle this, our group suggested using the skin-absorbed stimulus power to estimate perceived intensity. We empirically find a relation between the power and vibrotactile perceived intensity [9], as following way: When we perceive a vibration by using our fingertip, the physical energy of a vibrotactile stimulus transmitted to the body is determined by the biomechanical property of the hand-arm system, which is represented by the mechanical impedance Z. Z is defined in the frequency domain as $Z = F/v$, for applied force F and skin movement velocity v. The real part of impedance, $Re[Z]$ is a damping term related to the vibratory energy absorbed by the hand, while the imaginary part $Im[Z]$ contains the spring and mass terms related to the energy stored in the hand-arm system and transmitted to the movement of the other body parts, respectively [117]. Since the magnitude of the imaginary part is known to be much smaller than that of the real part in the frequency range (50 – 300 Hz) used in the experiment, and the vibration power absorbed by the hand is likely to be correlated with the subjective degree of discomfort [118].

Hence, the power absorbed by the hand at frequency f is:

$$P(f) = Re[F(f) \cdot v(f)] = Re[Z(f)] \cdot |v(f)|^2. \tag{3.2}$$

Therefore, for a sinusoidal vibration with acceleration $a(t) = Asin(2\pi f_s t)$, the averaged skin-absorbed power integrated over all frequencies is as follows:

$$P_a = P(f_s) = Re[Z(f)] \cdot |\frac{A}{2\pi f_s}|^2. \tag{3.3}$$

For Z, we took the mechanical impedances of fingertip measured under a pull-only condition from [118], which is the most similar contact condition to that considered in the experiments conducted in this study. Unfortunately, those work is valid for single vibrations, not considered vibrations with multiple frequency components.

To expand those investigations to the superimposed vibration, Based on the findings, we set a hypothesis that the spectral energy would be independently transmitted to the human hands and it is additive in frequency domain. Thus, the perceived intensity of superimposed vibrations can be estimated by the square root of the skin-absorbed power. To confirm this arithmetically, we applied a dual-frequency, superimposed sinusoidal vibration $a(t) = A_1 sin(2\pi f_1 t) + A_2 sin(2\pi f_2 t)$ as the input stimulus to the equation 3.3. Calculating the averaged skin-absorbed power integrated over all frequencies results in:

$$P_a = P(f_s) = Re[Z(f_1)] \cdot |\frac{A_1}{2\pi f_1}|^2 + Re[Z(f_2)] \cdot |\frac{A_2}{2\pi f_2}|^2. \quad (3.4)$$

by calculating average periodic sum of trigonometrical functions. The following is more detailed derivation procedure of the equation.

Let P_s is the skin-absorbed power of a superimposed vibration consists of sinusoids with frequencies of f_1, f_2 ($f_1 \neq f_2$) and amplitudes of a_1, a_2. Also, we assume that the duration of vibrotactile stimuli T is enough longer than the period of the beat of two sinusoids, i.e., $T >> \frac{1}{\|f_1 - f_2\|}$.

We are starting from calculating the power of a signal. The power of a signal in a period is equal to the summation of the squared velocity. For visibility, $2\pi f_1$ and $2\pi f_2$ are substituted to ω_1 and ω_2.

The squared velocity (i.e., power) of the two individual sinusoids are calculated as the following way, since $\sin^2 x = \frac{1+\cos 2x}{2}$.

$$\int_T \|v_1\|^2 = \int_T \| \int a_1 \sin(\omega_1 t)\|^2 dt = \frac{1}{2}\left(\frac{a_1}{\omega_1}\right)^2 \int_T \{1 + \cos(2\omega_1 t)\}$$
$$\int_T \|v_2\|^2 = \int_T \| \int a_2 \sin(\omega_2 t)\|^2 dt = \frac{1}{2}\left(\frac{a_2}{\omega_2}\right)^2 \int_T \{1 + \cos(2\omega_2 t)\} \quad (3.5)$$

Then, the average power of the signals can be calculated as the followings. The cosine terms are oscillating terms, so their limits are zeros. Thus,

$$\lim_{T\to\infty} \frac{1}{T} \int_T \|v_1\|^2 = \frac{1}{2}\left(\frac{a_1}{\omega_1}\right)^2$$
$$\lim_{T\to\infty} \frac{1}{T} \int_T \|v_2\|^2 = \frac{1}{2}\left(\frac{a_2}{\omega_2}\right)^2 \quad (3.6)$$

Then, let us consider the squared velocity of a superimposed vibration $|v_{1,2}|^2$.

$$\int_T \|v_{1,2}\|^2 = \int_T \| \int a_1 \sin(\omega_1 t) + a_2 \sin(\omega_2 t)\|^2 \quad (3.7)$$

Similar to the two sinusoid vibrations, the squared velocity can be calculated as the following.

$$\|v_{1,2}\|^2 = \| \int a_1 \sin(\omega_1 t) + a_2 \sin(\omega_2 t)\|^2 = \| -\frac{a_1}{\omega_1}\cos(\omega_1 t) - \frac{a_2}{\omega_2}\cos \omega_2 t\|^2$$
$$= \left(\frac{a_1}{\omega_1}\right)^2 \cos^2(\omega_1 t) + \left(\frac{a_2}{\omega_2}\right)^2 \cos^2(\omega_2 t) + \frac{2a_1 a_2}{\omega_1 \omega_2}\cos(\omega_1 t)\cos(\omega_2 t) \quad (3.8)$$

Then, integrating the squared velocity for a period can figure out the power of signal.

$$\begin{aligned}\int_T \|v_{1,2}\|^2 &= \int_T \left(\frac{a_1}{\omega_1}\right)^2 \cos^2(\omega_1 t) + \left(\frac{a_2}{\omega_2}\right)^2 \cos^2(\omega_2 t) + 2\frac{a_1 a_2}{\omega_1\omega_2}\cos(\omega_1 t)\cos(\omega_2 t)dt \\ &= \left(\frac{a_1}{\omega_1}\right)^2 \int_T \frac{1-\cos(2\omega_1 t)}{2}dt + \left(\frac{a_2}{\omega_2}\right)^2 \int_T \frac{1-\cos(2\omega_2 t)}{2}dt \\ &\quad + \left(\frac{2a_1 a_2}{\omega_1\omega_2}\right)\int_T \cos(\omega_1 t + \omega_2 t) + \cos(\omega_1 t - \omega_2 t)dt \\ &= \frac{T}{2}\left\{\left(\frac{a_1}{\omega_1}\right)^2 + \left(\frac{a_2}{\omega_2}\right)^2\right\} + (\cos\ terms) \qquad (3.9)\end{aligned}$$

Similarly, the cosine terms are oscillating terms; taking a periodic average of them would yield zero. Therefore, the stimulus energy of a superimposed vibration is equal to the energy of component sinusoids sum. That is,

$$\begin{aligned}\lim_{T\to\infty}\frac{1}{T}\int_T \|v_{1,2}\|^2 &= \lim_{T\to\infty}\frac{1}{2}\left\{\left(\frac{a_1}{\omega_1}\right)^2 + \left(\frac{a_2}{\omega_2}\right)^2\right\} + \left\{\frac{(\cos\ terms)}{T}\right\} \\ &= \frac{1}{2}\left\{\left(\frac{a_1}{\omega_1}\right)^2 + \left(\frac{a_2}{\omega_2}\right)^2\right\} \qquad (3.10)\end{aligned}$$

Now, let us consider the human skin as a system that has an impulse response of $Z(\omega)$, and let $X(\omega) = F(x(t))$ is the Fourier transform of the input signal. Since the total energy of a signal and its Fourier transform is equal (Parseval's theorem). That is,

$$\int_{-\infty}^{\infty} |x(t)|^2 dt = \frac{1}{2\pi}\int_{-\infty}^{\infty} |X(\omega)|^2 d\omega \qquad (3.11)$$

Human skin can be considered as a system with the impedance of $Z(\omega)$, so the skin-absorbed energy can be regarded as the output of the system. That is, $Y(\omega) = X(\omega)Z(\omega)$.

Let us consider two signals of $x_1(t) = a_1 \sin(2\pi f_1 t)$ and $x_2(t) = a_2 \sin(2\pi f_2 t)$. Their fourier transforms, $X_1(\omega)$ and $X_2(\omega)$ would be delta functions, $a_1\delta(\omega - \omega_1)$ and $a_2\delta(\omega - \omega_2)$, respectively. Thus, the output signals would be:

$$\begin{aligned} Y_1(\omega) &= X_1(\omega)Z(\omega) \\ Y_2(\omega) &= X_2(\omega)Z(\omega) \end{aligned} \tag{3.12}$$

Then, let us consider a superimposed vibration $x(t) = a_1 \sin(2\pi f_1 t) + a_2 \sin(2\pi f_2 t)$ consists of two different frequencies of f_1 and f_2. Since $x(t)$ can be easily decomposed to the two sinusoids of $x_1(t) = a_1 \sin(2\pi f_1 t)$ and $x_2(t) = a_2 \sin(2\pi f_2 t)$. Therefore, Fourier transform of input signal $x(t)$ would be rewritten as:

$$X(\omega) = F(x_1 + x_2) = X_1(\omega) + X_2(\omega) \tag{3.13}$$

Then, Fourier transforms of the output $Y(\omega)$ can be calculated to:

$$Y(\omega) = \{X_1(\omega) + X_2(\omega)\} Z(\omega) = X_1(\omega)Z(\omega) + X_2(\omega)Z(\omega) = Y_1(\omega) + Y_2(\omega) \tag{3.14}$$

The energy of $Y(\omega)$, $\mathbf{E}(Y)$, is:

$$\mathbf{E}(Y) = \mathbf{E}(Y_1 + Y_2) = \int_{-\infty}^{\infty} |Y_1(\omega) + Y_2(\omega)|^2 d\omega \tag{3.15}$$

Here, let us separate the real and imaginary parts of Y_1 and Y_2.

$$Y_1 = \mathfrak{Re}(Y_1) + i\mathfrak{Im}(Y_1) \tag{3.16}$$

$$Y_2 = \mathfrak{Re}(Y_2) + i\mathfrak{Im}(Y_2) \tag{3.17}$$

Then, the magnitudes of Y_1 and Y_2 can be written as:

$$\|Y_1\|^2 = \|\mathfrak{Re}(Y_1)\|^2 + \|\mathfrak{Im}(Y_1)\|^2 \tag{3.18}$$

$$\|Y_2\|^2 = \|\mathfrak{Re}(Y_2)\|^2 + \|\mathfrak{Im}(Y_2)\|^2 \tag{3.19}$$

The magnitudes of real and imaginary parts of $Y_1 + Y_2$ would be:

$$\begin{aligned}\|Y_1 + Y_2\|^2 &= \|\mathfrak{Re}(Y_1 + Y_2)\|^2 + \|\mathfrak{Im}(Y_1 + Y_2)\|^2 \\ &= \|\mathfrak{Re}(Y_1) + \mathfrak{Re}(Y_2)\|^2 + \|\mathfrak{Im}(Y_1) + \mathfrak{Im}(Y_2)\|^2 \end{aligned} \tag{3.20}$$

Calculating each part yields the following.

$$\begin{aligned}\|Y_1+Y_2\|^2 &= \mathfrak{Re}(Y_1)^2+\mathfrak{Re}(Y_2)^2+2\mathfrak{Re}(Y_1)\mathfrak{Re}(Y_2)+\mathfrak{Im}(Y_1)^2+\mathfrak{Im}(Y_2)^2+2\mathfrak{Im}(Y_1)\mathfrak{Im}(Y_2) \\ &= \|\mathfrak{Re}(Y_1)+\mathfrak{Re}(Y_2)\|^2+\|\mathfrak{Im}(Y_1)+\mathfrak{Im}(Y_2)\|^2+2(\mathfrak{Re}(Y_1)\mathfrak{Re}(Y_2)+\mathfrak{Im}(Y_1)\mathfrak{Im}(Y_2)) \\ &= \|Y_1\|^2 + \|Y_2\|^2 + 2(\mathfrak{Re}(Y_1)\mathfrak{Re}(Y_2) + \mathfrak{Im}(Y_1)\mathfrak{Im}(Y_2)) \end{aligned} \tag{3.21}$$

Since $\mathfrak{Re}(X) = \frac{X+\overline{X}}{2}$ and $\mathfrak{Im}(X) = \frac{X-\overline{X}}{2i}$,

$$\begin{aligned}2(\mathfrak{Re}(Y_1)\mathfrak{Re}(Y_2)+\mathfrak{Im}(Y_1)\mathfrak{Im}(Y_2)) &= 2\left\{\frac{(Y_1+\overline{Y_1})(Y_2+\overline{Y_2})}{4} - \frac{(Y_1-\overline{Y_1})(Y_2-\overline{Y_2})}{4}\right\} \\ &= (Y_1\overline{Y_2} + \overline{Y_1}Y_2) \end{aligned} \tag{3.22}$$

Thus, the energy of $Y_1 + Y_2$ would be

$$\mathbf{E}(Y_1 + Y_2) = \int_{-\infty}^{\infty} \|Y_1(\omega)\|^2 + \|Y_2(\omega)\|^2 + (Y_1(\omega)\overline{Y_2(\omega)} + \overline{Y_1(\omega)}Y_2(\omega))d\omega \tag{3.23}$$

Now, considering the term $\int_{-\infty}^{\infty} Y_1(\omega)\overline{Y_2(\omega)}$, and it turns into:

$$\int_{-\infty}^{\infty} Y_1(\omega)\overline{Y_2(\omega)} = \int_{-\infty}^{\infty} Z(\omega)\overline{Z(\omega)}X_1(\omega)\overline{X_2(\omega)}d\omega \tag{3.24}$$

$\overline{Z(\omega)}Z(\omega)$ is a finite real number (magnitude of Z at ω), and X_1 and X_2 are delta functions.

$$\overline{X_1(\omega)} = \overline{F(a_1 \sin(\omega_1 t))} = -a_1\frac{\delta(\omega-\omega_1)+\delta(\omega+\omega_1)}{2i},$$
$$X_2(\omega) = F(a_2 \sin(\omega_2 t)) = a_2\frac{\delta(\omega-\omega_2)+\delta(\omega+\omega_2)}{2i} \tag{3.25}$$
$$\tag{3.26}$$

Thus, calculating $\int_{-\infty}^{\infty} Y_1(\omega)\overline{Y_2(\omega)}$ yields:

$$\begin{aligned}
&\int_{-\infty}^{\infty} Y_1(\omega)\overline{Y_2(\omega)} \\
&= -a_1a_2\int_{-\infty}^{\infty} \overline{Z(\omega)}Z(\omega)\frac{\delta(\omega-\omega_1)+\delta(\omega+\omega_1)}{2i}\frac{\delta(\omega-\omega_2)+\delta(\omega+\omega_2)}{2i}d\omega \\
&= \frac{a_1a_2}{4}\int_{-\infty}^{\infty} \overline{Z(\omega)}Z(\omega)\{\delta(\omega-\omega_1)\delta(\omega-\omega_2)+\delta(\omega+\omega_1)\delta(\omega-\omega_2)+ \\
&\qquad \delta(\omega-\omega_1)\delta(\omega+\omega_2)+\delta(\omega+\omega_1)\delta(\omega+\omega_2)\}d\omega
\end{aligned} \tag{3.27}$$

Since the multiplication terms of delta functions are zeros, so all the terms in the integral are zeros. That means, $\int_{-\infty}^{\infty} Y_1(\omega)\overline{Y_2(\omega)}$ is zero. Similarly, $\int_{-\infty}^{\infty} \overline{Y_1(\omega)}Y_2(\omega)$ is zero, too.

Therefore, the following Equation holds.

$$\mathbf{E}(Y(\omega)) = \mathbf{E}(Y_1(\omega)) + \mathbf{E}(Y_2(\omega)) \tag{3.28}$$

Thus, the skin-absorbed power of a superimposed sinusoidal vibration is equal to the sum of two components' skin-absorbed power.

3.2 Methods

3.2.1 Apparatus

Figure 3.1 shows the hardware setup used in the experiments. We used a mini-shaker (Brüel-Kjær, model 4809; frequency bandwidth from DC to 18 kHz) and an amplifier (Brüel-Kjær, model 2719) to generate vibrations. A metal plate (16 cm × 16 cm; thickness 8 mm; Teflon-coated) was attached to the mini-shaker using a bar-shaped bracket. The metal plate worked as a mockup of current commercial tablets, and the total mass of the metal structures was about 550 g. The mini-shaker was placed inside a custom-made table; the metal plate protruded from the table and was covered by a plastic hand rest to provide participants with a stable contact in a comfortable posture. Participants sat in front of the mini-shaker table in a comfortable posture and placed their left index finger on the metal plate through a hole in the hand rest. A computer was used to control the shaker using a data acquisition card (National Instruments; USB-6251) at a sampling rate of 10 kHz. Shaker calibration was done by the standard procedure described in [119] for each vibration frequency used in the experiments.

3.2.2 Participants

Twelve volunteers (6 female and 6 male; average age 21.8 years) participated in Experiment I, and twenty (9 female and 11 male; average age 23.7 years) par-

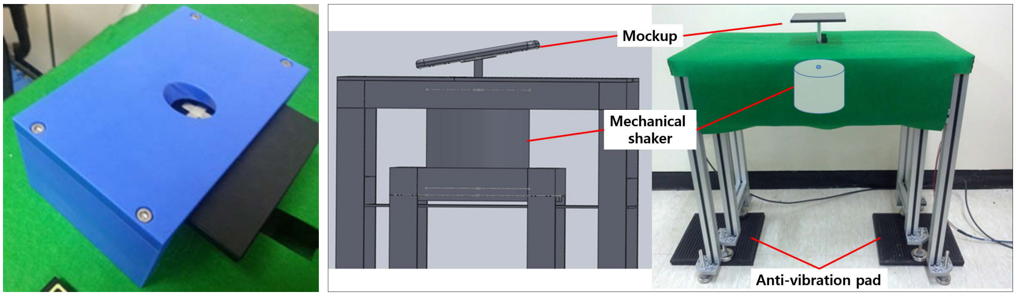


Figure 3.1: Hardware setup used in the experiments.

ticipated in Experiment II. All of them were students enrolled in the authors' institution without any sensory disorders by self-report. Participants of Experiment I were paid 10,000 KRW ($\simeq$ 9 USD) after the experiment, and those of Experiment II were paid 15,000 KRW ($\simeq$ 14 USD).

3.2.3 Procedure

Each experiment used a set of vibrations as the stimulus. Each experiment consisted of four sessions, and the participants perceived and rated every stimulus in each session; hence, each stimulus was repeated four times. The order of stimuli presented in each session was randomized for each participant. The first session was considered as training, and its data were not used for data analysis. Participants were given a 2-min rest between sessions to prevent tactile adaptation and fatigue.

We used the psychophysical method of absolute magnitude estimation [120, 121] as a rating method of perceived intensity. In each trial, the participants perceived a vibration, represented its perceived intensity by a positive number in a free scale without a standard stimulus, and entered the number using a keypad with their right hand. Prior to the experiments, participants were given the standard instructions of absolute magnitude estimation taken from [26, p. 254]. Participants wore headphones to block the noise produced by the mini-shaker. All the experimental procedures are approved by the Institution Review Board in the authors' institution (PIRL-2016-E042).

3.2.4 Data Analysis

Participants' responses collected in each experiment were standardized using the standard procedures given in [121]. We computed the geometric mean M_p over all the stimuli calculated for each participant and the grand geometric mean M_g across all the stimuli and participants. Then, a scaling constant for each participant, $M_n = M_g/M_p$, was multiplied to the participant's scores. These normalized perceived intensities were used for all further analyses.

3.3 Experiment I: Perceived Intensity of Single-Frequency Sinusoidal Vibrations

In this experiment, we gathered the perceived intensity of sinusoidal vibrations transmitted to a fingertip through a flat tablet-like surface (Figure 3.1). Then, we derived a psychophysical magnitude function from the intensities. The results were also utilized as background data to estimate the perceived intensity of superimposed vibrations in Experiment II.

Table 3.1: Parameters of the single-frequency vibrations used in Experiment I.

Frequency (Hz)	Amplitudes (g)				
50	0.300	0.575	0.850	1.125	1.400
80	0.321	0.612	0.903	1.195	1.486
120	0.343	0.652	0.960	1.268	1.577
160	0.368	0.694	1.020	1.347	1.673
200	0.393	0.739	1.085	1.430	1.776
250	0.421	0.787	1.153	1.519	1.885
300	0.450	0.838	1.225	1.613	2.000

3.3.1 Stimuli

The stimuli used in Experiment I were 35 sinusoidal vibrations as specified in Table 3.1. First, we selected seven frequencies ranging from 50 Hz to 300 Hz. Then, we determined five equidistant amplitudes, from $0.3g$[1] to $1.4g$ for the lowest frequency (50 Hz). The amplitudes of the other six frequencies were calculated by multiplying a common ratio of 1.07. Since vibrations of higher frequencies are perceived to be weaker than those of lower frequencies in the same physical amplitude [24, 9], the range was selected to cover more effective area than that we use in actual. The vibration duration was 1 s, which is sufficiently long to avoid the underestimation caused by the temporal summation of the Pacinian channel [22].

[1] In this paper, vibration amplitudes are represented in an acceleration unit g (gravitational constant; $\simeq 9.8\,\mathrm{m/s^2}$) unless specified otherwise.

Table 3.2: Coefficients of the psychophysical magnitude function obtained in Experiment I.

k	0	1	2	3
α_k	225.2	-276.7	126.2	-20.37
β_k	3.718	2.311	-3.801	0.9818

3.3.2 Results

Figure 3.2 shows the perceived intensities of the 35 single-frequency vibrations and a psychophysical magnitude function derived from the experimental data. The magnitude function corresponds to a two-dimensional extension of Stevens' power law:

$$\psi = k\phi^e, \tag{3.29}$$

where ψ is the perceived intensity and ϕ is the physical intensity (in our case, the vibration amplitude). The slope k and exponent e were regressed using the following equations:

$$k = \sum_{i=0}^{3} \alpha_i (\log_{10} f)^i, \;\; e = \sum_{i=0}^{3} \beta_i (\log_{10} f)^i, \tag{3.30}$$

This function form is the same as that used in [9], and it suits our data very well with a high goodness of fit ($R^2 = 0.999$). The values of the coefficients α_i's and β_i's are presented in Table 3.2.

3.3.3 Discussion

The general trends observed from Fig. 3.2 are: (1) Confirmation that the psychophysical model [24, 9] of perceived intensity also can be fitted to the fingertip. (2) Vibrations with high amplitudes are perceived to be stronger, and

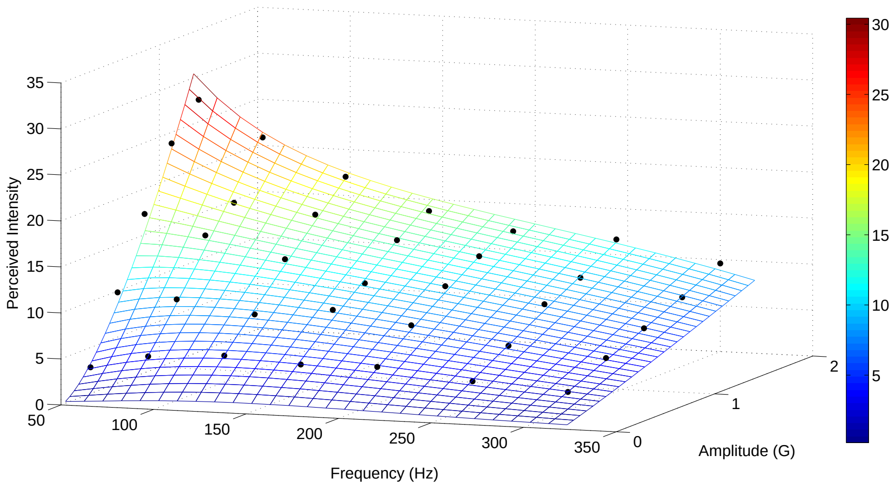


Figure 3.2: Perceived intensities of single-frequency vibrations measured in Experiment I. The measured points are denoted by black dots, and the fitted surface is indicated by a mesh surface.

lower frequency vibrations are perceived to be stronger than higher frequency vibrations for the same amplitude.

(3) Relatively large exponents of Stevens' power law, compared to those reported in previous studies [23, 24, 9].

We have listed the experimental setups of the present and previous literatures in Table 3.3 for comparison. The main differences in the setup are stimulus location and the size of the contact area. Our setup has a small contact area (index fingertip), while the other studies have relatively large ones (whole hand or thenar eminence). Other conditions are similar, except amplitude ranges in [23, 122].

The exponents of Stevens' power law are listed and compared to those of the

Table 3.3: Comparison of experimental setup and conditions used in the previous studies.

Reference	Ours	Hwang 2013 [9], Exp. 2	Ryu 2010 [24], Exp. 2	Morioka 2006 [23], Exp.2	Verrillo 1975 [123], without surround	Verrillo 1969 [122]
Contactor shape	Square plate	Cell phone mockup	Cell phone	Cylinder	Small rod ($0.28\,\text{cm}^2$)	Small rod ($2.9\,\text{cm}^2$)
Contactor mass (g)	550 g	110 g	120 g	2300 g	n.a.	n.a.
The way of contact	Contact without pressure	Grasp	Grasp	Grasp	Attached on the thenar eminence	Attached on the thenar eminence
Vibration actuator	Desktop shaker	Voice-coil actuator	Desktop shaker	Floor shaker	Desktop shaker	Desktop shaker
Test variables	Amplitude, frequency	Amplitude, frequency, direction	Amplitude, frequency	Amplitude, frequency, direction	Amplitude, frequency	Amplitude, frequency
Frequency range (Hz)	50–300	60–320	20–320	8–400	60, 250	25–700
Amplitude range (g)	0.3–2	0.2–2.5	0.02–2	0.02–14	0.01–1.3	0.01–28
Evaluation method	Absolute magnitude estimation	Absolute magnitude estimation	Absolute magnitude estimation	Magnitude estimation	Absolute magnitude estimation	Magnitude estimation and production

literature in Table 3.4. In our results, they exceed 1.0 for low frequencies (50–80 Hz) and 300 Hz; showed larger exponents than those reported in the literatures.

Two plausible reasons for this are: 1) the narrow amplitude range of vibrations, and 2) the size and the location of contact area. First, the narrow amplitude range of vibrations increased the exponent, which is the typical form of stimulus context effect [124]. We used amplitudes of 0.3 g to 2.0 g. The results from [9], which used the most similar stimulus set as ours, also showed larger exponents compared to the others.

The small size of contact area and stimulated location (the index fingertip) also affect the results. The perceived intensity of a sensory stimulus is highly correlated to the power of the stimulus. Though fingertips are a highly sensitive body site in vibrotactile perception, the participants seem to assign much small number to weak vibrations, due to the contrast effect. In addition, such small contact area is not sufficient for the saturation of the Pacinian channel (PC)'s spatial summation. Thus, participants assigned larger number for stronger vibrations. Consequently, the exponents increased.

We plotted equal sensation-contours for frequencies we used in the experiment 3.3. The shape of contours are similar to those in the previous work [9]. The contours exhibited U-shaped forms with valleys around 150 Hz at a weak perceived intensity level (less than 5). This is similar to the typical detection threshold curve of the PC channel that has lower thresholds than the other non-Pacinian (NP) channels in the frequency range tested in our experiment. The valleys disappeared as the intensity of vibration became more intense (intensity

Table 3.4: Exponents of Stevens' power law representing the rate of sensation growth.

Frequency (Hz)	40	50	60	80	100	120	150	180	200	250	300
Ours	.	1.17	1.09*	1.02	0.98*	0.94	0.83*	0.76*	0.74	0.95	1.02
Hwang 2013 [9], Exp. 2	.	.	0.92	0.74	0.68*	0.62	0.63*	0.64	0.66*	0.71	0.78
Ryu 2010 [24], Exp. 2	0.68	.	0.61*	0.55	0.55*	0.54*	0.54	0.54*	0.54*	0.55	0.58*
Morioka 2006 [23], Depth	0.60	0.49	0.47*	0.42	0.41	0.44*	0.39*	0.42	0.46	0.52	0.53*
Verillo 1975 [123]	.	0.40	.	.	.	.	.	.	.	0.35	.
Verillo 1969 [122]	0.89 (from 25 to 350 Hz)										

*: Interpolated values

level higher than 5). At this point, other NP channels such as RA and SA1 channels also respond and contribute to the intensity perception.

3.4 Experiment II - Perceived Intensity of Superimposed Vibrations

In Experiment II, we estimated the perceived intensity of superimposed vibrations. We hypothesized that the perceived intensity of superimposed vibrations can be estimated by the squared sum of skin-absorbed energy. To this extent, we measured the perceived intensities of vibrations and compared them

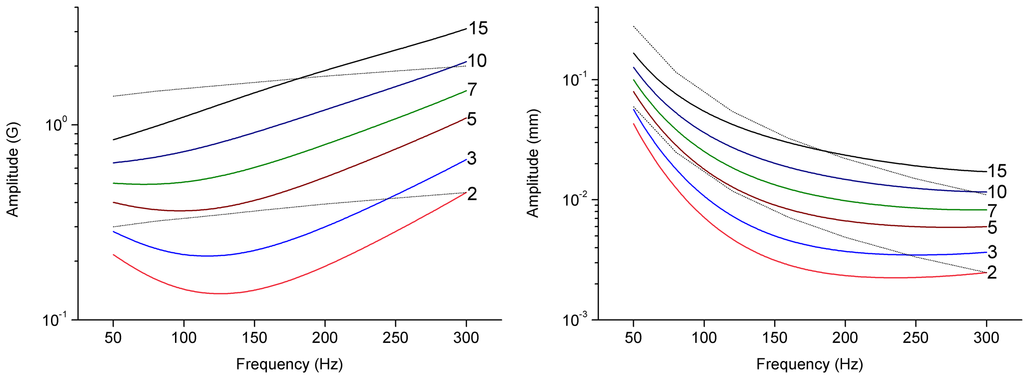


Figure 3.3: Equal sensation contours for fingertip vibrations. Vibration amplitudes are represented in terms of acceleration (left) or displacement (right), where acceleration amplitude = displacement amplitude $\times(2\pi f)^2$. Note that the logarithmic scale in the ordinates. Dotted lines represent the lower and upper bounds of the amplitude we used in the experiment. The contours outside these bounds should be considered extrapolated values.

to the estimation from the squared sum of intensity, irrespective of them holding the hypothesis.

3.4.1 Stimuli

We used both the single- and dual-frequency sinusoidal vibrations. To prevent the stimuli context effect [124], we composed a stimuli set that includes the complete range of frequency and amplitude combinations used in this experiment. Nine frequencies were selected which were evaluated as single-frequency vibrations by themselves, as well as used to compose superimposed vibrations. As amplitude, we selected three levels (strong, medium, and weak) for each frequency. Table 3.5 summarizes the 27 single-frequency vibrations.

We designed the superimposed stimuli with a wide range of parameters.

Table 3.5: Single-frequency stimuli used in Experiment II. (Estimated intensities and amplitudes were taken from the results of Experiment I.)

Frequency (Hz)	50	60	75	90	120	150	170	250	300
Weak	5	5	5	5	5	4	4	3	3
	0.401	0.386	0.371	0.363	0.371	0.317	0.349	0.437	0.664
Medium	15	15	13	11	11	9	9	7	6
	0.839	0.883	0.845	0.772	0.878	0.809	0.897	1.075	1.291
Strong	25	25	21	17	17	14	14	11	9
	1.182	1.296	1.277	1.17	1.411	1.347	1.501	1.737	1.904

We considered three parameters of superimposed vibrations to evaluate range of design spaces. First, we designed 18 frequency combinations, among which six were superpositions of two different low frequency vibrations (< 100 Hz), six were those of two high frequency vibrations (> 100 Hz), and six were those of both low frequency vibration and high frequency vibration. This was done for investigating the effects of frequency range in superposition. Second, the intensity ratio of two components (a1 : a2) was considered. We selected three ratios of 25:75, 50:50, and 75:25. Finally, two amplitudes for each vibration were selected. The amplitudes were decided based on the results of Experiment I. Table 3.6 lists the physical amplitude levels.

In total, 108 superimposed vibrations were generated. Thus, 135 vibrations (27 single-frequency, 108 superimposed) consist of the stimuli set. The duration of stimuli was 1 s, which is same to Experiment I.

Table 3.6: Superimposed stimuli used in Experiment II. (The estimated perceived intensities were calculated from the orthogonal sum hypothesis.)

Frequency (Hz)	Weak				Strong			
	Est. PI	25:75	50:50	75:25	Est. PI	25:75	50:50	75:25
50 + 60	10	0.295	0.506	0.616	20	0.469	0.806	0.982
		0.625	0.501	0.274		1.053	0.845	0.461
50 + 75	9.5	0.285	0.489	0.595	18.5	0.445	0.765	0.932
		0.616	0.478	0.239		1.094	0.849	0.425
50 + 90	9	0.274	0.471	0.574	17	0.421	0.723	0.880
		0.606	0.457	0.212		1.112	0.840	0.389
60 + 75	9.5	0.263	0.482	0.602	18.5	0.435	0.796	0.993
		0.616	0.478	0.239		1.094	0.849	0.425
60 + 90	9	0.253	0.463	0.578	17	0.408	0.747	0.932
		0.606	0.457	0.212		1.112	0.840	0.389
75 + 90	8.5	0.217	0.435	0.560	15.5	0.365	0.729	0.940
		0.574	0.433	0.201		1.018	0.769	0.356
50 + 120	9	0.274	0.471	0.574	17	0.421	0.723	0.880
		0.666	0.483	0.201		1.332	0.967	0.402
50 + 170	8.25	0.259	0.445	0.542	15.75	0.400	0.686	0.836
		0.762	0.541	0.212		1.619	1.150	0.450
50 + 250	7.5	0.243	0.417	0.508	14.5	0.378	0.649	0.791
		1.094	0.801	0.341		2.202	1.612	0.686
90 + 120	8	0.189	0.409	0.541	14	0.323	0.698	0.924
		0.586	0.425	0.177		1.078	0.782	0.325
90 + 170	7.25	0.172	0.372	0.493	12.75	0.296	0.638	0.845
		0.656	0.466	0.182		1.266	0.899	0.352
90 + 250	6.5	0.155	0.335	0.444	11.5	0.268	0.578	0.766
		0.940	0.688	0.293		1.722	1.261	0.537
150 + 170	6.5	0.144	0.372	0.523	11.5	0.284	0.719	1.010
		0.577	0.410	0.161		1.122	0.797	0.312
150 + 250	5.75	0.128	0.323	0.454	10.25	0.249	0.630	0.884
		0.825	0.604	0.257		1.524	1.116	0.475
150 + 300	5.5	0.121	0.307	0.431	9.5	0.228	0.577	0.810
		1.129	0.852	0.394		1.906	1.438	0.665
170 + 250	5.75	0.139	0.355	0.501	10.25	0.273	0.697	0.982
		0.825	0.604	0.257		1.524	1.116	0.475
170 + 300	5.5	0.132	0.337	0.475	9.5	0.250	0.638	0.898
		1.129	0.852	0.394		1.906	1.438	0.665
250 + 300	4.75	0.210	0.493	0.674	8.25	0.377	0.886	1.210
		0.981	0.740	0.342		1.665	1.256	0.581

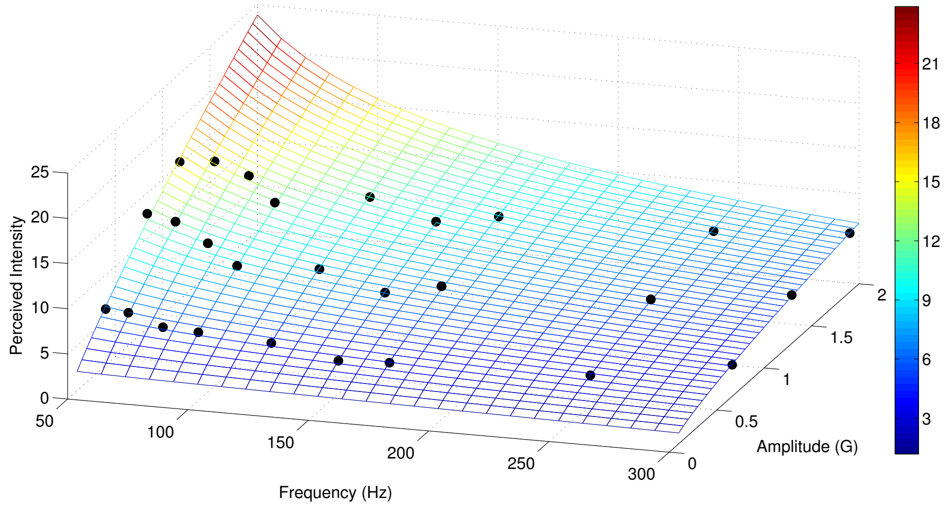


Figure 3.4: Perceived intensity of single-frequency vibrations in Experiment II. Black dots indicates the measured points and colored mesh describes the fitted function.

3.4.2 Results and Discussions

Fig. 3.4 shows the perceived intensity of single-frequency vibrations in Experiment II. However, the general trends and shape of the function remained the same, although the range of magnitude was narrower than that of Experiment I (see Figure 3.4). Thus, we fitted the psychophysical model again and used it for the estimation procedures. The results fitted well ($r^2 > .999$), and the coefficients α_k and β_k are listed in Table 3.7.

We estimated the perceived intensity using Pythagorean summation, and compared the estimations to the measured intensities. Fig. 3.5 and 3.6 show the comparison results of weak and strong vibrations, respectively. The estimation error ranges from 0.35% to 25.2%, with an average error of 4.23% (see Fig. 3.7).

Table 3.7: Coefficients of the perceived intensity model for single-frequency vibrations obtained the results of Experiment II

k	0	1	2	3
α_k	78.985	-72.4829	26.3773	-3.7367
β_k	-0.5272	2.5681	-1.4698	0.2475

The error was less than 10% in most cases. Such level of error is smaller than the difference threshold (i.e., Weber fraction) of vibration amplitude (around 25%) [119]. This indicates that Pythagorean summation is a plausible method for estimating the perceived intensities of superimposed vibrations.

In addition, we examined the estimation error by conditions. The amount of error seemed to be related to the frequency ratio of two components of superposition. If the ratio is near to 1.0, i.e., the difference between two components is small, the estimation error increases. For example, the estimation of the 50+60 Hz superimposed vibration (ratio of 1.2) was about 10% larger than the measured, and that of 150+170 Hz vibration (ratio of 1.13) was about 20% larger. In such conditions, the vibrations evaluated by the participants were less intense than the estimations. Such underestimating tendency was eliminated when the frequency ratio between two components exceeds 1.5.

The acoustic beat generated from the difference between two different frequency components would affect the intensity perception [116, 32] For example, a 15 Hz beat would be generated in 60+75 Hz and 75+90 Hz vibrations, which would provide a distinctive sensation to the original two components. Similarly, a 30 Hz beat in 90+120 Hz, a 20 Hz beat in 150+170 Hz, and a 50 Hz beat in 250+300 Hz vibration would provide a distinctive sensation to the other two frequencies. Such low-frequency beats generate different sensations to usual vibrations [28, 30], and are likely to be perceived as slow fluttering or mechanical movement [43]. Thus, participants would not count those components for evaluating the intensity; therefore, they evaluate vibrations with small frequency ratios as less intensive.

3.5 Discussions

3.5.1 Relation Between Perceived Intensity and Skin-absorbed Power

We calculated the skin-absorbed power of each the vibration used, and found a linear regression between the square-root of power and the perceived intensity measured in our experiments (Fig. 3.8). As a result, a strong linear relationship (adjusted $R^2 = 0.972$) between the square-rooted power and intensity was observed. This indicates that the square of perceived intensity is proportional to the skin-absorbed power, which could be a theoretic ground of the Pythagorean summation suggested in this paper.

3.5.2 Effectiveness and Extendability of Intensity Estimation

The overall estimation error of Pythagorean sum was 4.23% on average. Considering that we use the mechanical impedance of skin in [118], such level of error is rather small. Also, it is significantly below the amplitude discrimination threshold. Therefore, the estimation method is plausible for the design of vibrotactile stimuli.

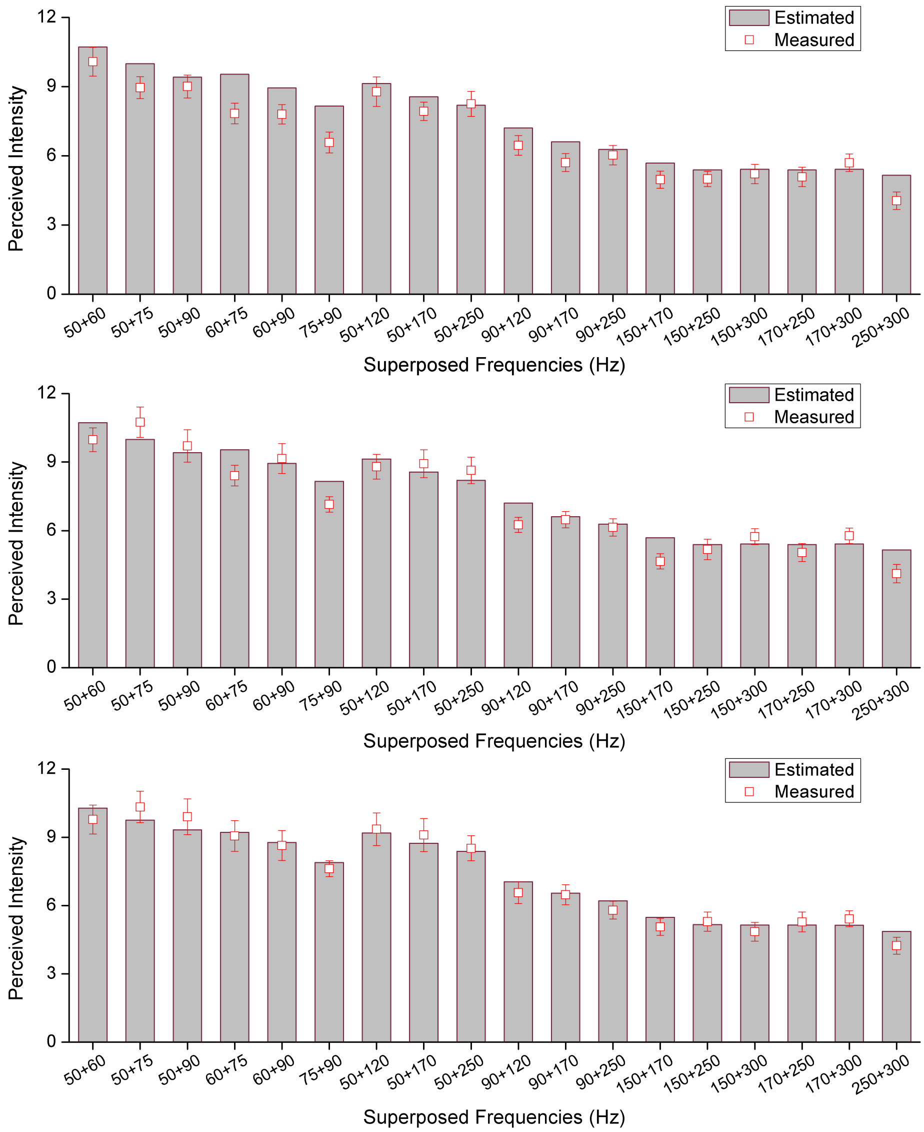


Figure 3.5: Perceived intensity of superimposed vibrations in Experiment II (Weak vibrations). Bars: estimated, dots: measured perceived intensity by triangular summation. Error bars stand for the standard errors. (Top: intensity ratio of 25:75, Middle: 50:50, Bottom: 25:75.)

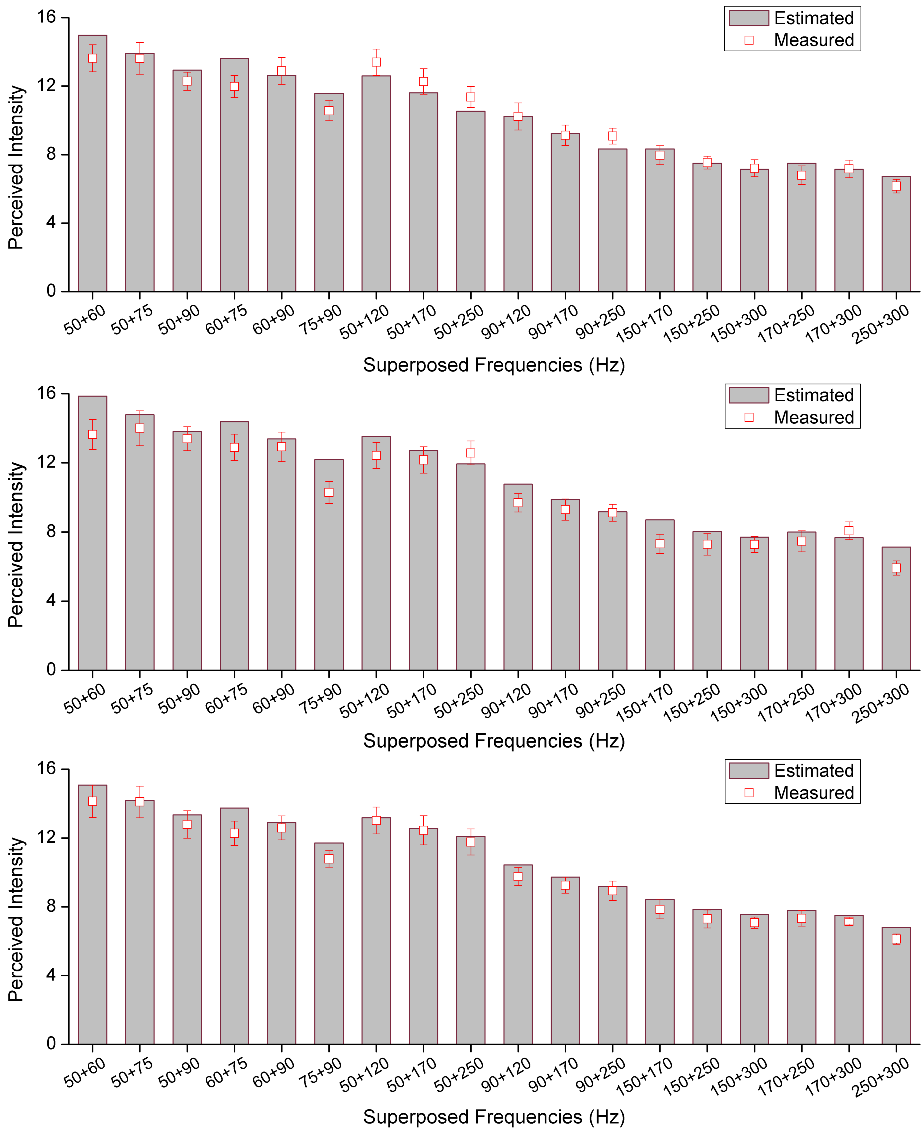
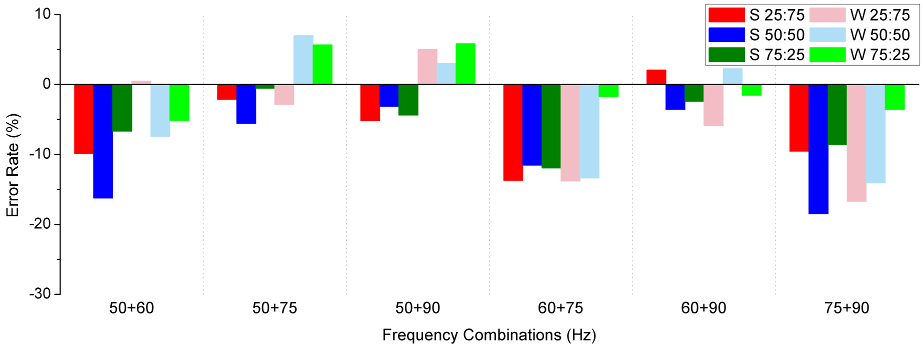
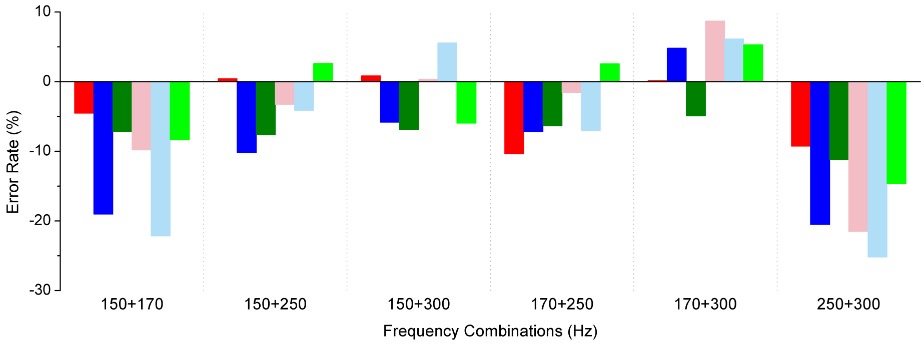


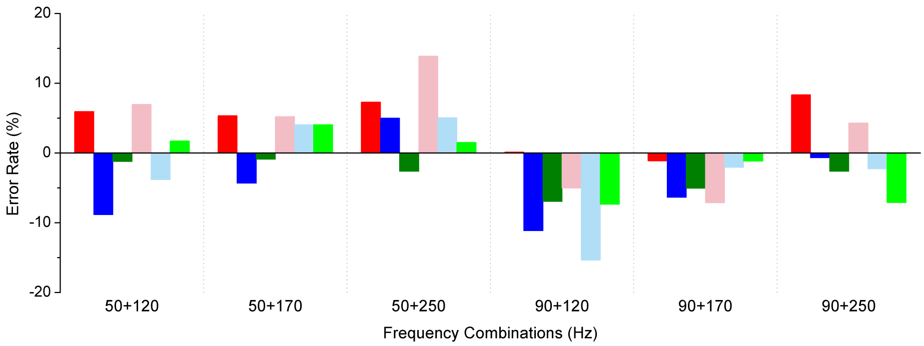
Figure 3.6: Perceived intensity of superimposed vibrations in Experiment II (Strong vibrations). Bars: estimated, dots: measured perceived intensity by triangular summation. Error bars stand for the standard errors. (Top: intensity ratio of 25:75, Middle: 50:50, Bottom: 25:75.)



(a) Combinations of low frequencies



(b) Combinations of high frequencies



(c) Combinations using each of low and high frequencies

Figure 3.7: The error percentage of the estimated intensity obtained using orthogonal summation. S and W means intensity (S: Strong, W: Weak). Positive error indicates that the measured intensity is larger than the estimated intensity.

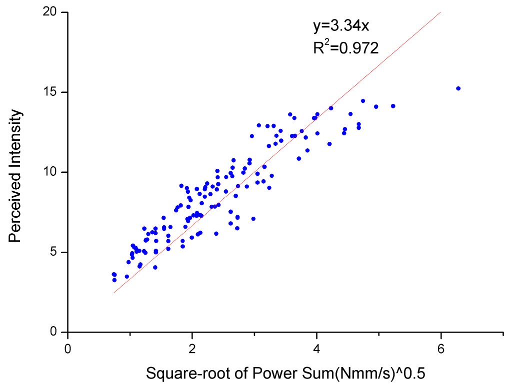


Figure 3.8: The relation between skin-absorbed power and perceived intensities of vibrations.

For example, building a set of vibrotactile icons is a time-consuming task for haptic designers. In the conventional way, the testing of all frequency combinations is required to design superimposed vibrations. Further, matching the intensity of the vibrations through an experiment is needed. Although experts utilize their prior experiences, such procedures are labor-intensive. Whereas, our Pythagorean estimation of the intensity requires data only from single-frequency components, leading to a considerable reduction of work for such procedures.

Extending the estimation method to the continuous frequency domain will be the next step of study. Vibrations with complex frequency spectrums are widely used in many HCI applications such as vocoder or noise vibrations. We expect that the following equation that can be regarded as a continuous form of our estimation would work well with such kind of vibrations. By substituting the summation into an integral in the frequency domain, the following equation (3.31) is obtained:

$$P_a = P(f_s) = \int Re[Z(f)]|\frac{A(f)}{2\pi f}|^2 df \tag{3.31}$$

3.5.3 Estimation Error in Superimposed Vibrations with Low Frequency Ratio

We observed relatively large estimation errors in superposed vibrations with low ratios between two frequencies (see Fig. 3.9). Considering the individual difference in vibrotactile perception, such error would not be treated as critical. Although it is smaller than the discrimination threshold of amplitude, it must be discussed.

The role of low-frequency beats caused by the adjacent frequencies seems crucial. They produce different quality of sensations, as well as are perceived to be weaker than the two original components. It requires larger displacement to achieve the same level of perceived intensity in low-frequency (see Fig. 3.3). Since the amplitude of the beats is the average of two components, the perceived intensity would be decreased consequently.

Another possible reason is the context effect of the vibrotactile stimuli. Since we did not include very low (< 40 Hz) frequencies in the stimulus set, such low-frequency beat components can be perceived only in superimposed vibrations. Participants might not count such sensation as vibrations and evaluated such vibrations as weak.

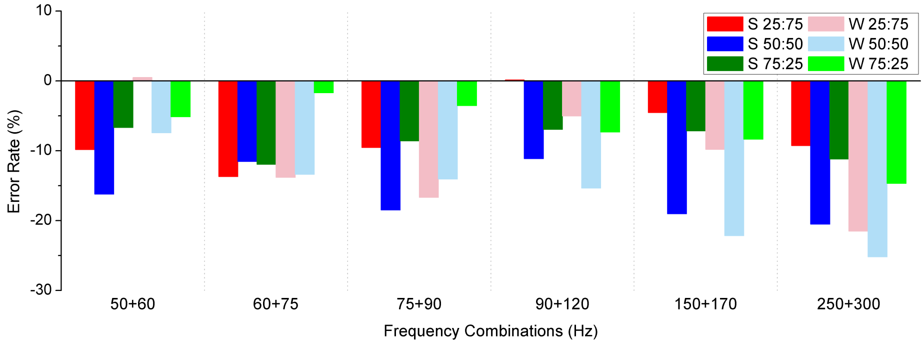


Figure 3.9: Estimation of superimposed vibrations with low-frequency beats.

3.5.4 Stimulus Context Effect

Since we used the AME method, a stimulus context effect would exist [124]. The different stimuli sets of Experiments I and II may cause such effect. In the stimuli set of Experiment I, we considered only single-frequency vibrations, and five different amplitude levels for each frequency. However, in the set of Experiment II, we considered both single-frequency and dual-frequency vibrations, and only three levels of amplitude were used for each frequency. Such a narrow range of amplitude decreases the slope of the perceived intensity in Experiment II. Fig. 3.10 compares the perceived intensities of the single-frequency vibrations used in both Experiments I and II. Stevens' coefficients and exponents were decreased, as shown in the results of Experiment II.

3.6 Conclusions

In this chapter, we investigated the perceived intensities of vibrations, and suggested two research hypotheses on the perceived intensity: 1) The skin-absorbed

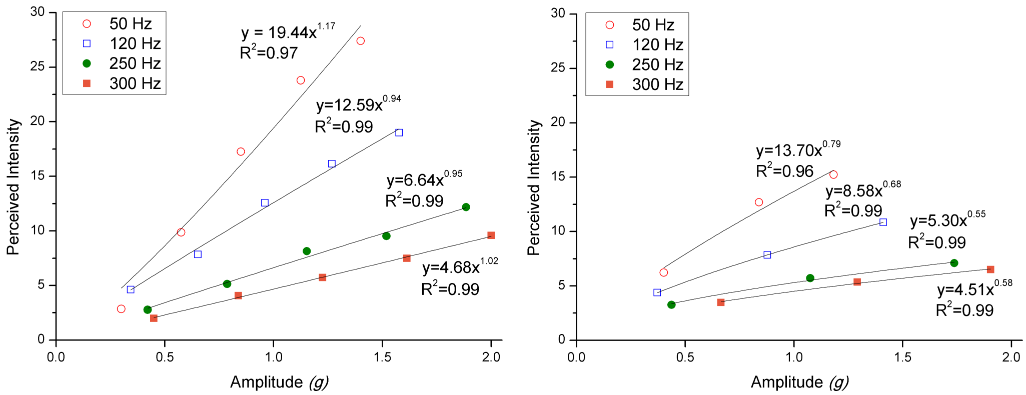


Figure 3.10: Comparisons on the exponents and coefficients of Stevens' power law from perceived intensities in Experiments I and II.

power of a vibration is related to the perceived intensity of a vibration, and 2) the Pythagorean summation, $I_1^2 + I_2^2 = I_S^2$, can be used to estimate the intensity of dual-frequency superimposed vibrations. The results of the two perceptual experiments demonstrated that 1) the perceived intensity of a vibration is correlated with its skin-absorbed power to a large extent, and 2) Pythagorean summation can estimate the perceived intensity of dual-frequency superimposed vibrations with a small amount of error. The findings of this study can be beneficial in reducing the efforts of haptic designers in vibrotactile interaction design.

4. Consonance Perception of Dual-Frequency Vibrotactile Chords

In this chapter, the perceptual characteristics of superimposed vibrations in terms of *consonance*, adapted from a similar concept for music perception, is investigated. A superimposed vibration is a combination of several sinusoidal vibrations with different frequencies into one signal. In our experience, the perceptual impression of superimposed vibrations can be substantially different from that of simple sinusoidal vibrations. For example, in the case of a mobile device, a vibrotactile stimulus with high consonance can be appropriate for a gentle reminder of appointments, while one with high dissonance can be useful for emergency alarm.

In music, a chord is any set of notes (with different frequencies) that are sounded simultaneously. When a musical chord is perceived as harmonious, its degree of consonance is said to be high. The degree of *dissonance* reflects the opposite concept. We apply the same idea to investigating the perceptual characteristics of superimposed vibrations. If each single frequency component of a multiple-frequency signal is regarded as one note, then the mixed signal can be called a *vibrotactile chord*. The concept of vibrotactile consonance can be used in ways similar to those in which audio consonance is utilized. Figure 4.1 shows the examples of the vibrotactile chords.

The following three research questions about vibrotactile consonance:

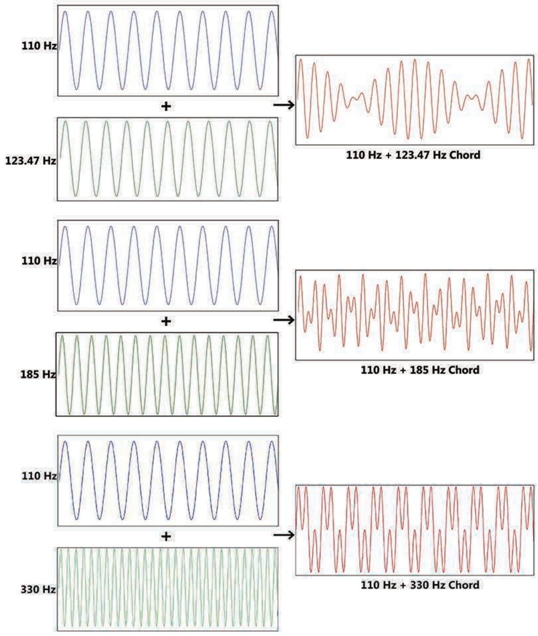


Figure 4.1: Examples of vibrotactile chords.

Q1: *Can we reliably evaluate the degree of consonance for vibrotactile chords?*

Q2: *If the answer to Q1 is positive, does the frequency difference in a vibrotactile chord affect its degree of consonance in systematic manner?*

Q3: *If the answers to Q1 and Q2 are both positive, can we find a measure that maps the physical parameters of a vibrotactile chord to its degree of consonance?*

To find answers to the above three questions, we conducted a perceptual experiment using 80 vibrotactile dyads (chords consisting of two notes) that were designed based on musical dyads. Forty participants evaluated the degrees of consonance of the 80 vibrotactile chords in a 0–100 scale. A set of adjectives that are suited to describing the perceived attributes of vibrotactile consonance or dissonance were also collected in a post-experimental survey. Further details are presented in the following sections.

4.1 Methods

This section presents the methods used in our perceptual experiment carried out to answer our three research questions about vibrotactile consonance.

4.1.1 Participants

Forty participants (28 male and 12 female; 19 to 27 years old with an average 21.57; 38 right-handed, 1 left-handed, and 1 ambidextrous) participated in this experiment. All were native Koreans, and no one reported to have any known somatosensory disorder. Four had considerable experience of haptic devices, while the other 36 had little or none. They were each paid (about 15 USD) after the experiment.

4.1.2 Apparatus

A mini-shaker (Brüel & Kjær; model 4810) with a power amplifier (Brüel & Kjær; model 2718), shown in Fig. 4.2, produced all vibrotactile chords used in this experiment. The mini-shaker is a voice-coil actuator with a very wide frequency bandwidth (DC to 18 kHz) and high linearity. A mobile device mockup made of acrylic resin ($11.5 \times 4.5 \times 1.5$ cm; 91.7 g) was attached to the mini-shaker using a screw-type aluminum bracket. Participants grasped the mockup with their left hand to feel the vibrations produced by the shaker. A triaxial accelerometer

Figure 4.2: Mini-shaker with a mobile device mockup.

(Kistler; model 8765C) was attached to the mockup to measure the vibrations. A computer with a data acquisition board (National Instruments; model PCI-6251) controlled the shaker system at a 10 kHz sampling rate. The linear relationships between input voltage amplitude and output vibration amplitude were calibrated for the frequencies between 40 and 330 Hz in 10 Hz steps, following the procedure detailed in [119]. Gains for in-between frequencies were linearly interpolated from the calibrated gains.

4.1.3 Stimuli

All vibrotactile stimuli used in the experiment were 2 s long. They consisted of two frequency components. Their base frequency was one of 40, 55, 80, and 110 Hz. The frequency of 40 Hz was chosen as a representative of the vibrations mediated by the RA (Rapidly Adapting) channel that give fluttering sensations [125]. Its double, 80 Hz, is an analogy with musical octaves. The frequency 110 Hz is one of the tuning standards for musical pitch (A2) for low-pitched musical instruments, such as the contrabass and tuba. This frequency is also on the boundary at which the role of the PC (Pacinian) channel begins to become dominant in glabrous skin [43]. Lastly, 55 Hz was selected as a half of 110 Hz to constitute a one-octave difference.

In each vibrotactile chord, the chordal frequency was one of the 19 vibrotactile semitones with respect to the base frequency. For example, the chords for the 110 Hz base frequency were the superimposed vibration pairs of $110 + 116.54$ Hz, $110 + 123.47$ Hz, $110 + 130.81$ Hz, $\cdots$, and $110 + 329.63$ Hz. For comparison, the stimulus set also included single-frequency vibrations with the base frequencies and doubled intensities. Thus, a total of 80 (4×20) vibrotactile chords were used in the experiment. For the base frequencies of 40, 55, 80 and 110 Hz, the ranges of the chordal frequencies were 40–119.86 Hz, 55–164.81 Hz, 80–239.73 Hz, and 110–329.63 Hz, respectively.

For each stimulus, the amplitudes of the two frequency components were set so that each resulted in the same perceived intensity. For this purpose, we used a psychophysical magnitude function presented in [115]. This magnitude function was measured with the same shaker under closed-loop control. Each frequency component had a perceived intensity of 10 according to this magnitude function, which allowed clear perception of the superimposed signals.

4.1.4 Procedure

During the experiment, the participants were seated in front of a computer. They grasped the mobile device mockup with their left hand in a comfortable posture. They also wore headphones that played pink noise to preclude any auditory cue. In each trial, the participant perceived a vibrotactile chord and assessed its degree of consonance using a slider bar displayed on a monitor screen. The participant could perceive the chord repeatedly by clicking a play button. The relative position of the slider bar was mapped to a number in the range 0–100. Two more buttons were provided on the screen, for proceeding to the next trial or going back to the previous trial, respectively.

The experiment consisted of nine sessions, and each session was finished within 5 min. The first session was for training, and it presented 20 vibrotactile chords evenly sampled from the entire 80 chords. During this session, the participants were instructed to establish consistent criteria for assessing the degree of consonance of vibrotactile chords. The data of this session were not used in data analysis. Each of the next eight sessions presented 20 vibrotactile chords. As a result, each participant was tested with the 80 vibrotactile chords twice, resulting in 160 consonance scores. The presentation order of the chords was randomized for each participant. The participants were required to take a 5-min rest between sessions to prevent tactile adaptation and fatigue. The entire procedure took 70–90 min per participant.

In addition, all participants completed pre- and post-experimental surveys. The pre-experimental survey was to collect the demographic information about the participants, such as their gender, handedness, and experience of haptic devices. In the post-experimental survey, the participants were asked to write down the criteria that they had used for rating vibrotactile consonance in a free form.

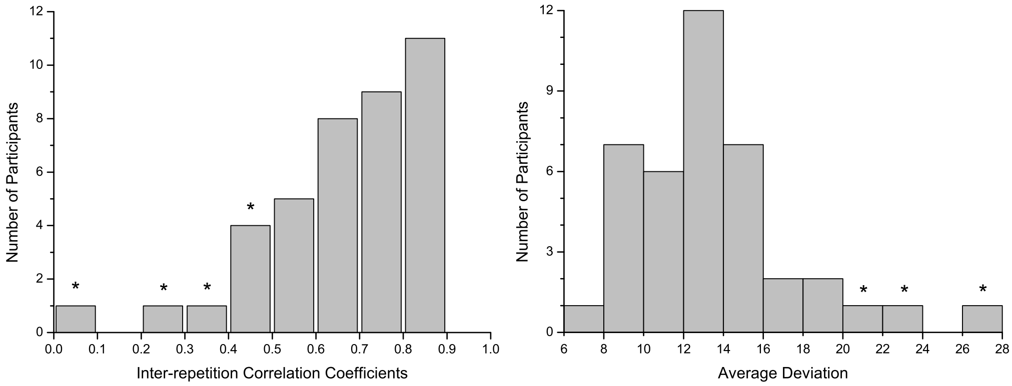


Figure 4.3: Histograms of the inter-repetition correlation coefficients (top) and the average deviations (bottom). Asterisks indicate data of the seven screened-out participants.

They also assessed the difficulty of establishing the criteria on a five-point Likert scale. Moreover, the participants were provided with two sets of adjectives, and they evaluated the agreement of each adjective to vibrotactile consonance and dissonance, respectively, on a seven-point Likert scale. Some of the adjectives were extracted from [11], which listed a set of adjectives suitable for describing the perceptual impressions of sinusoidal vibrations. The other adjectives were chosen by the experimenter from among those commonly used to account for musical perception. The adjectives for consonance generally had positive meanings, while those for dissonance had negative meanings. These adjectives were presented in Korean (the mother tongue of the participants) to the participants; their English translations are shown in Table 4.1.

4.2 Results

4.2.1 Consistency of Consonance Evaluation

The first objective of this study was to determine whether the participants could assess the consonance of vibrotactile chords with consistency. To this end, we examined an inter-repetition correlation coefficient and an average deviation of the consonance scores of each participant. If the correlation coefficient was less than 0.5 or the average deviation is greater than 20, the participant was regarded as incapable of reliable consonance evaluation. The experimental data of such participants were excluded from further analysis. The histograms of the inter-repetition correlation coefficients and the average deviations are provided in Fig. 4.3.

This procedure detected 7 participants out of the 40 participants. Three of the seven did not meet either criterion, while the other four satisfied the criterion for the average deviation but not that for the correlation coefficient. Their correlation coefficients and average deviations ranged from 0.021 to 0.485 and from 13.90 to 27.21, respectively.

The participants who satisfied the screening criteria showed much higher consistency in the vibrotactile consonance scores. Their average inter-repetition correlation coefficient was 0.725 (SD 0.103), and their average deviation was 12.28 (SD 2.58). This was also despite the training session that was intentionally made short only using one quarter of the 80 vibrotactile chords used in the main sessions. Therefore, it can be said that 82.5% of the participants (33 out of 40) were able to consistently evaluate the degree of consonance.

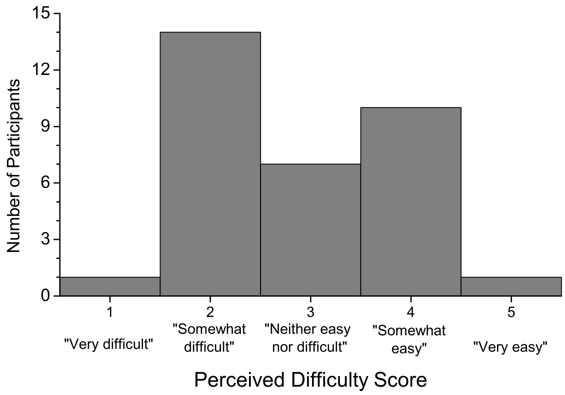


Figure 4.4: Histogram of the difficulty in evaluation criteria establishment for vibrotactile consonance.

In addition, the difficulty in establishing consistent criteria had a mean of 2.88 (SD 0.98) on a 5-point Likert scale, where score 1 represented "very difficult" and score 5 "very easy." A histogram of these difficulty scores is shown in Fig. 4.4. This result suggests that the participants were able to assess the degree of consonance of vibrotactile chords with moderate difficulty.

4.2.2 Degrees of Consonance

The average degrees of vibrotactile consonance scored by the 33 participants who passed the consistency test are shown in Fig. 4.5, for the ratio of chordal frequency to base frequency (a) and for the chordal frequency itself (b). Individual standard deviations are not shown for visibility, but they ranged from 9.7 to 20.3 with a mean of 13.8.

Important observations drawn from these plots are as follows. First, the single frequency (base-frequency only) stimuli resulted in very high consonance

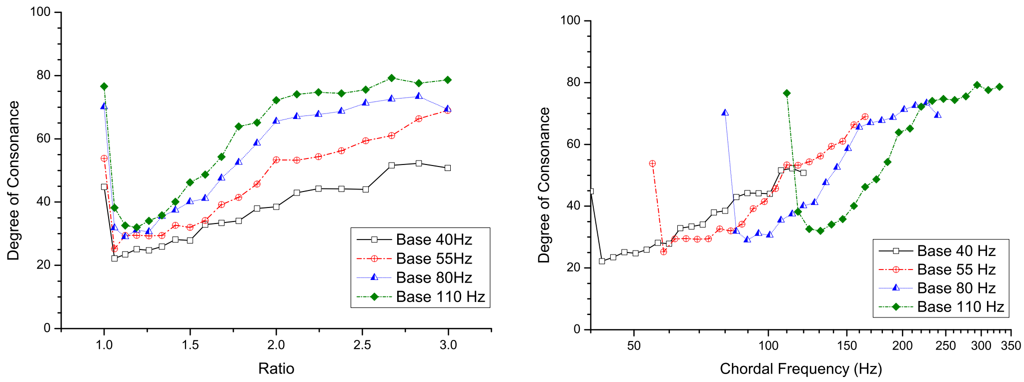


Figure 4.5: Degree of consonance (a) vs. the ratio of chordal frequency to base frequency and (b) vs. chordal frequency.

scores compared with the superimposed stimuli. The maximum degrees of consonance of the superimposed stimuli with the base frequencies of 80 and 110 Hz were comparable to the degrees of consonance of the corresponding single frequency stimuli. On the other hand, for the superimposed vibrations with the base frequencies of 40 and 55 Hz, their maximum degrees of consonance, which appeared at the highest chordal frequencies, were greater than the degrees of consonance of the corresponding single frequency signals. Second, vibrotactile chords with very small frequency ratios (slightly greater than 1.0) were evaluated as the most dissonant, as can be seen in the abrupt drops of both consonance plots. Further increases of the frequency ratio improved the degree of consonance. Third, the increasing behavior of the degree of consonance for the frequency ratios greater than about 2.0 depended on the base frequency. While the degree of consonance continued to increase with the frequency ratio for the 40- and 55-Hz base frequencies, it eventually saturated for the 80- and 110-Hz base frequencies. Lastly, vibrotactile chords with higher base frequencies showed the greater degrees of consonance for the same frequency ratio.

4.2.3 Model for the Degree of Consonance

Our next analysis was to find a measure function that maps the base and chordal frequencies of a vibrotactile chord to its degree of consonance. To this end, we tested a number of functions of known forms and evaluated their goodness of fit to the collected degrees of consonance. However, we were unable to find a function that accounts for the entire consonance data with a high degree of fit. This was because the consonance data included only a very small number of base and chordal frequencies at which the degree of consonance decreased abruptly with chordal frequency (the dropping regions in Fig. 4.5). Furthermore, the general shapes of the two regions with decreasing and increasing consonance were extremely asymmetric. Thus, we partitioned the data to two sets, one for the decreasing consonance region and the other for the increasing consonance region, found two best-fitting functions, one for each region, and then connected the two functions together.

The chordal frequencies that belonged to the decreasing consonance region were 40–42.37 Hz, 55–58.25 Hz, 80–89.72 Hz, and 110.0–123.47 Hz for the base frequencies of 40, 55, 80, and 110 Hz, respectively (recall that each pair of the same base and chordal frequencies means a single sinusoidal vibration at that frequency). The other chordal frequencies were included in the decreasing consonance region with each base frequency. Denoting the base and chordal frequencies by f_b and f_c, the boundary between the two regions was determined to be:

$$f_B(f_b) = f_b\, 2^{\frac{1}{12}\lfloor \frac{f_b}{30} \rfloor}, \tag{4.1}$$

where $\lfloor \cdot \rfloor$ is the floor function. If $f_c < f_B(f_b)$, (f_b, f_c) is in the decreasing consonance region. Otherwise, the point is in the increasing consonance region.

In the decreasing consonance region, we used a power function to take care of the abrupt decreases in the degree of consonance. A measure function for the degree of consonance C in this region was:

$$\begin{aligned} C &= K + 15.60 + 0.1678 f_b \\ &\quad + 0.7611\, f_b\, 60.01^{-\frac{10(f_c - f_b)}{f_b} + 0.001570 f_b} \end{aligned} \tag{4.2}$$

where $K = \Sigma_{i=0}^{3} \alpha_i {f_b}^i$ with $\alpha_0 = 22.76$, $\alpha_1 = -1.070$, $\alpha_2 = 0.01560$, and $\alpha_3 = 7.014 \times 10^{-5}$. Here, K has the role of equating the values of the two measure functions at their boundary points. This function was suitable for modeling the abrupt drops of the degree of vibrotactile consonance.

To determine a measure in the increasing consonance region, we used a generalized logistic function:

$$C = 61.97 + 0.1434 f_b - \frac{42.99}{1 + \left(\frac{f_c - f_b}{0.4371 f_b} \right)^{0.1175 f_b}} \tag{4.3}$$

This generalized logistic model well fitted the relatively slow increases of the degree of consonance with chordal frequency.

A 3D plot of the two measure functions is provided in Fig. 4.6, where a good match between the consonance data and the measure functions can be seen. The goodness of fit of this model was sufficiently high (Pearson's $R = 0.9929$).

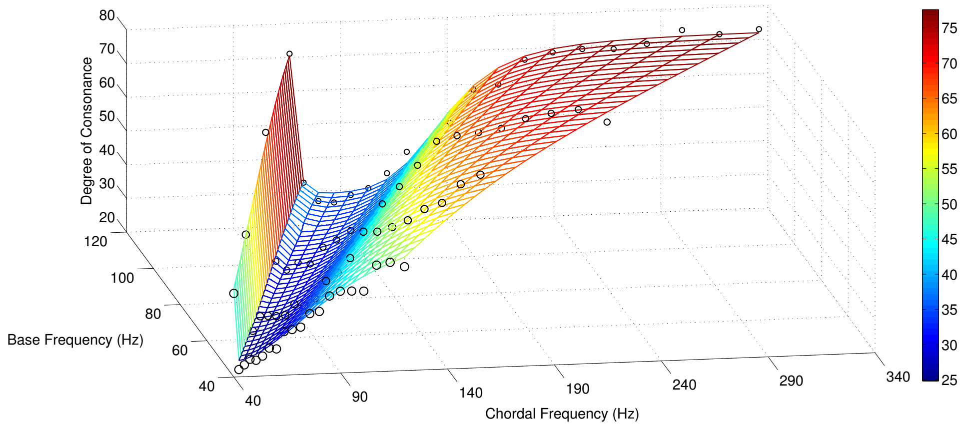


Figure 4.6: A 3D plot of the two measure functions (shown connected at the minimum points) obtained from the collected degrees of vibrotactile consonance. The measured points are represented by black open circles.

4.2.4 Post-experimental Survey

Among the participants' consonance criteria reported in the free-form questionnaire, those frequently mentioned were "smoothness" (10 of 33; 30%), "regularity"(21%), "perceived as one" (18%), "high frequency" (18%), "continuity" (15%), and "weakness" (15%). The criteria for dissonance were associated with "high intensity" (12 of 33; 36%), "fluctuation" (24%), "discontinuity" (24%), "roughness" (21%), and "irregularity" (18%).

The average relevances of adjectives to vibrotactile consonance and dissonance rated by the participants are shown in Table 4.1. The sensations described as "pleasant," "smooth," "even," and "clear" were highly relevant to consonance (scores higher than 5 on a 1–7 Likert scale), whereas those described as "jagged," "bumpy," "rough," "sparse," and "muddy" were closely associated with dissonance. Hence, theses adjectives can be regarded as decision criteria for the degrees of consonance of vibrotactile chords.

4.2.5 Summary of Results

Based on the experimental results reported above, the three research questions we raised earlier can now be answered.

Q1: *Can we reliably evaluate the degree of consonance for vibrotactile chords?*

A1: The answer to Q1 is affirmative to a large extent, supported by the high rate (82.5%) of the participants who passed the consistency test (Section 4.2.1), the moderate perceived difficulty (2.88/5) of consonance assessment (Section 4.2.1), and the existence of the adjectives highly correlated with the degree of consonance (Section 4.2.4).

Q2: *If the answer to Q1 is positive, does the frequency difference in a vibrotactile chord affect its degree of consonance in systematic manner?*

A2: Fig. 4.5 shows a well-defined functional relationship between the degree of consonance and the ratio of chordal frequency to base frequency, as detailed earlier in Section 4.2.2. Hence, the answer to Q2 is also affirmative.

Q3: *If the answers to Q1 and Q2 are both positive, can we find a measure that maps the physical parameters of a vibrotactile chord to its degree of consonance?*

A3: The functions given in (4.2) and (4.3) provide a compact representation of the degrees of consonance collected in the experiment. However, a unified measure that accounts for the entire data with a high degree of fit was unavailable. Therefore, the answer to Q3 is positive, but to limited extent.

4.3 Discussion

4.3.1 Consonance Evaluation

In general, people have relatively little life-time exposure to diverse vibrotactile stimuli with different frequencies, and it is more so for superimposed vibrations. The emphasis of our experiment was on looking into the immediate responses of participants about superimposed vibrations when they were still unfamiliar with such complex vibrations. For this reason, the training session was made brief, presenting only 20 superimposed vibrations out of the total 80 vibrations. Despite the short training session, a high proportion (82.5%) of the participants could consistently evaluate the degrees of consonance of the vibrotactile chords. However, the participants considered the task as moderately difficult, as demonstrated in the subjective difficulty scores. Most participants also reported in post-experimental interviews that establishing decision criteria for vibrotactile consonance was not straightforward.

The experimental data of the seven screened-out participants showed three tendencies. First, the consonance scores of four participants were generally similar to those of the other 33 participants who passed the screening test, but their data lacked consistency. It is possible that these four participants could show better agreement in consonance judgments if provided with more training. Second, two other participants resulted in rather erratic consonance scores, wherein no

Table 4.1: Relevance of adjectives to vibrotactile consonance and dissonance (on a scale of 1–7). The adjectives that received high scores greater than 5 are highlighted.

Consonance		Dissonance	
Adjective	Score	Adjective	Score
Even	5.788	Jagged	6.424
Smooth	5.636	Bumpy	6.152
Pleasant	5.455	Rough	5.970
Clear	5.424	Sparse	5.670
Clean	4.970	Muddy	5.667
Gentle	4.878	Unpleasant	4.970
Dense	4.697	Dark	3.424
Bright	3.455	Blasphemous	2.607
Beautiful	2.818	Dirty	2.182
Divine	2.091	Ugly	2.121

clear patterns could be found. Third, the other one participant showed clear patterns in the consonance judgements, but the patterns were disparate from those of the other 37 participants who showed the same patterns. The data of this participant satisfied the average deviation criterion, but the inter-repetition correlation coefficient was 0.49, which was slightly below the threshold (0.5). The reasons for the second- and third-type behaviors are unknown at the moment; we only expect that such behaviors might disappear with further exposure to superimposed vibrations.

4.3.2 Effects of Base and Chordal Frequencies

Given a base frequency, the degree of consonance produced the lowest score when the frequency ratio was slightly greater than 1.0 (Fig. 4.5). The chordal frequencies in this range usually create intense low-frequency beats, which contribute to the fluttering, rough sensations. An example of such waveforms is shown in the top panel of Fig. 4.1. After this minimum point, the degree of consonance tended to increase monotonically with the chordal frequency. As the chordal frequency increases, the beats become higher in frequency as demonstrated in the bottom panel of Fig. 4.1. This may explain the consonance improvements for the frequency ratios between 1.0 and 2.0.

When the frequency ratios exceeded 2.0, two patterns were observed. For the two lower base frequencies (40 and 55 Hz), the degree of consonance was apt to increase further with the chordal frequency. These low-frequency components produce very strong pulsating sensations, which might have become further neutralized by the high frequency chordal components that impart smooth vibrational sensations. For the higher base frequencies (80 and 110 Hz) that corresponded to rather smooth vibrations, the degrees of consonance were saturated at high chordal frequencies. This suggests that the sensations from these vibrotactile chords with high base frequencies were already sufficiently smooth, and the use of even higher chordal frequencies did not further affect consonance perception.

4.3.3 Subjective Descriptions

Based on subjective descriptions, Tan classified sinusoidal vibrations into three groups by frequency [38]. Vibrations between 1 and 3 Hz were described as a slow kinesthetic motion, those between 10 and 70 Hz as a rough motion or a fluttering, and those between 100 and 300 Hz as a smooth vibration. In addition, we have previously shown that the perceptual space of sinusoidal vibrations perceived via a mobile device consists of the two perceptual dimensions that depend on frequency: one for 40–100 Hz and the other for 100–250 Hz [11].

The results of the present study appear to be consistent with these earlier findings. Fig. 4.5 shows that the degree of consonance improved as the base frequency increased from 40 to 110 Hz. The chordal frequencies were varied in the range 42.38–120 Hz for the 40-Hz base frequency and 116.59–330 Hz for the 110-Hz base frequency. The post-experimental surveys (both the questionnaire and the adjective rating) indicated that smooth and pleasant stimuli were considered as highly consonant. This implies that vibrotactile chords sensed as smooth and high-pitch vibrations are regarded as consonant. In contrast, the signs of dissonance seem to be low-frequency, fluttering, pulsatory, rough, and low-pitch sensations.

4.3.4 Effects of Beat Frequency

Some superimposed vibrations deliver apparent low-frequency beat sensations. To look into this issue further, we performed additional analysis focusing on the beat frequency of superimposed vibrations. Given a superimposed vi-

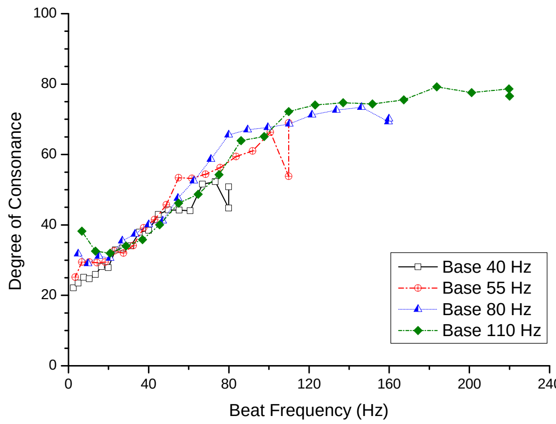


Figure 4.7: The degree of consonance vs. the beat frequency of vibrotactile chords.

bration, its beat frequency is the primary frequency of its envelope. It can be found by constructing the envelope using Hilbert transform [126], transforming the envelope into the frequency domain using FFT, and then finding the peak frequency.

A plot that shows the beat frequencies and the degrees of consonance of the vibrotactile chords is presented in Fig. 4.7. This plot indicates that the degree of consonance increased with the beat frequency almost monotonically. Correlations between them were also very high, as summarized in Table 4.2. It is also notable that even the degrees of consonance between vibrotactile chords with different base frequencies were very similar if their beat frequencies were close. This is somewhat in agreement with the general guideline for tactile icon design that rhythm, which is determined by the envelope of a vibrotactile stimulus, is the most effective feature for improving the discriminability of the icons [42].

Further, the beat frequencies that corresponded to the neutral consonance

Table 4.2: Correlation (r^2) between the beat frequency and the degree of consonance.

Base Frequency	40 Hz	55 Hz	80 Hz	110 Hz
r^2 (Linear Fit)	0.9279	0.9094	0.8775	0.8550
r^2 (Logistic Fit)	0.9548	0.9455	0.9883	0.9892

score (50) were between 52 and 66 Hz for the four base frequencies. This suggests that if the beat frequency is less than 52 Hz, thereby stimulating the RA channel and eliciting rough, fluttering sensations, then the vibrotactile chord begins to feel dissonant. If the beat frequency is above 66 Hz and the PC channel is more activated, the sensation turns into smooth vibration, increasing the degree of consonance.

This analysis indicated that beat frequency is the dominant sensory cue for consonance perception. The roles of other higher spectral components for consonance perception seem to be far less significant, although they may contribute to other perceptual tasks such as discrimination. This finding reminds us of Helmholtz's theory [58] in which acoustic beat is the central concept; vibrotactile beat may have the same role. This is also in line with the concept of critical band in audio perception in that interference is limited to a range of neighbor frequencies [127].

4.3.5 Measure for the Degree of Consonance

The measure of the degree of consonance, which consists of the two functions given in (4.2) and (4.3), allows for the estimation of the degree of consonance in the parameter range used in our experiment. This measure, however, has two limitations. First, we were not able to find a function that fits to the measured data on the entire frequency range tested. This was mostly due to the fact that only a very small number of data points were available in the narrow region of sharply decreasing degree of consonance. Strengthening this region with more data points may improve the situation. Second, the measure is only for the case in which the two frequency components of vibrotactile chords have the same perceived intensity. A more general measure that can handle arbitrary combinations of different vibratory amplitudes is left as future work.

4.3.6 Comparison with Auditory Consonance

There exist several computational models for auditory consonance and roughness developed by fitting a function to empirical data. These models are frequently used to analyze audio signals using computers. We noticed that the form of the degree of vibrotactile consonance, when inverted, closely resembles that of the degree of auditory dissonance and roughness. To assess their similarity, we computed Parncutt's approximation of Hutchinson's auditory dissonance D [128] and Vassilakis' auditory roughness R [107] using the frequencies and amplitudes of the vibrotactile chords used in our experiment.

The estimated dissonance D and roughness R of our vibrotactile chords are plotted against the measured degree of vibrotactile consonance in Fig. 4.8. $\log D$ and $\log R$ are used in the plots as they had reasonably linear relationships with the degree of vibrotactile consonance. Both $\log D$ and $\log R$ were highly correlated with the degree of vibrotactile consonance. The correlation coefficients were -0.942 and -0.874, respectively (note the negative correlations).

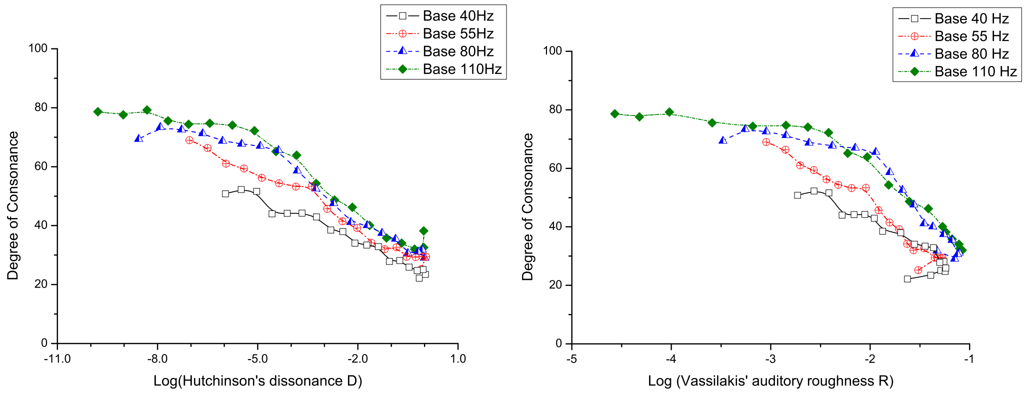


Figure 4.8: Degree of vibrotactile consonance vs. Hutchinson's dissonance factor (left) and Vassilakis' roughness factor (right).

This comparison, along with the finding that the effect of beat is similar between auditory and vibrotactile perception (Section 4.3.4), suggests that noticeable similarity between the two modalities seems to exist in consonance perception. Even the subjective descriptions for consonant/dissonant vibrotactile chords were similar to those of auditory chords. This is despite the disparate neurophysiological mechanisms of vibrotactile and auditory perception, although it was recently reported that crosstalk exists between auditory and tactile stimuli in frequency perception [129]. In this regard, the computational models of auditory consonance and roughness may be clues for finding more general vibrotactile counterparts that account for both vibration frequencies and amplitudes.

4.3.7 Practical Implications

Our experimental results also have some implications for practical applications. First, vibrotactile chords can be easily rendered using wideband actuators, such as voice-coil, piezoelectric, and electroactive polymer (EAP) actuators.

While these actuators enable designers to use sinusoidal vibrations of various frequencies, superimposed vibrations may provide an alternative means for expressive vibrotactile rendering with well-understood perceptual characteristics. Second, vibrotactile chords can also be produced by narrow-band actuators, e.g., linear resonance actuators (LRAs) popular in commercial smartphones. The actuators can generate vibrations in only a small range of frequencies, but our results indicate that superimposing two vibrations in that frequency range (e.g., those around the resonance frequency of an LRA) suffices to deliver distinctively rough and fluttering sensations with a high degree of dissonance. Since such vibrations feel immediately different from smooth high-frequency vibrations, they can contribute to diversifying the perceptual impression of vibrotactile stimuli and the subsequent design of meaningful vibrotactile signals for information transmission.

4.4 Conclusions

In this chapter, we have investigated the consonance perception of vibrotactile chords, superimposed vibrations with two different frequencies, as a way of studying the perception of complex vibrotactile stimuli that include multiple spectral components. An experiment with a large number of participants (40) demonstrated that people are able to reliably evaluate the degree of consonance of various vibrotactile chords. A well-defined functional relationship was observed between the degree of consonance and vibration frequencies, suggesting that vibrotactile consonance can be a good metric to represent the perceptual characteristics of superimposed vibrations. The beat frequency of the envelope of superimposed vibrations was shown highly relevant to consonance perception. The subjective impressions associated with vibrotactile consonance and dissonance were smooth vibrational feeling and rough, fluttering sensations, respectively. In addition, our analysis indicated that vibrotactile consonance perception is correlated to auditory consonance perception on the basis of the resemblance between their physical measures. All of these results can contribute to broadening our knowledge of the perceptual characteristics of complex vibrations, as well as facilitating the design of diverse vibrotactile stimuli with well-understood perceptual properties.

5. Adjectival Ratings and Verbal Expressions of Complex Vibrotactile Stimuli

In this chapter, we explored the *verbal expressions* of vibrotactile stimuli. The capability of such expressions is very limited compared to that of the ability of discrimination and subjective difference in vibrotactile sensation.

Essentially, the capability of such expressions is very limited compared to that of the abilities of discrimination and subjective differences in vibrotactile sensations; thus, we have been using vibrotactile stimuli without knowing how to express them. This problem, i.e., the lack of expressions, undermines the advantages of the current vibrotactile rendering that enables providing diverse and rich vibrotactile stimuli. The roles of vibrations in current mobile devices have been limited to delivering a simple feedback for basic functions, such as a text message or an alarm.

To this end, we investigated expressions that can serve as a standard representation term of the subjective quality of a vibrotactile sensation. We conducted three experiments to investigate a verbal expression of subjective quality for various sinusoidal vibrations.

In Experiment I, the frequency that separates the quality of vibrotactile sensation, e.g., the division point between the low- and high- frequency region, was investigated. According to the well-known four channels theory [43], the rapid adapting 1 (RA1; mechanoreceptor of Meissner corpuscle) channel accepts low frequency vibrations, and the Pacinian (PC; mechanoreceptor of Pacinian corpuscle) channel accepts high frequency vibrations. We expected that the differences of the sensory channels would result in different verbal expressions on the subjective responses of vibrotactile sensations.

In Experiment II, a large-scale survey was carried out to associate adjectives to the vibrotactile sensations to evaluate for single- and dual-frequency superimposed vibrations. In the experiment, aims to gather immediate, natural responses to the frequencies of vibrotactile sensation from general non-expert users. Other salient features such as rhythm, envelope, and amplitude also have important roles to assess the subjective quality, but in this study, we did not consider them. In Experiment III, we conducted a magnitude estimation of three representative adjectives to quantify the sensation. The adjectives were extracted from the result of Experiment II.

The chapter proceeds as follows. Sec. 5.1 to Sec. 5.3 describe the experiments. The sections of the general discussions and conclusions follow the experiment sections.

5.1 Experiment I: The Borderline Frequency of Low- and High- Frequency Regions

Before the commencement of the survey on the expressions, an experiment was conducted to find the *borderline* frequency that discriminates the perceptually distinguishable low- and high-frequency ranges. This is based on the four-channel theory [43], and we expect that the sensation quality that is likely to

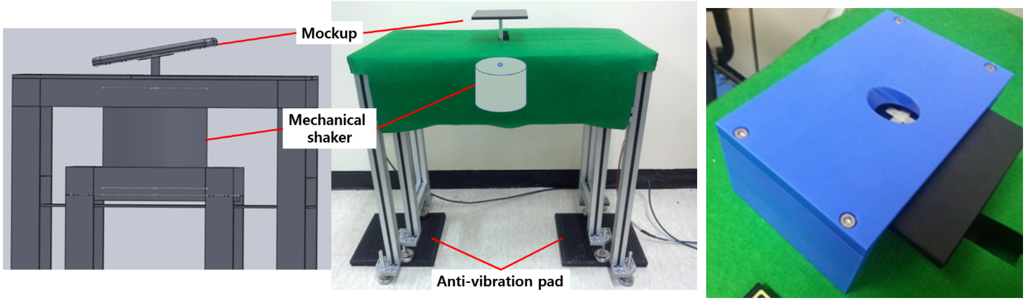


Figure 5.1: Side-view (top-left), front-view (top-right) and enclosure configuration (bottom) of the experimental table setup.

affect the subjective expressions of the participants.

5.1.1 Apparatus

A mechanical shaker (Brüel & Kjær; model 4809) with a power amplifier (Brüel & Kjær; model 2719) produced all of the vibrotactile stimuli used in all three experiments. The shaker is a voice-coil actuator with a very wide frequency bandwidth (dc to 18 kHz) and high linearity. A rectangular aluminum plate ($15 \times 15 \times 0.6$cm; 550 grams) was attached to the mini-shaker using a bar-type aluminum bracket. Participants were asked to lay their left index finger on the metal plate, with a comfortable posture. A two-level separable table was designed to hide the shaker. The shaker was hidden in the table, and the part of the aluminum plate was revealed on the top of the table. To block the propagation of the acoustic vibration generated by the shaker, anti-vibration pads were used underneath the table legs. A multipurpose data acquisition card controlled by a computer (DAQ; National Instruments; model USB-6251) was used to produce vibrotactile stimuli. Figure 5.1 describes the hardware configuration. Calibration

Figure 5.2: Experimental site setup in POSTECH Student Union building.

of the shaker was done by the method described in [119], in a range from 50 Hz to 350 Hz.

5.1.2 Participants

Sixty university students (51 males, 9 females, average 22.78 years old) participated in the experiment. Nobody reported any sensory disorders. A snack pack was provided to the participants after the experiment as compensation.

5.1.3 Stimuli and Procedures

The stimuli comprise a series of vibrations consisting of 10 vibrotactile stimuli, with a gradually increasing or decreasing frequencies. The frequency in the series started at 50 Hz, and it was then increased to 60, 71, 85, 102, 122, 146, 175, 209, and 250 Hz to compose a geometric series. The other direction, i.e., a series of stimuli with decreasing frequencies, was also used. The frequency started at 250 Hz and was gradually decreased to 50 Hz. Three vibration durations of 25, 100, and 1000 ms were used, representing very short (such as a button click), medium (vibrotactile notice or event alarm), and long (vibration bell) vibration feedback, respectively. Each of these durations was presented to 20 participants (10 increasing series, 10 decreasing series). The inter-stimuli interval (ISI) between each vibration was 0.5 s. The perceived intensity of vibration was adjusted to be equal for each frequency used in this experiment through the method presented in [115]. In total, six (2×3) vibration series were tested in this experiment.

An experimental site was established in the students' union building at the authors' institute (Fig. 5.2). Prior to the experiment, the participants were asked to read the written instructions carefully, and then they signed a consent form. Afterward, each participant sat in front of the shaker table and lightly touched the center of the tablet mockup using their left index finger. Participants were asked to perceive a series of vibrations repeatedly (at least five times), and then were asked to pick the point between frequencies where the perceived quality of vibrations was discriminated. For example, "between 85 and 102 Hz," or "between 102 and 122 Hz" could be the answers of the participants. The procedure was done within three minutes for each participant.

5.1.4 Data Analysis

We calculated the individual borderline frequency first, as the mean of the two frequencies in the participant's answer. For example, if a participant's answer was "between 85 and 102 Hz," then the borderline frequency would be 93.5 Hz. For each of the durations (25, 100, 1000 Hz), the borderline frequency was calcu-

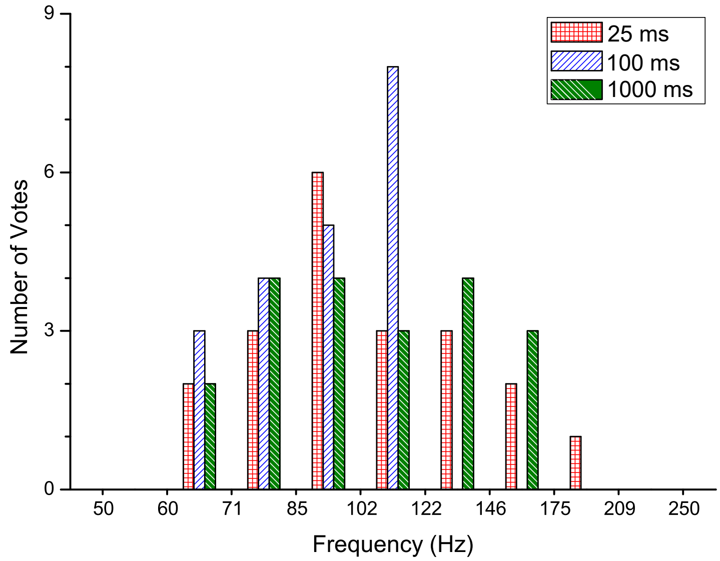


Figure 5.3: Histogram of The Experiment I.

Table 5.1: The borderline frequency result between the low- and high- frequency range.

Duration (ms)	25	100	1000	Total
Average	108.85	93.6	108.53	103.66
Median	93.5	93.5	102.75	93.5

lated by the mean of the 20 participants' results.

5.1.5 Results and Discussion

Fig. 5.3 is the histogram of the result. Most of the individual borderline frequencies were distributed between 71 and 146 Hz. A relatively large deviation was observed in the results of 25 ms vibrations, compared to those of 100 and 1000 ms vibrations. The mean and median of borderline frequencies are listed in Table 5.1, where the grand mean and grand median were 103.66 and 93.5 Hz.

The general tendency is consistent with previous studies, which observed that the subjective quality of vibration is changed at a frequency around 100 Hz [38, 11]. In [11], we showed the perceptual distance of vibrations with different frequencies using the perceptual space, and a '<' shape with an apex point of 100 Hz was observed. This indicates the perceptual quality of vibrations changed considerably at that point. Such results would be related to the four channel's activation levels. According to the four-channel theory of tactile perception, the RA channel mainly responds to low-frequency vibrations, whereas the PC channel responds to high-frequency vibrations [43]. In [130], the maximum activation of the RA channel occurs between 8–32 Hz, while that of the PC channel occurs 128–256 Hz. The frequency around 100 Hz seems to be the point at which the activation of the PC channel gets more dominant than the RA channels. A similar tendency was observed in the ratio coding of vibrotactile stimuli [44]. The activation level of the RA channel was more dominant to decide the perceptual pitch of vibrations where the frequency was below 100 Hz.

A large deviation was observed in the result of short vibrations (25 ms). In our observation, the participants tended to try and perceive the vibrations with more repetitions, as compared to the 100 and 1000 ms vibrations. It seems that the sensations of the vibrations are not long enough to be discriminated between, and they tended to memorize the sensation of each short vibration first. Then, they compared the sensations of adjacent vibrations. This procedure would degrade the discrimination performance of the participants. Despite this, the results are not different from those of the 100 and 1000 ms vibrations, which means that participants were able to discriminate the subjective quality of vibrations even with a very short duration, although such discrimination cannot be robust.

5.2 Experiment II: Verbal Expressions of Vibrotactile Stimuli

Unlike the other modalities such as visual and auditory modalities, vibrotactile sensation is difficult to perceive in daily life. Due to this, to our knowledge, only a few expressions exist to describe vibrotactile sensations. In this experiment, we focused on the verbal expressions of vibrotactile stimuli that describe the subjective quality of sensations. To this end, we conducted a large-scale survey with 520 participants to gather the expressions of vibrotactile stimuli, with a large variety of parameters such as frequency, duration, and superposition ratio.

5.2.1 Apparatus

The hardware configuration was same as the Experiment I, which is described in Sec. 5.1.1.

5.2.2 Extraction of Adjectives

A pilot experiment was conducted with 16 participants (all native Koreans; 10 males, 6 females; 21.2 years old average) to extract the candidate expressions that would be used in the main survey. None of the participants reported any sensory disorders. Participants received 15,000 KRW ($\simeq$ 13 USD) after the experiment as compensation.

The participants were asked to place their left index finger on the metal plate

Table 5.2: Top 10 adjectival expressions occurred in the pilot experiment.

Adjective	Occurrence	Adjective	Occurrence
heavy–light	29	regular–irregular	13
high–low	21	blunt–sharp	13
thick–thin	15	dull (shape)	10
slow–fast	15	deep–shallow	10
unpleasant	13	smooth–rough	10

attached to the shaker. Then they were asked to perceive the series of vibrations repeatedly (more than five times) and to write down what they perceived, using verbal expressions in a free form. The participants were encouraged to catch the quality of the sensation, which gradually changed in each series of vibration. The vibrations are listed in Table 5.4 and Table 5.5, and the same as the vibrations used in the main survey. Similar to Experiment I, the perceived intensity of each vibration was adjusted to the same level.

From the answers of participants, we extracted the adjectives among the expressions. Antonyms were counted together when they described the same subjective quality. Expressions related to the magnitude (e.g., big, small) and the duration (long, short) were discarded, because we adjust them to the same level. Though we blocked faint noise in the setup, we also discarded expressions regarding auditory perception (high pitch, woofer-like) to avoid possible interference between auditory and vibrotactile perception. Instead, we targeted on gathering the independent expressions representing the subjective quality of vibrations. The top 10 adjectives are shown in Table 5.2.

Based on Table 5.2 and also in reference to the previous works [11, 28], 16

Table 5.3: The list of adjective pairs used for the survey.

Adjectives	Subjective descriptions from free-form writing of participants
slow – fast	speed of fluctuations
deep – shallow	extent of vibratory displacement
thick – thin	a pencil lead's extent, or perceived thickness of a vibration plate
muddy – clear	metaphoric use; a stream, or a solution's muddiness
heavy – light	perceived weight
blunt – sharp	sensation of vibratory peak
warm – cold	metaphoric use; trembling in cold weather
dark – bright	metaphoric use; color
thick – light	metaphoric use; movement in fluid
fluttering – (not)	low-frequency vibrotactile sensation
hard – soft	analogy; active touch of object edges
rough – smooth	a widely-used term for vibratory feeling
bumpy – even	analogy; active touch of surface
ambiguous – distinct	existence of discriminable peaks
sparse – dense	from density of distinguishable peaks
irregular – regular	metaphoric use; off-road car vibrations

* thick–thin: extent, heavy–light: weight, thick–light: color *'fluttering–(not)' represents 'fluttering–not fluttering.'

adjectival pairs were selected for the main survey. They were given in Korean (the participants' mother tongue), and the corresponding English translations are listed in Table 5.3. Adjectives that present accompanying or consequential phenomena of vibrations were not included in the set. For example, "high–low" would indicate the perceived pitch accompanying the actuation of vibrations, and 'unpleasant' is likely to explain the accompanying emotional states during the perception of a vibration.

5.2.3 Stimuli and Procedures

In the main survey, 13 series of vibrations were constituted and used. Six of them consisted of single-frequency sinusoidal vibrations, and the other seven sets consisted of dual-frequency superimposed vibrations.

The single-frequency vibration series mainly aims to find the effect of duration and frequency variation. As we confirmed the effects of the frequency range in Experiment I, we set and used two different frequency ranges: low (L; 50–110 Hz) and high (H; 100–250 Hz) frequency ranges. For durations, we chose three different values: 1000 ms (long), 100 ms (medium), and 25 ms (short), to see the effects of the temporal summation of the Pacinian channel on the subjective quality [131]. The inter-stimulus interval (ISI) was 0.5 s. Each series contains eight vibrations with different frequencies (Table 5.4). The vibrations were presented sequentially.

The dual-frequency superimposed vibration series are focused on investigating the effect of the lower frequency component (base frequency) and the mixing ratio between the two frequencies. These two variables are known to determine the perceptual properties of superimposed vibrations [28]. First, we designed four series by combining two frequency ranges (low and high) with two different (but fixed; 1.2 and 2.0) mixing ratios, to understand their effects. Five superimposed vibrations were presented sequentially in these series. Then, we designed three series to see the effect of the frequency ranges of component vibrations: low- (L; 50–104 Hz), middle- (M; 92–184 Hz), and high-frequency(H; 175–350 Hz) ranges. Seven vibrations were presented in the series. All of the dual-frequency vibrations

Table 5.4: Single-frequency vibration sets.

Set	Duration (ms)	Frequencies (Hz)
S-L-1000	1000	50, 56, 63, 70, 78, 88, 98, 110
S-L-100	100	50, 56, 63, 70, 78, 88, 98, 110
S-L-25	25	50, 56, 63, 70, 78, 88, 98, 110
S-H-1000	1000	100, 114, 130, 148, 169, 193, 219, 250
S-H-100	100	100, 114, 130, 148, 169, 193, 219, 250
S-H-25	25	100, 114, 130, 148, 169, 193, 219, 250

Table 5.5: Dual-frequency superimposed vibration sets.

Set	Ratio	Vibrations (base–superposed freq.) (Hz)
D-L-1.2	1.20	50–54, 58–70, 66–79, 76–91, 87–104
D-L-2.0	2.00	50–100, 58–116, 66–132, 76–152, 87–174
D-H-1.2	1.20	100–120, 115–138, 132–158, 152–182, 175–210
D-H-2.0	2.00	100–200, 115–230, 132–264, 152–304, 175–350
Set	**Base**	**Vibrations**
D-L-V	50 Hz	50–55, 50–61, 50–68, 50–75, 50–82, 50–90, 50–100
D-M-V	92 Hz	92–101, 92–112, 92–124, 92–137, 92–151, 92–167, 92–184
D-H-V	175 Hz	175–192, 175–213, 175–236, 175–261, 175–287, 175–317, 175–350

had the same duration of 1000 ms, and the ISI was 0.5 s.

The perceived intensities of all the vibrations were adjusted to be equal, by a pilot experiment that used the method of adjustment with 10 participants. Here, the reference stimulus was a sinusoidal vibration (100 Hz, 1000 ms, 1 g). We did not consider the phase difference between two vibrations in this study, as the effect of the phase difference was minimal [29]. This also enables reducing the efforts of the participants.

We configured an experimental site in the students' union building of the authors' institution (Fig. 5.2), the same as that in Experiment I. Prior to the experiment, the participants were asked to read written instructions carefully, and then they signed on the consent form. Afterward, each participant sat in front of the shaker table and lightly touched the center of the tablet mockup with their left index finger.

For each participant, one of the 13 vibration series was presented. The participants were instructed to perceive the continuous changes in the frequency components of the vibrations, and to pick three adjectives that were appropriate to express the change of the sensations from Table 5.3. This procedure took less than five minutes per participant. This design allowed each participant to experience vibrations briefly, in order to obtain their immediate responses. Each vibration series was evaluated with a large number (40) of participants.

5.2.4 Participants

520 students (all native Korean; 411 males, 109 females; average 22.0 years old; 40 for each of the 13 vibration series) participated in the survey. All of them were recruited at the experimental site, and they were compensated with a snack pack ($\approx$ 2 USD). Nobody reported any sensory disorders.

5.2.5 Results and Discussion

Table 5.6 shows the results of single-frequency vibrations. Under each condition, the top-five adjectives that were selected more than 10 times are marked with colored cells for visibility.

The adjective pair “heavy-–light” was the most frequently selected pair over all of the six single-frequency vibration sets. It was selected 110 times overall

Table 5.6: Survey results of single frequency vibrations

Adjectives	S-L-25	S-L-100	S-L-1000	S-H-25	S-H-100	S-H-1000	(Low)	(High)	25 ms	100 ms	1000 ms	Total
slow–fast	2	2	9	1	3	7	13	11	3	5	16	24
deep– shallow	16	11	9	15	11	11	36	37	31	22	20	73
thick–thin	14	14	10	16	14	14	38	44	30	28	24	82
muddy–clear	9	14	7	6	7	8	30	21	15	21	15	51
heavy–light	21	15	17	23	16	18	53	57	44	31	35	110
blunt–sharp	12	8	10	10	12	12	30	34	22	20	22	64
warm–cold	1	3	1	0	1	1	2	5	1	4	2	7
dark–bright	0	3	0	0	1	1	3	2	0	4	1	5
thick–light	11	11	8	19	13	10	30	42	30	24	18	72
fluttering–(not)	4	5	6	2	8	5	15	15	6	13	11	30
hard–soft	8	5	3	2	2	2	16	6	10	7	5	22
rough–glabrous	1	4	5	3	5	4	10	12	4	9	9	22
bumpy–even	8	12	15	5	7	5	35	17	13	19	20	52
vague–distinct	4	5	7	8	10	10	16	28	12	15	17	44
sparse–dense	5	5	9	5	4	7	19	16	10	9	16	35
irregular–regular	4	2	5	4	4	3	11	11	8	6	8	22

in the six single sinusoidal vibration series. To our knowledge, adjectives related to heaviness were not reported in the literature to describe vibrotactile sensations. This would be related to the wide metaphoric use of heaviness terms. Literally, the "heavy-light" pair does not implicate any physical properties of vibration. However, such terms are frequently used to present many perceived characteristics. For example, we use expressions such as "heavy snoring," "heavy discussions," or a "heavy dish." This wide use of the terms may account for its popularity as an immediate response to the continuous changes of vibration frequency, which were a new experience to most of the participants. Two limitations, however, might be relevant here, as follows: First, the percentage of participants who selected "heavy-light" was 37.5–57.5%, which is not very high. Second, this result might depend on language and culture, so it needs to be cross-validated through an experiment with the same procedures for peoples of different cultural and linguistic backgrounds.

The "thick-thin" pair was also frequently selected (82 times), and was evenly selected over all of the six series. It literally concerns an extent, so it seems that participants thought about and selected this pair as a metaphoric use. However, it is difficult to interpret the participants' thought, and it is uncertain which attribute of vibrations is related to this expression. The pairs of "thick-light" (72 times) and "deep-shallow" (73 times) were also selected frequently.

Some of the pairs were selected frequently in a certain series only. "Bumpy—even," for example, was frequently selected in only the two low-frequency vibration sets(S–L–100 and S–L–1000). This would be related to the adjectival rating results of low-frequency vibrations [11]. In the rating results, low-frequency vibrations were rated high scores for bumpy–(even). In contrast, the pair "dense–thin" was more frequently chosen in short vibrations (25 and 100 ms; total 54 times), but was relatively less chosen in 1000 ms vibrations (18 times). In our guess, participants would associate the color density with the frequency change of short pulses.

It is also interesting that adjectives from other sensations, such as vision or warmth, were rarely picked. For example, "dark-bright," "warm-cold," and "hard-soft," which stand for luminance, temperature and surface hardness, respectively, were selected only 5, 7, and 22 times. These results indicate that adjectives from other sensations may not be appropriate for the subjective quality expression of vibrations. In addition, widely-used adjectives in tactile perception studies (e.g., rough–glabrous, and fluttering) were chosen relatively infrequently in these single vibration series.

Such a difference in results seems to be associated with the different contexts between a controlled laboratory experiment and a fresh response in a natural context. In a controlled laboratory experiment, participants have sufficient time to think about and evaluate the vibrations. Moreover, in most cases, relatively long vibrations (over 500 ms) were used. In contrast, we asked participants to answer immediately in this experiment, and we used four series of short vibrations (25 and 100 ms), as well as long vibrations (1000 ms).

Table 5.7 shows the results of the superimposed vibration series. "Slow–fast" and "thick–thin" consistently appeared in both single- and dual-frequency

Table 5.7: Survey results of dual-frequency superimposed vibrations

Adjectives	D– L–1.2	D– L–2.0	D– H–1.2	D– H–2.0	D–L–V	D–M–V	D–H–V	(Low)	(High)	(1.2)	(2.0)	(Vary)	Total
slow–fast	10	11	11	9	20	16	15	21	20	21	20	51	92
deep–shallow	8	8	8	5	6	5	9	16	13	16	13	20	49
thick–thin	6	11	16	17	13	6	6	17	33	22	28	29	79
muddy–clear	5	7	10	4	2	7	7	12	14	15	11	16	42
heavy–light	10	16	7	18	9	5	8	26	25	17	34	22	73
blunt–sharp	16	7	7	5	1	6	3	23	12	23	12	10	45
warm–cold	1	0	3	0	0	1	2	1	3	4	0	3	7
dark–bright	0	2	3	2	1	0	0	2	5	3	4	1	8
thick–light	6	13	8	12	3	2	4	19	20	14	25	9	48
fluttering–(not)	8	7	9	5	7	8	9	15	14	17	12	24	53
hard–soft	2	3	1	3	1	3	2	5	4	3	6	6	15
rough–smooth	2	5	9	8	5	13	16	7	17	11	13	34	58
bumpy–even	13	10	11	7	19	17	13	23	18	24	17	49	90
vague–distinct	14	9	7	13	4	7	3	23	20	21	22	14	57
sparse–dense	14	8	7	9	22	19	15	22	16	21	17	56	94
irregular–regular	5	3	3	3	7	5	8	8	6	8	6	20	34

vibrations. Contrary to the results of single vibration series, the pair "heavy–light" was selected less (top 5th; 73 times). Instead, "sparse–dense," "slow–fast," and "bumpy–even" were frequently selected. They are the top-three adjectives selected in the six vibration series (94, 92, and 90 times, respectively). "Sparse–dense" was selected most frequently, especially under the varying ratio (V) and low-frequency (L) series' conditions. "Bumpy-even" was not frequently chosen in the D–H–2.0 set, which consists of only high-frequency superimposed vibrations.

All of the three expressions seem to indicate the effects of acoustic beats. A superimposed vibration provides an acoustic beat that has a frequency equal to the difference between the two frequencies. Hence, usually, the beat frequency is (often greatly) lower than the two components. For example, a 50 Hz + 60 Hz superimposed vibration has a 10 Hz beat. Such effects of acoustic beats are frequently investigated [28, 30, 32]. It seems that participants noticed the existence of the beat, and they the associated the appearance period of the low-frequency beat's pulse-like sensation. The speed of pulses would be represented as "slow-–fast," or the density of pulses as "sparse-–dense." "Bumpy-–even" would be related to scanning a bumpy surface with a finger. Interestingly, however, the results of D-L-2.0 and D-H-2.0 are similar to those of single-frequency vibrations. These vibrations consist of a base frequency and its first harmonics; thus, the beat frequency is equal to the base frequency. Therefore, the effects of the beat did not appear, as the results indicate that "sparse–dense" and "bumpy–even" appeared consistently in all series except D–H–2.0.

A noticeable result is that of "rough–smooth." The pair was rarely selected in fixed ratios, regardless of frequency ranges. However, it was frequently selected in the D-92-VR and D-175-VR series, which are medium- to high-frequency range with varying mixing ratio. Interestingly, in these series, “heavy–light” was picked less frequently. It seems that “heavy–light” and “rough–smooth” seem to present an independent subjective quality relative to the other adjectives. Thus, we investigated such independency by conducting a magnitude estimation experiment, and calculated the correlation coefficient in the next experiment. There were no adjective pairs that had been voted for by a majority of the participants (the highest 57.5%), similarly to the single-frequency vibration data.

The findings of this study can be summarized as:

- Expressions that have a large extent of applicability such as “heavy-–light” and “thick–thin” were frequently selected to describe single-frequency vibrations.
- Dual-frequency superimposed vibrations were largely attributed to three adjective pairs that bear a more physical meaning, i.e., “slow—fast,” “sparse-–dense,” and “bumpy-–even,” largely from the effect of beats.
- No adjective pairs were selected for a majority of the participants, for both single-frequency and superimposed vibrations. The highest selection ratio was 57.5%.
- The “rough–smooth” pair and “heavy–light” pair seem to represent different qualities from each other.

5.3 Experiment III: Magnitude Estimation of Adjectives

In Experiment III, we chose three adjectives and conducted absolute magnitude estimation (AME) experiments to understand how people evaluate the subjective quality of vibrations and which parameters are related to the scores. Then, we conducted statistical analyses, and compared the correlation coefficients between the three adjectival rating scores. Three AME experiments with 34 participants were conducted.

5.3.1 Selection of Adjectives for Magnitude Function

In the previous results, we could not find a consensus by a majority of people (maximum of 57.5%). Instead, we could find a variety of individual expressions. As vibrations are not natural, common stimuli for most people, the participants are likely to express them with metaphoric use of familiar terms. For the same vibrotactile stimuli, some participants used heaviness, and some others used expressions of extent or depth. Therefore, the selections of participants were distributed. Such individual differences were expected, so we chose adjectives that could reflect a characteristic of vibration from a specific physical parameter.

We chose the most frequently selected adjective pair, "heavy–light," to investigate the most salient characteristic. In the results of Experiment II, the top-five adjectives appeared and disappeared together with the heaviness term. "Heavy–light" and "thick–thin" always occurred in the top-five adjectives in the single-frequency results, but they appeared and disappeared together. This would indicate that the participants would express different words, although they perceived a similar quality of sensations. For the same reason, "slow–fast," which appeared frequently in superimposed vibration sets, was not selected.

Then, we chose the roughness term ("rough–smooth"), which seems to be independent from the heaviness ("heavy–light"). We tried one more pair that was expected to contain another characteristic of vibrations. "Rough–smooth" was not in the top-five frequently selected adjective pairs, but it emerged in the results of the D–VR–92 and D–VR–175 series. In those series, the heaviness term was not included in the top-five adjectives, while "rough–smooth" was always included in the top-five. Therefore, we expected that the term would represent the subjective quality difference due to the effect of the superposition ratio.

Finally, we selected the bumpiness term ("bumpy–even"), by noticing that it was picked frequently in low-frequency single vibrations (S–L–1000 and S–L–100) and superimposed vibrations except for the D–H–2.0 series. That reflects the subjective quality of sensation that can be expressed as bumpiness would come from the low-frequency vibrations and beats. We also observed that some participants used an analogy between an uneven surface scanning and low-frequency vibrations in their free-form writing pilot experiments. We anticipate the bumpiness rating would present the properties of low-frequency vibrations.

5.3.2 Apparatus

The hardware configuration is same as that of Experiment I and II. While the other two experiments were conducted in an open environment, this experiment was done in a controlled environment in a laboratory. The same apparatus was installed but in a quiet, isolated laboratory space.

5.3.3 Participants

Eleven participants(8 males, 3 females, 18–31 years old; average of 22.0) participated in the experiment for perceptual heaviness assessment. Another 11 participants(8 males, 3 females, 18–23 years old; average of 21.5) participated in the roughness assessment, and another 12 (8 males, 4 females, 19–26 years old; average of 20.3) participated for bumpiness. All of them were university students enrolled at the authors' institute. Nobody reported any known mental or sensory disorders. The experiment was done within one hour for each participant. Participants were paid 10,000 KRW ($\simeq$ 10 USD) after the experiment.

5.3.4 Stimuli

As we need to consider the effects of all of the physical parameters of frequency, amplitude, and superposition ratio, we used eight base frequencies, five superposition frequency ratios (ratio from 1.0 to 2.0; including single vibrations) and two amplitude levels. However, some combinations of the parameter levels that cannot be generated by the apparatus were excluded in the stimuli set. In total, 70 vibrations were used. The amplitude of each vibration was adjusted to perceptually the same intensity for each amplitude level (strong and weak), based on a perceived intensity model that was derived using the method introduced in [9]. For dual-frequency superimposed vibrations, we estimated their intensity using a Pythagorean summation of each component vibration's perceived intensity (Chapter 3). For example, if vibration A has intensity of 3 and vibration B (a different frequency from A) has intensity of 4, then the superposed vibration's perceived intensity would be $5 = \sqrt{3^2 + 4^2}$. Table 5.8 summarizes the stimuli frequencies and amplitudes for single and superimposed vibrations.

5.3.5 Methods

We used the absolute magnitude estimation (AME) to evaluate the perceptual magnitude of each adjectival scores. The presenting order of stimulus was random, and the stimulus was given only once in each trial. The participants perceived the vibration, and then evaluated the perceived magnitude of the given measure with a positive number with their own criteria. To prevent faint noise, participants wore earplugs and noise-cancelling headphones (Bose, QuietComfort 15). Participants were instructed not to evaluate the intensity. Instead, they were asked to evaluate their perceived degree of each adjectives with their own evaluating criteria.

A session contained 70 trials, to enable evaluating all of the vibrations in the stimuli set. The experiment consisted of four sessions. Therefore, participants evaluated 280 times (70×4) in the experiments. A three-minute break was provided between sessions, and participants could take a rest whenever they wanted.

5.3.6 Data Analysis

We discarded the data from the first session, regarded as a training. The data from the remaining three sessions were averaged and used for the analysis.

The absolute magnitude scores collected in each experiment were standard-

Table 5.8: The combinations of frequencies (Hz) and amplitudes (G) of vibrations used in Experiment III. (Top: base frequency–superposed frequency, middle: strong, bottom: weak vibrations' amplitude)

Base	Frequency Ratio				
Freq.	Single(1)	1.12	1.25	1.5	1.8
	50	50–56	50–63	50–75	50–90
50	0.72	0.57–0.57	0.57–0.58	0.57–0.59	0.57–0.60
	0.45	0.36–0.35	0.36–0.34	0.36–0.32	0.36–0.31
	70	70–78	70–88	70–105	70–126
70	0.77	0.58–0.59	0.58–0.60	0.58–0.63	0.58–0.68
	0.44	0.33–0.32	0.33–0.31	0.33–0.31	0.33–0.32
	90	90–101	90–138	90–135	90–162
90	0.84	0.60–0.62	0.60–0.65	0.60–0.71	0.60–0.80
	0.43	0.31–0.31	0.31–0.31	0.31-0.32	0.31-0.36
	110	110–123	110–138	110–165	110–198
110	0.92	0.64–0.67	0.64–0.71	0.64–0.82	0.64–0.98
	0.43	0.31–0.31	0.31–0.33	0.31–0.36	0.31–0.44
	140	140–157	140–175	140–210	140–252
140	1.07	0.72–0.78	0.72–0.86	0.72–1.41	0.72–1.34
	0.49	0.33–0.35	0.33–0.38	0.33–0.48	0.33–0.64
	170	170–190	170–213	170–255	170–306
170	1.26	0.84–0.94	0.84–1.07	0.84–1.36	0.84–1.88
	0.56	0.37–0.42	0.37–0.49	0.37–0.66	0.37–0.97
	200	200–224	200–250	200–300	
200	1.47	0.99–1.13	0.99–1.32	0.99–1.80	-
	0.67	0.45–0.53	0.45–0.63	0.45–0.93	
	240				
240	1.81	-	-	-	-
	0.86				

ized separately using a standard procedures [121]. For each participant, multiple magnitude scores were averaged per experimental condition using a geometric mean. Following which, a subjective geometric mean Mp over all of the conditions was calculated for each participant, as well as a grand geometric mean Mg across all conditions and participants. Finally, a scaling constant per participant, $Mn = Mg/Mp$, was multiplied by each participant's scores. All further analyses were performed using these normalized perceived intensities.

5.3.7 Results and Discussions

Fig. 5.4 shows the perceived heaviness results. We could find some noticeable tendencies: (1) vibrations with a lower base frequency are perceived as heavier, (2) the perceived heaviness decreases as frequency increases, (3) stronger vibrations are perceived as heavier but to a limited extent (doubled perceived intensity leads to 25% increased perceived heaviness), and (4) the effect of the superposition frequency ratio is limited except for the ratio of 1.12:1. The maximum and minimum of heaviness were 20.9 and 4.03, and thus the maximum value is approximately five times larger than the minimum.

In Experiment II, the "heavy–light" adjectival pair was picked most frequently in all of the single frequency vibration series. The pair mostly represents the change in frequency components of vibrations. However, it was not frequently chosen in superimposed vibrations, especially D–H–1.2, D–L–V, D–M–V, and D–H–V. Such series mainly emerge with the change in the frequency ratio of the superimposed vibrations.

The current results are consistent with those of Experiment II. The perceived

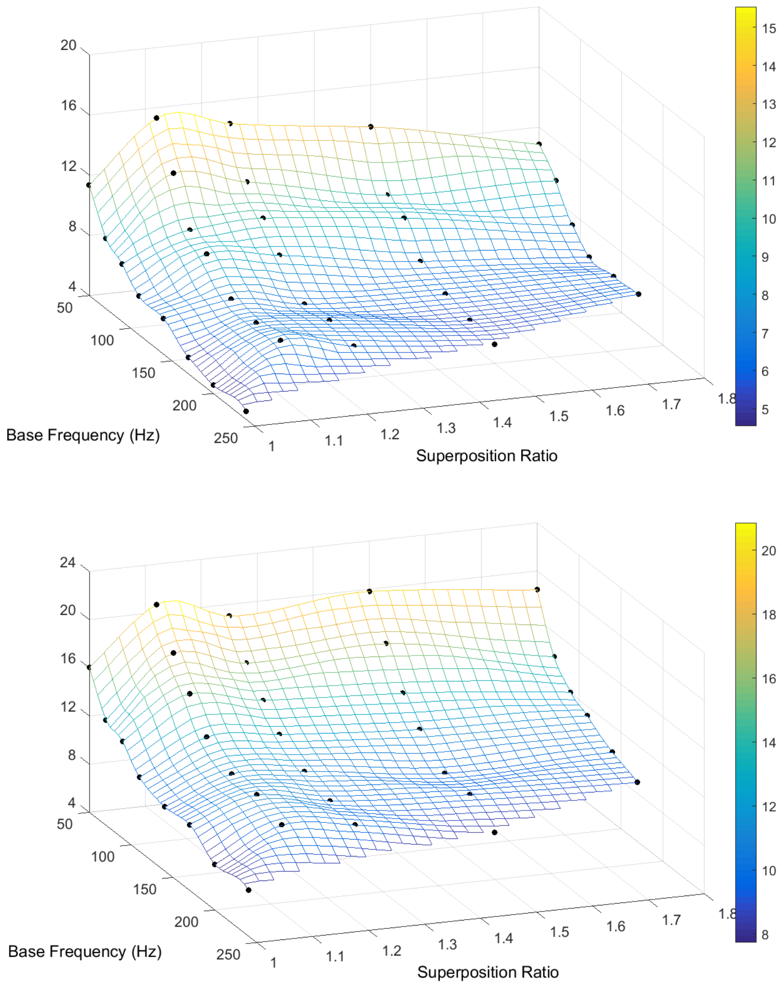
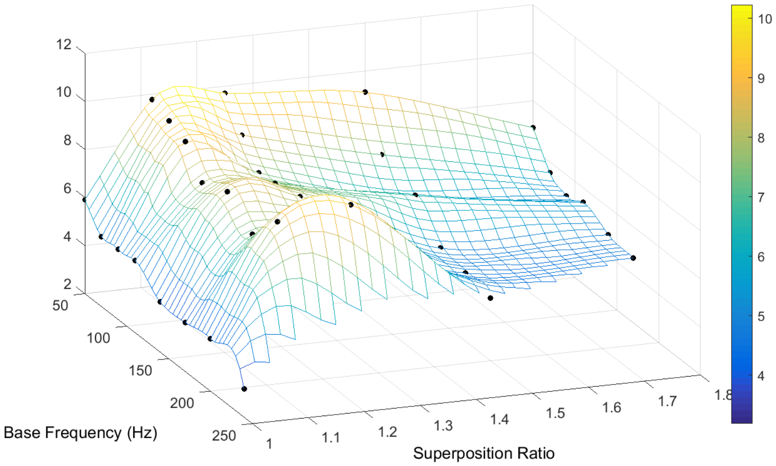


Figure 5.4: AME results of heaviness for strong (top) and weak (bottom) vibrotactile stimuli. Larger number indicates perceptually heavier. Black dots indicate measured points and the colored mesh is the best-fit surface.



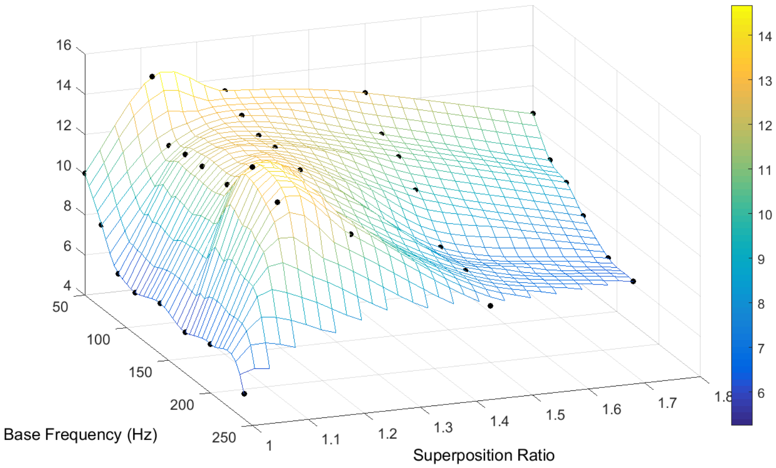
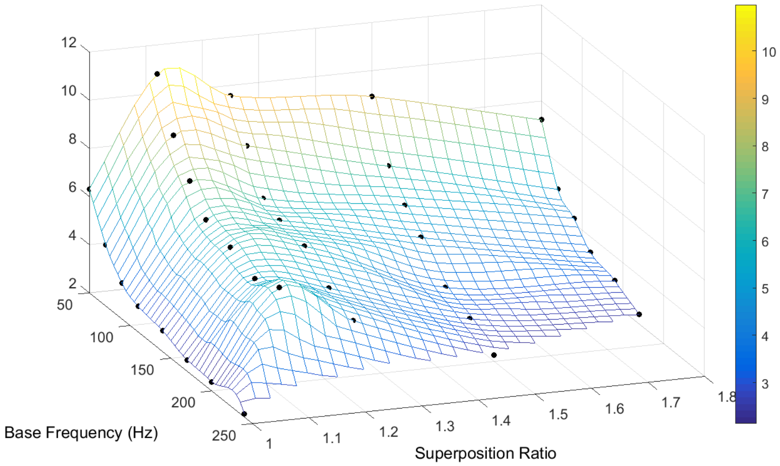


Figure 5.5: AME results of roughness for strong (top) and weak (bottom) vibro-tactile stimuli. Larger number means perceptually more rough.



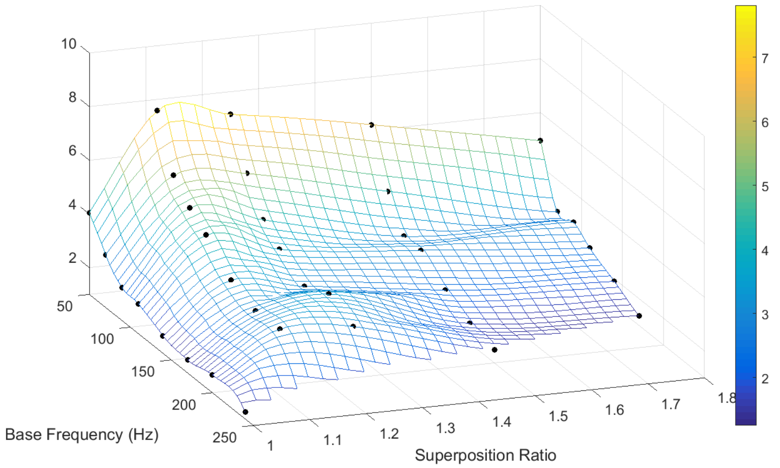


Figure 5.6: AME results of bumpiness for strong (top) and weak (bottom) vibrotactile stimuli. Larger number indicates perceptually more bumpy.

heaviness is mostly correlated with the frequency, and generally, it monotonically increased as the frequency decreased. However, other two parameters showed a limited effect on the perceived heaviness. The doubled intensity leads to only a 25 % increase in perceived heaviness.

Fig. 5.5 shows the perceived roughness of vibrations. The perceived roughness increased abruptly at the frequency ratio of 1.12 and remained so to the ratio of 1.25:1, and then, it decreased as the ratio increased. This tendency seems consistent with the previous works that address the effects of beats [28, 106]. Frequency also has an effect; the roughness score decreased as frequency increased, but such an effect is not as large as the effect of the ratio. Strong vibrations showed higher roughness scores, with the same combinations of the frequency and the superposition ratio. This is the same tendency as the heaviness score, in which it is natural that a higher amplitude leads to higher physical displacement of the contact surface, and that the power transmitted to the finger would be larger.

First, in Experiment II, roughness was frequently selected in the D–M–V and D–H–V series only, which mainly presents the change in the superposition frequency ratio. Therefore, we expected that roughness would be mainly affected by the superposition, and the results indicated exactly the same. Second, in addition, we observed that single-frequency 50 Hz and 80 Hz vibration showed considerably high roughness scores, compared to the other single-frequency vibrations. This would indicate that the subjective quality that can be verbally represented as “rough” would be related to the low-frequency component itself, instead of the existence of a beat.

Fig. 5.6 shows the perceived bumpiness of vibrations. The shape of the plot resembles the roughness plot; a peak appeared around the ratio of 1.12 to 1.25, and then gradually decreased as the superposition ratio increased. However, the slope of the peak was not as steep as that of the plot of the perceived roughness. The height of peak and steepness of slope in the plot are smaller than those of the roughness plot, and therefore the values were distributed in a narrower range. In addition, with a high-frequency (200 to 250 Hz) and a low superposition ratio (1.1 to 1.25), the bumpiness score plot did not show peaks.

The "bumpy–even" adjectival pair was chosen frequently in the low-frequency vibration series ('L', i.e., S–L–100, S–L–1000, etc.) in Experiment II. The magnitude results of heaviness also confirm that the sensation quality of bumpiness is highly affected by the low-frequency components of vibrations.

Table 5.9) shows the results of a three-way repeated measures ANOVA to see the effect of physical parameters. Since we could not test full factorial combinations of all the three parameters due to hardware limitations, we could analyze the main effects of physical parameters only (base frequency, amplitude, and superposition frequency ratio). All of the parameters have significant effects on all adjective scores, with large F-statistics.

We also analyzed the effect sizes, which describe the contributions of physical parameters on each adjective score. Heaviness was affected mostly by frequency ($\eta_p^2 = 0.3279$) and amplitude ($\eta_p^2 = 0.2253$). The effect of amplitude was relatively weaker than that of frequency. The effect of superposition ratio was relatively

Table 5.9: ANOVA results of Experiment III.

Dep. Variable	Indep. Variable	F-statistics	Effect size (η_p^2)
Heaviness	Freq.	$F(7,70) = 784.95$, ($p < .0001$)	0.3279
	Amp.	$F(1,40) = 539.53$, ($p < .0001$)	0.2253
	Ratio	$F(4,64) = 15.889$, ($p < .0001$)	0.0067
Roughness	Freq.	$F(7,70) = 65.343$, ($p < .0001$)	0.0588
	Amp.	$F(1,40) = 206.12$, ($p < .0001$)	0.1853
	Ratio	$F(4,64) = 15.032$, ($p < .0001$)	0.0135
Bumpiness	Freq.	$F(7,70) = 383.24$, ($p < .0001$)	0.2399
	Amp.	$F(1,40) = 181.80$, ($p < .0001$)	0.1138
	Ratio	$F(4,64) = 31.641$, ($p < .0001$)	0.0198

small, compared to the other two parameters ($\eta_p^2 = 0.0067$). The sum of the effect size is relatively large (0.5599).

Roughness was affected by amplitude to a large extent ($\eta_p^2 = 0.1853$). Frequency($\eta_p^2 = 0.0588$) and superposition ratio($\eta_p^2 = 0.0135$) had relatively little effect on the perceived roughness. It seems that participants evaluated the sensation of roughness from the magnitude first, and then they considered the lower frequency components. However, the effects of the superposition ratio were relatively small. Although the roughness score showed a peak between the ratio of 1.12 and 1.25, the trends of the graph were more affected by the frequency and amplitude. For example, the roughness of superimposed vibrations with a base frequency of 50 Hz was abruptly increased at the ratio of 1.12 and the score was almost maintained as the ratio was increased, while the roughness of those with a base frequency of 150 Hz decreased as the ratio was increased.

Bumpiness was also affected by both the frequency and the amplitude ($\eta^2 = 0.2399$ and 0.1138, respectively). The effect of superposition ratio is the highest

Table 5.10: Correlation coefficients between adjective scores

Adjective	Heaviness	Roughness	Bumpiness
Heaviness	-	.67	.93
Roughness	-	-	.85

Table 5.11: Correlation coefficients at high and low superposition ratio regions

Region	Adjective	Heaviness	Roughness	Bumpiness
High	Heaviness	-	.91	.94
	Roughness	-	-	.96
Low	Heaviness	-	.48	.92
	Roughness	-	-	.57

among the three scores ($\eta^2 = 0.0198$), but relatively small compared to the effects of frequency and amplitude.

We calculated the correlation coefficients between the adjectival score values to see the independency of the adjectival scores (Table 5.10). The coefficients over the whole data were considerably large (0.67 to 0.93). Such large coefficients were expected since there are some common trends rules all the scores. For example, lowering frequency, increasing amplitude, and setting a superposition frequency ratio of 1.12 always increased all the three of the scores.

Therefore, we separated the parameter space into two spaces. Considering both the small effect size of the superposition ratio and the noticeable difference in the shape of plots, we divided the domain into two regions by the superposition ratio; the low region (ratio of 1.1 and 1.2) and the high region (ratio of 1.5 and 1.8). Then, the correlation coefficient was 0.48 in the low region, while the coefficient was 0.91 in the high region (Table 5.11). According to this, such high correlations between the adjectival scores owe to the similar tendencies of the scores in the high-frequency region. A similar trend was observed between "heavy-light" and "bumpy-even." (0.57 and 0.96, respectively). However, heaviness and bumpiness scores always showed a high correlation coefficient (0.92 in low, and 0.94 in high regions). The participants seem to evaluate the two scores using common physical parameters.

Here, we can summarize the results of the effects of physical parameters on the adjectival scores.

- Amplitude was important for all of the variables. Intense vibrations were scored higher for all three of the adjectival scores, with large effect sizes.
- Vibrotactile frequency showed large effects on all three of the adjectival scores. Heaviness and bumpiness evaluations are highly affected, with quite large effect sizes (over 0.2). The effect of frequency was relatively weak on roughness perception, but still considerable.
- The superposition ratio showed relatively small effects overall, but at the low superposition ratio, it affects the roughness and bumpiness perception considerably.
- The three adjectival scores are considerably correlated with each other. However, the correlation between heaviness and roughness perception seems weak, especially in the low superposition ratio region.

5.4 General Discussion

5.4.1 Towards Systematic Expressions of Vibrotactile Stimuli

We evaluated three adjectival scores which seem to be linked with some physical parameters of vibrations, as well as representing the subjective characteristics of sensations. The ultimate goal of the research would be the development of an appropriate, systematic way to express vibrotactile stimuli, like the brightness of color or the height of a pitch. For example, in visual perception, there are several measurement sets to describe color, which also can be utilized to synthesize any color. In music, a 12-semitone scale, with a standard tuning fork (440 Hz for A4) is a standard for pitch. Those terms have been developed, standardized, and accepted for a long time.

However, for haptic stimuli, we do not currently have any terms. Unlike visual or auditory sensations, people are exposed to vibration fewer times. People may feel some vibrations, but they have fewer ideas as to how to express the sensation. Even in our pilot experiment of Experiment II, we could observe that participants struggled in representing the expressions with appropriate expressions or metaphors.

We would suggest two strategies to build the systematic expression of vibrotactile stimuli. One feasible strategy is making an artificial, but perceptually appropriate term, and training the users to be familiar with it. For example, the taste of wine is delicate, but several terms were developed and used to verbally present the taste for consumers. Even non-experts use terms like dry, fruity, and thick, although it is difficult to discriminate what these terms actually mean. The same strategy could be applied to vibrotactile stimuli. In particular, a strategy including steps of developing several expressions and their degrees to express the subjective quality of vibrations, and making familiar them to the users. The users would be exposed to the terms of expressions, and finally, the terms could be accepted.

The other strategy is grouping and naming the vibrations. There were several attempts to teach the users vibrotactile stimuli for naming and learning [132, 133]. Several studies investigated the discriminability of vibrations, and large sets of distinguishable vibrotactile icons [42, 45] were built. Based on such results, we would analyze the relationship between design parameters and subjective sensations. Then, matching the design parameters to a certain subjective sensation, we would get some categorical expressions for the vibrotactile stimuli. The remaining procedure would be similar; the users become familiar with the expressions and the concept, and finally, it would be accepted.

5.5 Conclusions

In this study, we investigated the subjective qualities of sensations of vibrotactile stimuli. First, we investigated the borderline frequency, which discriminates perceptually distinguishable frequency ranges in the frequency domain. The result indicated that around 100 Hz is the perceptual borderline frequency, which is consistent with the literature. Second, we conducted a large-scale survey that sought appropriate verbal expressions to describe the subjective quality of vibrotactile sensations with a large number of participants. The results indicated as follows. 1) Metaphoric expressions of heaviness, and thickness (extent) were frequently selected to describe the single frequency vibrations' sensation. 2) Dual-frequency superimposed vibrations were largely described by expressions of speed (slow–fast), density (sparse—dense), and bumpiness of a spatial structure (bumpy—even), that bear a more physical meaning. 3) Expressions of roughness and bumpiness were highly associated with the low-frequency components of vibrations, especially the acoustic beats of superimposed vibrations. Finally, we selected three adjectival expressions of heaviness, roughness, and bumpiness and established magnitude functions that explain the relations between physical parameters such as frequency, amplitude, and superposition ratio and the degree (magnitude) of the subjective qualities. The adjectival magnitude scores are highly correlated with each other in high superposition frequency ratios, whereas they are relatively less correlated in low ratios. These results would contribute to understanding the subjective qualities of vibrotactile sensations, and would be directly utilized in human-centered vibrotactile interaction design for various applications.

Part III

Affective Characteristics of Complex Multimodal Tactile Stimuli

6. Emotional Responses of Vibrotactile Stimuli

From this chapter, the emotional aspects of haptic stimuli were discussed. Tactile icons, or haptic stimuli in a broader sense, have an inherent appealing virtue for enhancing the emotional aspects of interaction. While researchers have paid more attention to using tactile icons for communicating objective information, attempts such as [72, 73] showed the feasibility of delivering emotions using tactile icons.

There have been increasing interests on understanding the affective characteristics of synthetic tactile stimuli. The effects of physical parameters on the emotional responses were investigated. The emotional responses of various skin-shearing tactile stimuli [12] and saltation [74] were investigated. Seifi et al. evaluated the affective responses of vibrotactile stimuli with different frequencies and rhythms [76]. Affective ratings of intensity, roughness, pleasantness, rhythmic–nonrhythmic, and alarming–calm were used. Rhythm had a statistically significant effect in all the measures, but frequency was significant for only alarming–calm. However, still a great part of emotional aspects of tactile icons are unrevealed.

In light of the aforementioned research status, in this chapter, we investigated the emotional aspects of vibrotactile stimuli using a large set of icons. The following two research questions as to the emotional responses of tactile icons are addresses:

Q1: How do physical parameters of tactile icons affect emotional responses?

Q2: Does changing the physical parameters in a wide range lead to tactile icons that cover a large region in the V-A space?

To answer the two questions, we carried out a perceptual experiment that aimed to garner a systematic understanding as to how the four fundamental parameters of tactile icons—amplitude, frequency, duration, and envelope— affect users' emotional responses using a V-A space. Further details are provided in the following sections.

6.1 Methods

6.1.1 Participants

Twenty-four participants (12 male and female each; 18–31 years old with a mean 22.2) participated in this experiment. All participants were regular users of a smart phone. No participants reported known sensorimotor impairments. They were paid KRW 10,000 ($\simeq$ USD 10) after the experiment.

6.1.2 Apparatus

We used a commercial smart phone (Samsung, Galaxy Note 2; 186 g, $151.1 \times 80.5 \times 9.4$ mm, 5.5" screen) to present visual instructions and vibrotactile stimuli, which is the most common platform for tactile icons since its versatility and wide contacting area with human hands. A wide-band vibrotactile actuator (TactileLabs, Haptuator) was attached to the back panel of the phone (Fig. 6.1) to

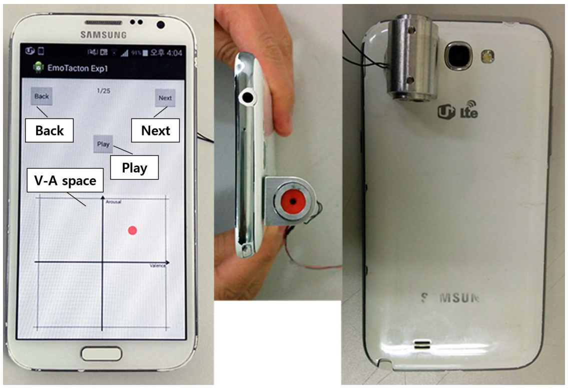


Figure 6.1: Apparatus used in the experiment.

provide diverse vibrations. The actuator was controlled by an Android program running on the phone through an audio output port.

6.1.3 Stimuli

As stimuli, we used amplitude-modulated sinusoidal vibrations given in the following form:

$$x(t) = E(t)\sin(2\pi F_c t), \tag{6.1}$$

where $E(t)$ is the envelope function and F_c is the (carrier) frequency. The stimulus duration is denoted by D.

Realizing that the envelope function $E(t)$ is a key for the design of effective tactile icons, many previous studies proposed design heuristics for $E(t)$ using rhythm [42], melody [45], and musical dynamics [134]. However, most of the design heuristics is unstructured or requires a high-dimensional parameter space. To investigate the effect of envelope without any interference of other parameters' effect, especially that of amplitude, we used a simple envelope function such that

$$E(t) = A \sin(2\pi F_e t), \quad (6.2)$$

where A is the amplitude and F_e is the envelope modulation frequency. This sinusoidal envelope modulation has been frequently used in tactile perception and rendering research, and it was shown to change the perceptual properties of vibrotactile stimuli in a clear fashion [34].

Therefore, the stimuli used in our experiment can be represented by four parameters: amplitude A, carrier frequency F_c, duration D, and envelope frequency F_e. The values used for each parameter are provided in Table 6.1. The range of carrier frequencies covered from 60 Hz that stimulates the RA (rapidly adapting) channel to 300 Hz that excites the PC (Pacinian) channel. For each carrier frequency, we used five amplitude levels (A1–A5) that were equally distant in perceived intensity. This was to eliminate the effect of carrier frequency on the perceived intensity, since signal frequency which strongly affects [9]. To this end, we picked five equally-spaced perceived intensities for 100-Hz vibration and found their physical amplitudes, both using a psychophysical magnitude function presented in [9]. Then, we tuned physical amplitudes for the other frequencies so that they would feel as strong as 100-Hz vibrations in the five levels.[1] The physical amplitudes used in the experiment are specified in Table 6.2. The stimulus duration ranged from a very short value (50 ms), which is used to render virtual button clicks, to a very long one (2 s), which is regarded as the maximum for

[1]For this intensity equalization, we could have used a more rigorous psychophysical procedure. We rather used a simpler method because of a large number (25) of the amplitude and frequency combinations. We expected that errors caused by this would be much less important than the large measurement noise inherent in valence-arousal assessments.

tactile icons. The envelope frequency varied from 1 Hz, which imparts pulsating sensations, to 16 Hz, which feels like fast fluttering.

Testing all combinations ($5 \times 5 \times 6 \times 6 = 900$) of the four physical parameters was nearly impossible. Therefore, we constituted three sets of stimuli to investigate the effects of each parameter: set AF for amplitude and carrier frequency, set D for duration, and set E for envelope frequency. Specific parameter values are summarized in Table 6.3.

6.1.4 Procedure

Prior to the experiment, the experimenter explained the concepts associated with valence and arousal to each participant using a written script. The script also included some examples of valence and arousal scores for emotion-related words such as exciting, restful, and lazy. The participant was allowed to ask any questions in this period to have a clear understanding. The participant then signed on an informed consent form and started the experiment.

Participants' task was to rate the valence and arousal of tactile icons after perceiving them. Participants held the smart phone shown in Fig. 6.1 with their non-dominant hand while not touching the vibration actuator. The experimental program running on the smart phone provided a "play" button that allowed participants to feel the same tactile icon repeatedly. Participants entered valence and arousal scores by touching on a point in the 2D V-A space displayed on the touchscreen of the phone. The V-A space consisted of a horizontal line for valence and a vertical line for arousal, both 5.5-cm long, with their crossing point as the origin. Participants used their dominant hand to control the graphical user

Table 6.1: Parameter values used for tactile icons.

Parameter	Values
Amplitude	A1, A2, A3, A4, A5
Carrier Frequency (Hz)	60, 100, 150, 200, 300
Duration (ms)	50, 100, 300, 500, 1000, 2000
Envelope Frequency (Hz)	0*, 1, 2, 4, 8, 16

* Envelope frequency 0 Hz represents no modulation, i.e., $E(t) = A$.

Table 6.2: Vibration amplitudes for each carrier frequency.

Carrier Frequency (Hz)	A1$^{\sharp}$	A2	A3	A4	A5
60	0.12	0.15	0.17	0.12	0.25
100	0.20	0.23	0.31	0.3	0.48
150	0.26	0.39	0.43	0.45	0.74
200	0.33	0.53	0.60	0.63	0.98
300	0.45	0.70	0.81	0.83	1.40

$^{\sharp}$ All amplitudes are peak-to-peak values (unit: gravitational acceleration g) measured from the smart phone grasped in the user's hand.

Table 6.3: Three stimulus sets tested in the experiment.

Set	F_c (Hz)	A	F_e (Hz)	D (ms)	# of Icons
FA	All$^{\top}$	All	0	1000	25
D	60, 100, 200	A2, A5	0	All	36
E	100, 200	A2, A5	All	1000	24

$^{\top}$ "All" means all values listed in Table 6.1.

interface. Then, the horizontal and vertical positions of the response point were converted to valence and arousal scores, each from -100 to 100, for data analysis. This directly-reporting method is often used in computer-based experiments such as [135], due to its efficiency.

The experiment consisted of three sessions, each for one of the three tactile icon sets shown in Table 6.3. The order of the icon sets was balanced using a Latin square across the 24 participants. Each session included three blocks of trials. In each block, all tactile icons in the corresponding icon set were tested once in a random order. After completing each block of trials, the participant took a break of 3 min, and then started the next block or session. This procedure provided three V-A scores for each tactile icon per participant.

Participants wore noise-cancelling headphones during the experiment to block faint noise produced by the vibrotactile actuator. They were allowed to take a rest whenever necessary. All participants finished the experiment in an hour.

6.1.5 Data Analysis

In each session, the first block was regarded as training to enable participants to experience all tactile icons and determine their range and scale of rating. Hence, the data from the first block were discarded, and those from the other two blocks were used for data analysis. The valence and arousal scores for each icon were averaged using an arithmetic mean of the 24 participants' data, without normalization[2].

[2] Normalization of the data may help understanding the relative emotional differences between icons, however, it may distort the results since variances and biases of distributions will be neglected.

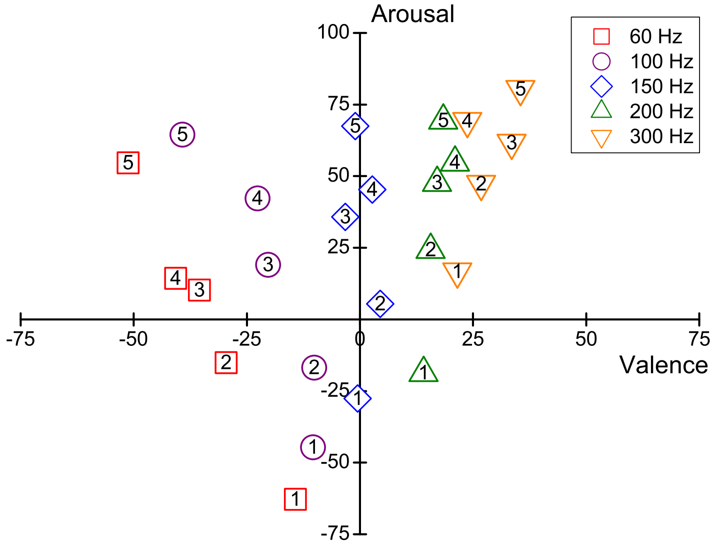


Figure 6.2: Experimental results of the tactile icon set AF. A number within each symbol represents amplitude (A1–A5).

6.2 Results

The measured V-A responses are shown in Fig. 6.2–6.4 for the three tactile icon sets. Standard errors for valence and arousal scores were 4.27–11.36 (mean 7.22) and 2.45–10.65 (6.10) in the set AF, 4.35–10.66 (6.68) and 2.74–10.11 (6.37) in the set D, and 4.71–10.71 (7.16) and 2.70–7.73 (5.87) in the set E. The standard errors are not shown for visibility. A repeated-measures ANOVA was conducted for each set, and results with effect sizes (η^2) are provided in Table 6.4–6.6. The slopes of linear regressions were also calculated.

6.2.1 Effects of Amplitude and Carrier Frequency

Table 6.4 shows that amplitude, carrier frequency, and their interaction had statistically significant effects on both the valence and arousal scores of the tactile icons, except amplitude for valence. This result and examination of Fig. 6.2 allow us to present the following findings.

Given F_c, increasing A increased the arousal score to a large extent regardless of F_c. However, the effects of A on valence depended on F_c. Increasing A decreased the valence score at $F_c = 60$ and 100 Hz, but did not affect the valence scores significantly at $F_c = 150$, 200, and 300 Hz. This was confirmed by additional linear regression analysis for each F_c. In the V-A plane, the best-fitting lines of equal-frequency points had a slope of 107.6° at $F_c = 60$ Hz and 103.9° at $F_c = 100$ Hz, both with statistical significance ($p = 0.0005$ and 0.0298). The slopes for the other three F_c's were not statistically different from 90° ($p = 0.765$, 0.090, and 0.180).

Given A, increasing F_c tended to increase both the valence and arousal scores. As A is increased, the range of valence resulted from changing F_c is increased, but the range of arousal is decreased. As a result, the slope of equal-perceived intensity line was quite steep at $A =$A1, but the slope decreased as A increased. At $A =$A5, arousal seems to be nearly independent of F_c, although all the slopes were significantly different from 0° (linear regression; $p = 0.012, 0.024, 0.0002, 0.023,$ and 0.027 for A1–A5).

Table 6.4: ANOVA results of the tactile icon set AF.

Ind. FA	Dep. FA	Statistics	η^2
A	Valence	$F(4, 92) = 1.28, p = 0.284$	0.0066
	Arousal*	$F(4, 92) = 123.91, p < .0001$	0.4397
F_c	Valence*	$F(4, 92) = 22.92, p < .0001$	0.2893
	Arousal*	$F(4, 92) = 24.70, p < .0001$	0.1469
A × F_c	Valence*	$F(16, 368) = 3.34, p < .0001$	0.0267
	Arousal*	$F(16, 368) = 5.61, p < .0001$	0.0232

Table 6.5: ANOVA results of the tactile icon set D.

Ind. FA	Dep. FA	Statistics	η^2
A	Valence*	$F(1, 23) = 11.76, p = .0023$	0.0173
	Arousal*	$F(1, 23) = 112.15, p < .0001$	0.1548
F_c	Valence*	$F(2, 46) = 72.68, p < .0001$	0.3557
	Arousal*	$F(2, 46) = 29.21, p < .0001$	0.0633
D	Valence	$F(5, 115) = 1.95, p = .091$	0.0127
	Arousal*	$F(5, 115) = 83.42, p < .0001$	0.3600
A × F_c	Valence*	$F(2, 46) = 6.54, p = .0032$	0.0051
	Arousal*	$F(2, 46) = 11.13, p = .0001$	0.0046
A × D	Valence	$F(10, 230) = 0.50, p = .773$	0.0011
	Arousal*	$F(10, 230) = 3.04, p = .012$	0.0044
F_c × D	Valence*	$F(10, 230) = 8.11, p < .0001$	0.0307
	Arousal*	$F(10, 230) = 3.46, p = .003$	0.0072

Table 6.6: ANOVA results of the tactile icon set E.

Ind. FA	Dep. FA	Statistics	η^2
A	Valence*	$F(1, 23) = 8.10, p = .0091$	0.0218
	Arousal*	$F(1, 23) = 96.55, p < .0001$	0.4593
F_c	Valence*	$F(1, 23) = 39.12, p < .0001$	0.1553
	Arousal*	$F(1, 23) = 4.91, p = .0370$	0.0053
F_e	Valence*	$F(5, 115) = 4.67, p = .0006$	0.0558
	Arousal*	$F(5, 115) = 6.91, p < .0001$	0.0225
A × F_c	Valence*	$F(1, 23) = 4.78, p = .0393$	0.0035
	Arousal*	$F(1, 23) = 24.74, p < .0001$	0.0095
A × F_e	Valence	$F(5, 115) = 1.71, p = .138$	0.0037
	Arousal*	$F(5, 115) = 2.97, p = .014$	0.0053
F_c × F_e	Valence	$F(5, 115) = 1.15, p = .340$	0.0040
	Arousal	$F(5, 115) = 1.87, p = .1046$	0.0033

* indicates a statistically significant case.

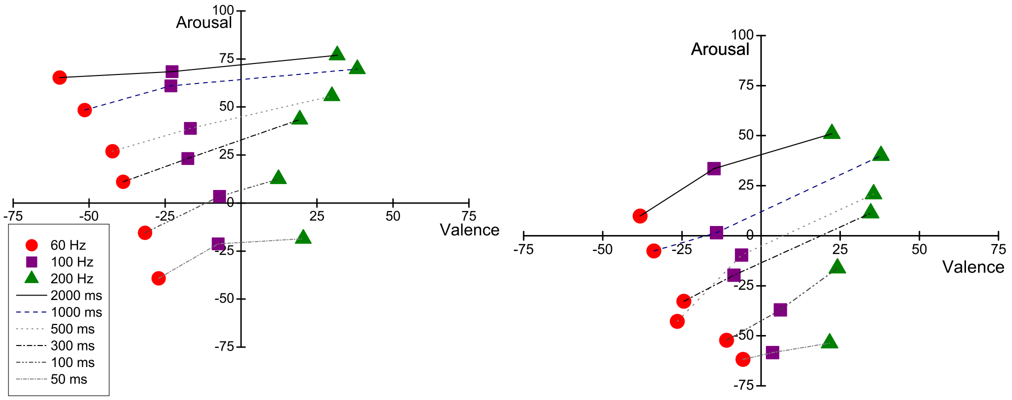


Figure 6.3: Experimental results of the tactile icon set D (left: $A = A5$ and right: $A = A2$).

6.2.2 Effects of Duration

According to the ANOVA results shown in Table 6.5, all main factors of amplitude, carrier frequency, and duration, as well as all their two-way interactions, were statistically significant for both valence and arousal, except duration for valence and amplitude×duration for valence.

Fig. 6.3 shows the effects of duration more clearly. The effects of D were similar to those of A (Section 6.2.1). Increasing D increased the arousal of the tactile icons consistently. The effect of D on valence depended on F_c. The best fitting line of the equal-frequency points in the V-A space with $F_c = 60\,\text{Hz}$ showed a negative slope for both A =A2 and A5 (linear regression; $p = 0.0071$ and 0.0004), indicating that valence was decreased with D. Those for $F_c = 200\,\text{Hz}$ showed a slope not statistically different from 90° for both A levels (linear regression; $p = 0.3495$ for A2 and 0.0866 for A5), meaning that valence was rather independent of D.

6.2.3 Effects of Envelope Frequency

ANOVA results for the tactile icon set E are shown in Table 6.6. All main factors of amplitude, carrier frequency, and envelope frequency and their two-way interaction terms were statistically significant for both valence and arousal, except amplitude×envelope frequency for valence and carrier frequency×envelope frequency for both valence and arousal.

Fig. 6.4 shows that, for a given pair of F_c and A, increasing F_e from 0 to 16 Hz generally decreased the valence of the tactile icons. The effect of F_e on arousal was not as clear; increasing F_e made the arousal scores fluctuate within a small interval. Further, it seems that F_e had less salient effects on the valence and arousal scores compared to F_c, A, and D. The areas in which the valence and arousal scores moved around when F_e was changed from 0 to 16 Hz were noticeably smaller than the corresponding areas of the other parameters. The effect sizes of F_e also reflect this fact, which are quite smaller than those of A and F_c.

6.3 Discussion

6.3.1 Effects of Physical Parameters

The experiment uncovered clear relationships of the four tactile icon parameters to emotional responses, as summarized in Table 6.7. This provides answers to our research question "Q1: How do physical parameters of tactile icons affect emotional responses?".

Amplitude and duration showed similar effects on emotional responses. In-

Table 6.7: Effects of Tactile Icon Parameters on Emotional Responses

Parameter	Emotional Variable	Effects
Amplitude*	Valence	Amplitude $\uparrow \implies$ Valence $\downarrow$ for Carrier Frequency $\leq$ 100 Hz. Unrelated for Carrier Frequency $\geq$ 150 Hz
	Arousal	Amplitude $\uparrow \implies$ Arousal $\uparrow$
Carrier Frequency	Valence	Carrier Frequency $\uparrow \implies$ Valence $\uparrow$, with a rate increasing with Amplitude
	Arousal	Carrier Frequency $\uparrow \implies$ Arousal $\uparrow$, with a rate decreasing with Amplitude
Duration	Valence	Duration $\uparrow \implies$ Valence $\downarrow$ for Carrier Frequency $\leq$ 60 Hz. Unrelated for Carrier Frequency $\geq$ 100 Hz
	Arousal	Duration $\uparrow \implies$ Arousal $\uparrow$
Envelope Frequency	Valence	Envelope Frequency $\uparrow \implies$ Valence $\downarrow$
	Arousal	No clear relationship

*In this study, amplitude means perceived intensity, not the physical amplitude of a vibrotactile signal.

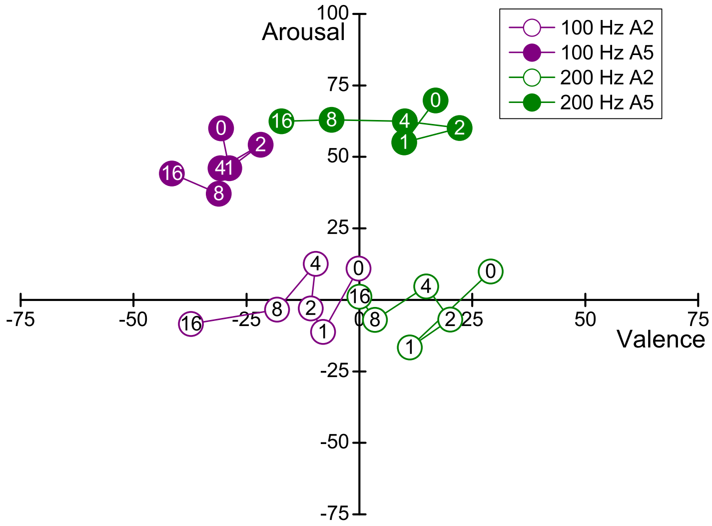


Figure 6.4: Experimental results of the tactile icon set E. A number within each symbol represents the envelope frequency.

creasing amplitude or duration increases the signal energy transmitted to the hand. Skin-absorbed stimulus power was shown to be a robust metric for the perceived intensity of vibratory stimulus [9]. The PC channel is also capable of integrating signal energy over time (temporal summation) [5]. This similarity may account for the similar effects of amplitude and duration.

It is also interesting that the effects of amplitude and duration on valence depended on carrier frequency. The boundary was between 100 and 150 Hz, indicating that the difference may have stemmed from the tactile channel responsible for perception (RA vs. PC channel [5]).

Carrier frequency showed a positive correlation with valence. This was well expected based on previous studies. Low-frequency vibrations are associated with negative feelings such as unpleasant and rough while high-frequency vibrations are with positive ones such as pleasant and smooth [11, 28]. However, we are not aware of clear grounds for the positive correlation of carrier frequency to arousal, except that it might be related to the fact that higher perceived intensity increases the perceived pitch of a vibratory stimulus [47].

Envelope frequency was negatively correlated to valence. This seems to be related to the perception of very low-frequency vibrations. Movements with a frequency of 1–3 Hz are regarded as a slow kinesthetic motion, and those for 10–70 Hz feel like fluttering vibrations [38]. Thus, increasing envelope frequency from 0 to 16 Hz is likely to amplify rough and bumpy sensations, thereby decreasing valence. However, this cannot be guaranteed in short durations which cannot present the complete waveforms of envelopes.

6.3.2 Emotional Expressibility of Tactile Icons

In order to assess how diverse emotions the tactile icons could elicit, i.e., to seek an answer to "Q2: Does changing the physical parameters in a wide range lead to tactile icons that cover a large region in the V-A space?", we pooled the valence and arousal scores of all the tactile icons in the same V-A space. [3] Results are shown in Fig. 6.5 along with emotional labels taken from the circumplex of emotion [1]. A few interesting observations can be made from this figure.

[3] Four tactile icons (A =A2 or A5, F_c = 100 or 200 Hz, D = 1000 ms, and F_e = 0 Hz) were included in all the three tactile icon sets. To assess stimulus context effect, we performed a three-way repeated-measures ANOVA with icon set, amplitude, and carrier frequency as independent factors on the valence and arousal scores of the four tactile icons. Icon set was statistically significant for valence with a relatively large p-value ($F(2, 46) = 4.09, p = 0.0231$), but it was not significant for arousal ($F(2, 46) = 1.66, p = 0.2018$). Therefore, it can be said that the stimulus context effect existed among the three icon sets, but its degree was not very strong.

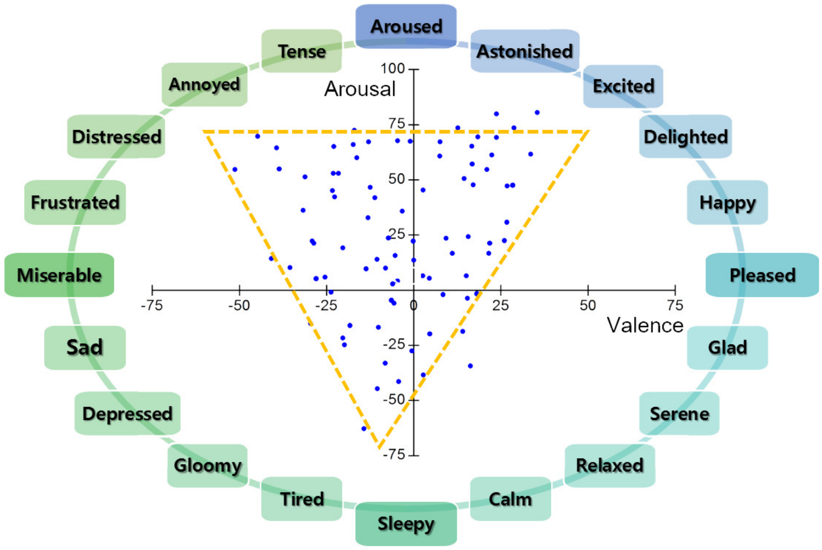


Figure 6.5: Emotional responses of all the tactile icons represented in the same V-A space. Emotional labels are taken from the circumplex of emotion [1].

First, the majority of the valence and arousal scores can be enclosed by an inverted triangle represented by a yellow dashed line in Fig. 6.5. This means that the range of valence our tactile icons could evoke depended on their arousal: the higher an arousal score is, the wider the valence range is. Second, the population of our tactile icons was scarce in the 3rd and 4th quadrants in the V-A space. This suggests that the tactile icons tested in our study might be inappropriate for expressing positive and relaxing emotions (e.g., serene and relaxed) and negative and relaxing emotions (e.g., depressed and gloomy). To be certain, however, we will need an additional study in which the emotions that tactile icons elicit are also explicitly labeled by participants. Third, compared to our previous study [75], we obtained more tactile icons in the 1st quadrant in the V-A space, but less in the 4th quadrant. The previous study included stronger low-frequency vibrations, and they appeared in the 4th quadrant. Lastly, the limited coverage of our tactile icons in the V-A space is in contrast to visual or auditory stimuli that can express emotions distributed in the entire V-A space [67, 135]. Finding more design parameters or even metaphors to enlarge the emotions that tactile icons can bring in can be a valuable research direction.

6.4 Conclusions

In this chapter, we investigated the effects of four parameters of tactile icons on their emotional responses. The four parameters—amplitude, carrier frequency, duration, and envelope frequency—showed clear relationships to the valence and arousal of tactile icons (Table 6.7), providing useful design guidelines for the tactile icons with desired emotional features. However, even though a wide range of parameter values were tested, there still existed unpopulated regions in the valence-arousal space (Fig. 6.5). Overall, our results can contribute to expanding an understanding of the emotional characteristics of tactile stimuli and their better uses in interaction design.

7. Emotional Responses of Vibrotactile-Thermal Stimuli

Thermal stimuli, such as warmth and coolness, serve an important role in emotional communications. Especially, temperature takes a key role in interpersonal relationships such as social warmth [16, 19]. Also, the thermal sensation have been utilized in several HCI applications such as VR [113], mobile interactions [80, 78, 112], and wearable devices [79] for emotional communications.

However, little is known as to the emotional aspects of thermal stimuli. Though researches as to the emotional responses caused by thermal stimuli has been done mostly for those containing temperature changes, but not those of constant temperature (except [20, 21] that included both kinds of stimuli). Moreover, complex stimuli such as vibrotactile-thermal stimuli, which can provide more holistic haptic experiences to users, were rarely investigated. To our knowledge, no researches investigated the emotional aspects of complex tactile stimuli, except [112], which designed multimodal icons using visual, audio, vibrotactile, and thermal stimuli for presenting emotions.

We first focused on the *constant* temperature stimuli, as a baseline. At a constant temperature, the heat gain (or loss) of the skin from a heat source (or sink) is equal to its heat loss (or gain) by atmospheric cooling (or heating). This process results in constant heat flux, either positive or negative, and stimulates the warm and cold receptors in the skin accordingly [125]. Therefore, the effects of constant-temperature stimuli are regarded as a baseline for understanding the effects of dynamic temperature changes. Further, constant-temperature stimuli are used much more frequently in applications to render the thermal condition of the scene [136, 137, 138] than temperature-changing stimuli. However, their emotional consequences may not be as intensive as those of dynamic thermal stimuli.

Then, we investigated the *dynamic* temperature stimuli, such as warming and cooling. Such stimuli can stimulate the warm and cold receptors more intensively. Thus, such effects of dynamic-temperature stimuli is expected to have stronger effects compared to those of constant-temperature stimuli. Due to this reason, several previous works already utilized the dynamic temperature-varying stimuli to convey messages and emotions [80, 79, 139].

This chapter is about the study on the effects of vibrotactile and constant thermal stimuli on the emotional characteristics of their combined stimuli. In particular, we present the V-A responses of users when they perceive 1) constant-temperature thermal stimuli alone, 2) vibrotactile and constant-temperature thermal stimuli simultaneously, and 3) vibrotactile and dynamic-temperature thermal stimuli, with emphasis on the latter two multimodal tactile stimuli.

7.1 General Methods

This experiment was approved by the Institutional Review Board of the authors' institution (PIRB-2016-E030 and PIRB-2018-E107).

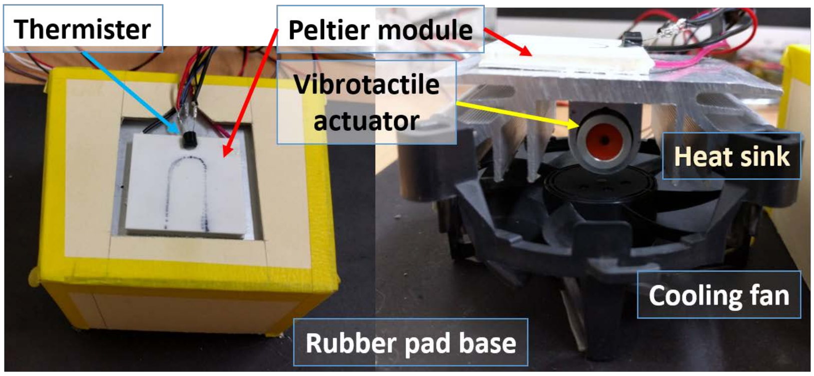


Figure 7.1: Vibrotactile-thermal tactile device. Top (left) and side view (right).

7.1.1 Participants

Twenty volunteers (10 for each gender; aged 19–29 years with a mean 22.0) participated in Experiment I. Another twenty participants (10 for each gender; aged 19–29 years with a mean 22.0) participated in Experiment II. They were compensated (approximately 15 USD for Experiment I and 10 USD for Experiment II) after the experiment. No participants reported known sensory or motor disorders.

7.1.2 Apparatus

We implemented a device for vibrotactile-thermal stimulation (Figure 7.1). In this device, a Peltier module (4.5 cm $\times$ 4.5 cm) for thermal stimulation was attached onto a rectangular heat sink. A voice-coil vibration actuator (Haptuator; TactileLabs) was affixed under the heat sink. An electric fan below was for rapid cooling. The two actuators were connected to a PC through a data acquisition card (PCI-6251; National Instruments).

The vibration output was calibrated using a high-precision accelerometer (8794A500; Kistler) fastened at the center of the Peltier module. A linear relationship between input voltage amplitude (in V) and output vibration amplitude (in g[1]) was experimentally derived for each frequency used in the experiment.

For temperature control, we designed a closed-loop PD controller for the Peltier module. A thermistor (LM35DZ; Texas Instruments) was attached onto the Peltier module, and calibrated using an infrared thermometer (LaserSight; Optris). This setup allowed us to control the skin temperature of a finger to vary between 18°C and 42 °C with a moderate rate (up to 4°C/s).

7.1.3 Procedure

Prior to the experiment, the experimenter explained the concept of valence, arousal, and V-A space with some examples of emotion-related words such as exciting and lazy to each participant based on a written script. We asked participants to respond reflecting their own emotional states, as in the instructions of IAPS [67]. Participants could ask any questions to have a clear understanding. Then they signed an informed consent form. They wore noise-canceling headphones during the experiment to block noise emanating from the vibration actuator.

In Experiment I, the experiment consisted of three sessions for training, thermal stimuli, and vibrotactile-thermal stimuli. In the training session, participants experienced the thermal stimuli and the vibrotactile stimuli (temperature 30°C only) separately to establish their perceptual references. The next session was

[1] Gravitational acceleration unit ($\simeq 9.8\,\mathrm{m/s^2}$).

for the five thermal stimuli. Each stimulus was repeated five times in a blocked design, and the order of the stimuli was randomized in each block. The last session was for the 36 vibrotactile-thermal stimuli with three repetitions each in a blocked design. The total numbers of trials were 25 and 108, respectively.

In Experiment II, the experiment consisted of three sessions. Each session contains a whole stimulus set of 48 vibrotactile-thermal stimuli. The first session was regarded as a training session and excluded from data analysis. Each stimulus was evaluated three times, and the total number of trials was 144.

Participants' task in each trial was to perceive a tactile stimulus and represent its emotional impression using V-A scores. They placed their index and middle fingers on the Peltier element of the vibrotactile-thermal device (Figure 7.1). Participants could feel the tactile stimulus repeatedly by pressing a 'play' button on the computer screen. They entered V-A scores using a mouse grasped in their right hand by clicking a point on a 2D V-A space (600×600 pixels; $12\,\mathrm{cm} \times 12\,\mathrm{cm}$; a horizontal line for valence and a vertical line for arousal). The response position on the screen was converted to V-A scores from -100 to 100 for data analysis. Transition to the next trial required 2-4 s depending on the temperature change.

Participants took a break of at least 2 minutes after each session. The experiment was completed in 1.5 hours for Experiment I and an hour for Experiment II.

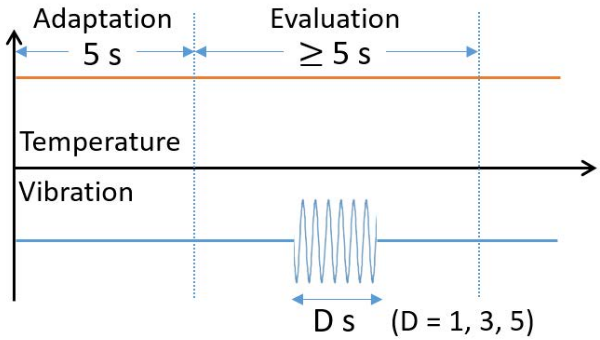


Figure 7.2: Time profile of vibrotactile-thermal stimuli (constant temperature).

7.1.4 Data Analysis

We collected multiple V-A scores for each stimulus in a blocked design. The data of the first block were regarded as training and excluded from data analysis. The V-A scores of the other blocks were averaged using the arithmetic mean across the 20 participants. The data were not normalized to preserve individual variances and biases.

7.2 Experiment I: Effects of Constant-Temperature Stimuli

7.2.1 Stimuli

Vibrotactile stimuli were simple sinusoids with three parameters—duration, frequency, and amplitude. The duration was one of 1, 3, and 5 s; all of them are long enough for stable perception, not affected by the temporal summation of the PC (Pacinian corpuscle) channel [140]. We tested two frequencies: 70 and 200 Hz. 70-Hz vibrations are largely mediated by the RA (rapidly adapting) channel and deliver low-frequency, fluttering sensations [5]. 200-Hz vibrations are representative of smooth high-frequency tactile stimuli processed by the PC channel [5].

Vibration amplitudes were first set for 200-Hz vibrations: $0.5\,g$ for a 'weak' vibration and $1.0\,g$ for a 'strong' vibration. These amplitudes were chosen to be similar to those used in a prior study [13]. Then we conducted two perceptual experiments to determine the amplitudes of 70-Hz vibrations with the same perceived intensities as those of the 200-Hz vibrations. Since the literature shows inconsistent evidence as to the effect of skin temperature on the perceived intensity of vibrotactile stimulus [141, 142], we carried out a pilot experiment using the vibrotactile-thermal device and found that skin temperature has little effect on vibrotactile perceived intensity for the stimuli to be used in our experiment. Therefore, we ignored skin temperature in calibrating vibration amplitudes. Second, it is well known that vibrotactile perceived intensity is largely affected by frequency [9]. Hence, we conducted another psychophysical experiment using the method of adjustment with six participants. The amplitudes of the equally-strong 70-Hz vibrations were found to be 0.38 and $0.63\,g$, respectively.

Thermal stimuli were those maintaining a constant temperature: 20°C (cold), 25°C (cool), 30°C (neutral), 35°C (warm), and 40°C (hot); the body temperature on the fingertip is about 30°C [143]. Their profile consisted of an adaptation interval (5 s) and an evaluation interval (≥ 5 s) (Figure 7.2). We experimentally confirmed that the adaptation interval was sufficient to make the finger temperature converge to the target value. Participants had perceived the stimulus in the evaluation interval for at least 5 s before they made a response. They were instructed to ignore the sensations perceived in the adaptation interval and concentrate on those in the evaluation interval. The room temperature of the experimental site was controlled to be 25°C.

Vibrotactile-thermal stimuli were made by combining the vibrotactile and thermal stimuli. A vibration stimulus appeared in only the evaluation interval (Figure 7.2). This design resulted in 36 different stimuli: 2 frequencies $\times$ 2 amplitudes $\times$ 3 durations $\times$ 3 temperatures. We used only three temperatures (20, 30, and 40°C) for the multimodal stimuli to avoid excessively many experimental conditions and focus on the assessment of factor effects.

7.2.2 Results and Discussion

Thermal Stimuli

The emotional responses of the constant-temperature thermal stimuli are shown in Figure 7.3. The plot is zoomed in for visibility from the full range (-100 to 100) of valance V and arousal A. At the neutral temperature T = 30°C, $(V, A) = (9.9, -13.0)$, and it is close to the origin (representing neutral emotion). When T is decreased to 25°C (cool), $(V, A) = (11.3, 9.4)$ with V almost the same and A turned to positive. At T = 20°C (cold), V is changed to negative, and A is increased further with $(V, A) = (-6.6, 24.7)$. Overall, the pattern is similar to a counterclockwise spiral from 30 to 20°C. For increasing T, the pattern is a clockwise spiral with greater changes: $(V, A) = (-11.6, -17.3)$ at T = 35°C (warm) and $(V, A) = (-32.0, 44.6)$ at T = 40°C (hot). (V, A) at the highest T shows abrupt changes, especially a large jump in A, suggesting

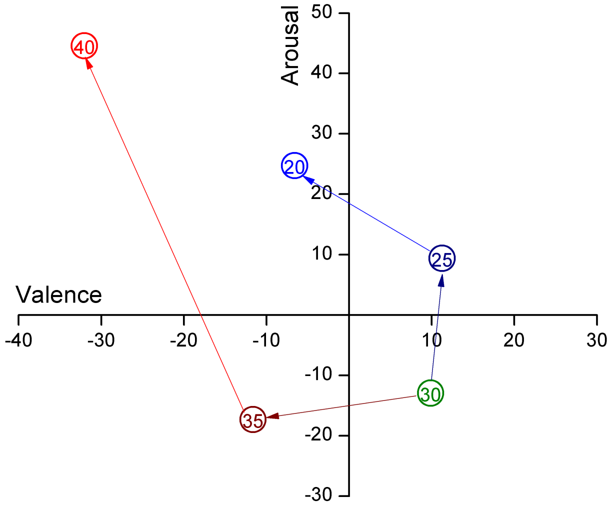


Figure 7.3: Emotional responses of the constant-temperature thermal stimuli. A numbers in each marker represents its temperature (°C).

that the participants were quite sensitive to this temperature. These effects of T were significant for both V and A by one-way repeated-measures ANOVA ($F(4,76) = 3.341$, $p = 0.014$, $\eta_p^2 = 0.103$ and $F(4,76) = 9.448$, $p < 0.001$, $\eta_p^2 = 0.221$).

In [20], the authors included thermal stimuli of both constant temperature and temperature changes. They used three constant temperatures of 25, 28, and 31°C as cold, neutral, and warm stimuli. For comparison, we used the pleasantness ratings in [20] as valance scores and linearly converted the ratings in [20] to match scales (± 4 to ± 100). At the neutral temperature $T = 28$°C, $(V, A) = (25, -37.5)$. This was changed to $(V, A) = (7.5, -17.5)$ at $T = 25$°C and to $(-7.5, 12.5)$ at $T = 31$°C. Thus, when T was decreased or increased from the neutral, V is both decreased. A was both increased with a larger change

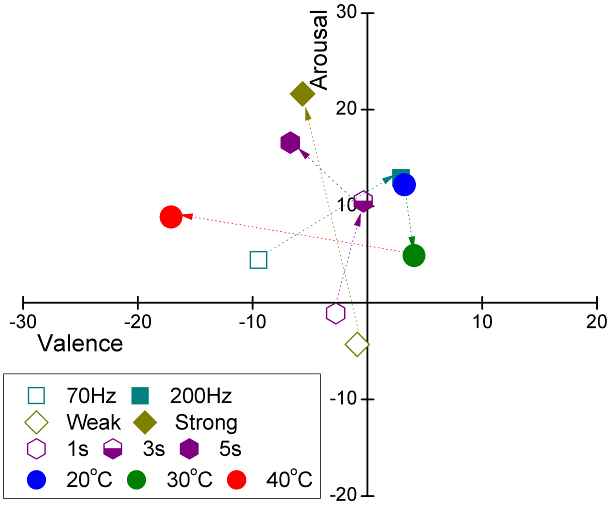


Figure 7.4: Emotional responses of the vibrotactile-thermal stimuli averaged for each independent factor.

toward the hot temperature. These patterns are consistent with those observed from Figure 7.3. However, our results provide stronger support by using more temperatures (5 vs. 3) in a much wider range (±10°C vs. ±3°C).

Vibrotactile-Thermal Stimuli

Figure 7.4 shows the mean V-A scores averaged across each independent factor to see factor effects. General tendencies are as follows: 1) Increasing the frequency F of vibration increases both V and A; 2) Increasing the amplitude Amp or duration D of vibration increases A but decreases V slightly; and 3) Increasing the temperature T from 20 to 30°C decreases A slightly and from 30 to 40°C decreases V by a large extent. Tendency 1 and 2 were also observed from the emotional responses of vibrotactile stimuli in [13].

To verify these factor effects, we performed a four-way repeated-measures

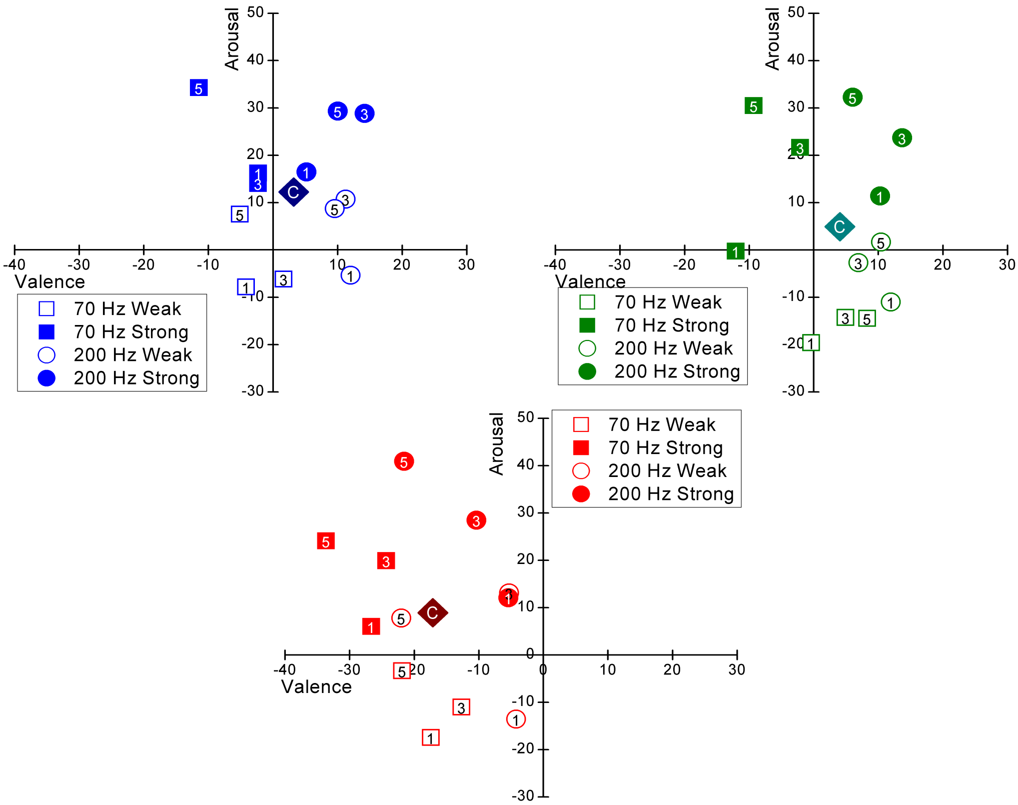


Figure 7.5: Emotional responses of the vibrotactile-thermal stimuli: 20 °C (top-left), 30 °C (top-right), and 40 °C (bottom). A number inside each data marker represents the duration of the vibrotactile stimulus in second. In each plot, the point marked by C is the center of mass of the data points.

Table 7.1: ANOVA results of the emotional responses.

Factor	Dep. Variable	Statistics	Effect Size (η_p^2)
F	V	$F(1, 19) = 3.754$, $p = 0.068$	0.1069
	A	$F(1, 19) = 1.478$, $p = 0.239$	0.0299
Amp	V	$F(1, 19) = 1.687$, $p = 0.210$	0.0157
	A*	$F(1, 19) = 18.80$, $p < 0.001$	0.3513
D	V	$F(2, 38) = 1.295$, $p = 0.286$	0.0189
	A*	$F(2, 38) = 16.71$, $p < 0.001$	0.1122
T	V*	$F(2, 38) = 3.855$, $p = 0.030$	0.2647
	A	$F(2, 38) = 1.198$, $p = 0.313$	0.0187
$F \times$	V*	$F(1, 19) = 5.493$, $p = 0.030$	0.0100
Amp	A	$F(1, 19) = 0.847$, $p = 0.369$	0.0024

* Only main and significant interaction factors are shown.

ANOVA, and results are summarized in Table 7.1. First, the main factor T and the interaction between F and Amp had significant effects on V. This can explain Tendency 3 and 1, respectively. F also affected V considerably ($\eta_p^2 = 0.1069$), but its effect was not significant with a p-value close to the significance level ($p = 0.068$). Second, both Amp and D had significant effects on A with large effect sizes, supporting Tendency 2.

For closer examination, we represent the emotional responses of all the 36 vibrotactile-thermal stimuli in the three plots of Figure 7.5. Each plot shows the V-A scores of 12 stimuli with the same temperature. The data of $T = 40$°C exhibits a clear shift to the left (V decreased) from the data of $T = 20$ and 30°C, which is consistent with the observation made earlier using the means. The data distributions of $T = 20$ and 30°C are similar, but the range of A is expanded slightly. In fact, the areas covered by the V-A values are 750.8, 1025.9, and 1029.3 for T = 20, 30, and 40°C, respectively. The ranges of V and A are also increased: 25.7, 25.8, and 29.4, and 42.1, 51.9, and 58.4. These suggest that the emotional intensities of vibrotactile stimuli are amplified when the skin temperature is increased. Therefore, we can conclude that increasing the temperature of vibrotactile-thermal stimuli decreases their valance noticeably, with a tendency of making the emotional responses more intense especially in arousal.

In each plot of Figure 7.5, the V-A scores are clustered by F and Amp, and in each cluster, the effect of D can be seen. The individual effects of F, Amp, and D are in agreement with those described using the means. Since the distributions within the clusters are similar, the three vibrotactile parameters and the temperature seem to have somewhat independent effects on the emotional responses.

Post-Experimental Survey

We had a post-interview with participants mostly to collect their subjective criteria used for the evaluation of emotional scores. As usual with emotion-related experiments, the participants' responses were diverse, and we provide only a summary of major ones below.

- Thermal stimuli: 1) (12 participants) Hotness conveyed a negative feeling, while coldness a positive one. Only three participants said the opposite; 2) (7 participants) Perceiving the extreme temperature stimuli (20 and 40°C) increased arousal; and 3) (3 participants) Stimuli around the body temperature (30°C) felt positive.

- Vibrotactile stimuli: 1) (9 participants) High-frequency vibrations felt positive. Two participants said the opposite; and 2) Duration (6 participants) and amplitude (9 participants) were correlated with arousal.

- Vibrotactile-thermal stimuli: 1) (4 participants) The thermal stimuli had more dominant effects on evaluating emotional responses; 2) (2 participants) The vibrotactile stimuli had higher effects; 3) (5 participants) The vibrotactile and thermal stimuli had similar effects; 4) (3 participants) Emotions elicited from the two modalities were sometimes contradictory, e.g., high-frequency vibration (positive valence) at a hot temperature (negative valence); and 5) Approximately a half of the participants were not able to express their evaluation criteria clearly in words.

7.2.3 Other Discussion

The experimental results provide guidelines for designing vibrotactile-thermal stimuli that convey desired emotional features. For example, to elicit a positive emotion, tactile stimuli should include a high-frequency vibration and a cool temperature. To present a negative and intense emotion, e.g., for warnings, a low-frequency, strong vibration can be combined with a hot stimulus.

Apparently, the emotional responses were not symmetric around the neutral temperature (30°C); participants responded to the hot stimuli (40°C) more sensitively than the cold stimuli (20°C) even though the temperature differences were identical. This asymmetry might have resulted from the distance to a pain thresh-

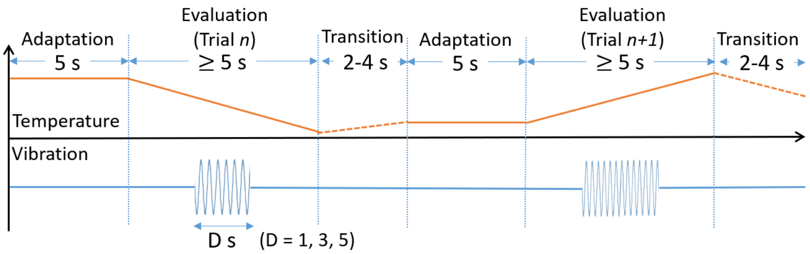


Figure 7.6: Time profile of vibrotactile-thermal stimuli (dynamic temperature).

old. According to [144], the pain threshold of heat on the hand is about 44°C, which is 4 °C higher than our hot stimulus. The pain threshold of cold is about 12.5°C, which is 7.5 °C lower than our cold stimulus. Thus, the hot stimulus was closer to the respective pain threshold. In fact, in the post-interviews, some participants associated the hot vibrotactile-thermal stimuli with unpleasant heat from a cell phone, hot summer, or ignition, sometimes even hazardous situations. Such responses were not observed for the cold stimuli. It would be interesting to see the emotional response of very cold stimuli that have temperatures closer to the pain threshold.

Lastly, we need to point out that the contact area and stimulus duration used in our experiment are small considering the human spatial and temporal summation properties of thermal perception, while they are sufficient for vibrotactile perception. Investigating the effects of contact area and stimulus duration on emotional responses elicited by thermal stimuli can be another intriguing issue.

7.3 Experiment II: Effects of Dynamic Stimuli

7.3.1 Stimuli

Vibrotactile stimuli were simple sinusoids with two parameters of frequency (F) and amplitude (Amp). The duration was 1 s, which provides a stable perception, but not affected by the temporal summation of the PC channel [140]. We used three frequencies: 60, 100 and 250 Hz. 60-Hz vibrations are mediated by RA1 channel and deliver low-frequency, fluttering sensations. 250-Hz vibrations present smooth high-frequency sensations, which are processed by PC channel. A frequency of 100-Hz is often regarded as a borderline of high- and low-frequency in vibrotactile perception; such vibrations are mediated by both RA1 and PC channels [5].

Vibration amplitudes were first set for 100-Hz vibrations: 0.2 g for a 'weak' vibration and 0.5 g for a 'strong' vibration. These amplitudes were chosen to be similar to those used in a prior study [13]. Then we conducted two perceptual experiments to determine the amplitudes of 60-Hz and 200-Hz vibrations with the same perceived intensities as those of the 100-Hz vibrations using the method of adjustment with eight participants. The amplitudes of the equally-strong 60-Hz vibrations were found to be 0.24, and 0.6 g, respectively, and those of 200-Hz vibrations were 0.6 and 1.1 g, respectively.

For the thermal stimuli, we used three parameters: the temperature change direction (D), rate (R), and extent (E). Two directions of warming and cooling were used. We chose two Rs of 2 °C/s and 4 °C/s, and two Es of 4 °C and 8 °C. The duration of change for each stimulus was determined by R and E. The initial temperature was fixed to 30°C, since the body temperature on the fingertip is about 30°C [143]. The profile of thermal stimuli consisted of an adaptation interval (5 s) and an evaluation interval (5 s), which is same to Experiment I.

Vibrotactile-thermal stimuli were made by combining the vibrotactile and thermal stimuli (see Figure 7.6). A vibration appeared in only the evaluation interval of thermal stimulus. This design resulted in 48 different stimuli: 3 $F \times 2$ Amps $\times$ 2 Es $\times$ 2 Rs $\times$ 2 Ds.

Participants had perceived the stimulus in the evaluation interval. They were instructed to ignore the sensations perceived in the adaptation interval and concentrate on those in the evaluation interval. The room temperature of the experimental site was controlled to room temperature (about 25 °C).

7.3.2 Results and Discussion

Mean Points and Effects of Parameters

Since we have five factors in the experimental design, we start the data analysis from the mean points. Figure 7.7 shows the mean V-A scores averaged across each independent factor to see factor effects. The plot is zoomed in for visibility from the full range (-100 to 100) of valance V and arousal A.

For thermal stimuli, we found some tendencies:

T1 A smaller extent of temperature change (4 °C) assessed as positive, while those have a larger extent (8 °C) was regarded as negative (except 8 °C, slow (2 °C/s) change rate of cooling stimulus).

T2 A faster change of temperature induced more positive responses of 4 °C extent

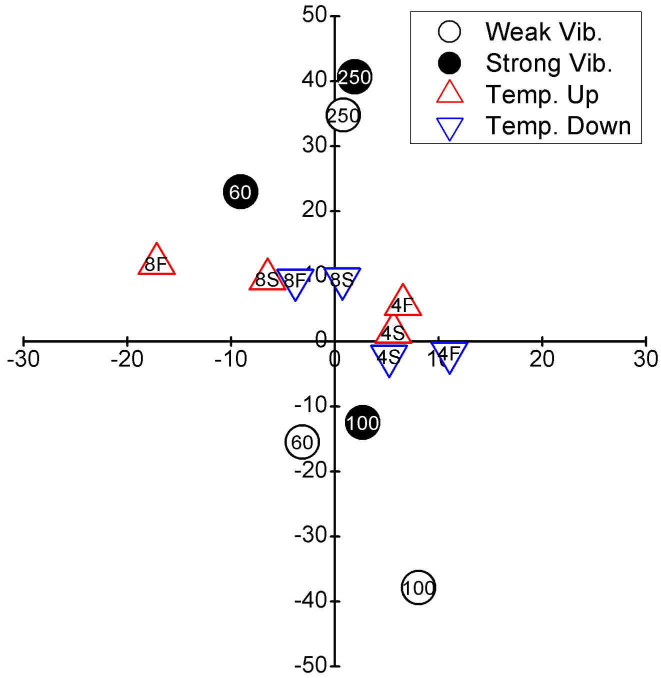


Figure 7.7: Emotional responses of the constant-temperature thermal stimuli. Number in each marker represents its temperature (°C).

stimuli, while more negative responses of 8 °C extent stimuli. The change rate has more salient effects in 8 °C extent.

T3 Thermal parameters rarely affect the arousal ratings, except the arousal difference between 4 °C extent and 8 °C extent stimuli.

T4 With the same extent of change, cooling stimuli are more positive than warming stimuli.

For vibrations, general tendencies are as follows:

V1 For frequency F, 100 Hz is regarded as the mildest (low arousal) and decreasing or increasing frequency leads to higher A.

V2 Increasing the amplitude Amp increases A but decreases V slightly for 60 and 100 Hz vibrations.

V3 250 Hz vibrations rated as intense (high arousal) regardless of amplitude.

Such tendencies are quite different from the emotional responses of vibrotactile stimuli in [13] and [14]. In other words, we observed a strong context effect when we add dynamic thermal stimuli to vibrations. We will discuss this later in the discussion section.

To verify the factor effects, we performed a five-way repeated-measures ANOVA, and results are summarized in Table 7.2. First, the factor E and the interaction between $E \times R$ had significant effects on V. E also had a significant effect on A. These factor effects can explain all the tendencies of thermal stimuli. Second, Amp and F, and their interaction $F \times Amp$ had significant effects on A with large effect sizes, which supports the first and the third tendency in responses of vibrotactile stimuli. Third, F and $F \times Amp$ had significant effects on V, which can explain the other one.

We present the emotional responses of all the 48 vibrotactile-thermal stimuli in the two plots of Figure 7.8 for further investigation. For visibility, we separated the plot by the change direction of temperature (warming/cooling). The top panel of the plot shows the V-A scores of 24 stimuli with cooling, and the bottom panel shows those of 24 stimuli with warming.

First, warming stimuli shifts the response to negative. This tendency is also presented in [14]. However, the amount of negative shifting depends on the frequency F. Comparing the valence scores of 250 Hz vibrations, those with cooling stimuli are more positive than those with warming stimuli. The same tendency can be also found in 60 Hz vibrations, but such tendency rarely occurred in 100 Hz. The interaction between factors F and D has a significant effect on V, which reflects this. Second, the rate of change R affects to the arousal scores of low frequency (60 and 100 Hz) vibrations; a rapid temperature change increased arousal ratings. In contrast, it rarely affects the arousal scores of 250 Hz vibrations. This would be associated with the significance of the interaction $F \times R$.

Post-Experimental Survey

We had a post-interview with participants to collect their subjective criteria used for the evaluation of emotional scores. The participants' responses were diverse; it is usual in emotion-related experiments. General tendencies for thermal

Table 7.2: ANOVA results of the emotional responses of the vibrotactile-thermal stimuli.

Factor	Dep. Variable	Statistics	Effect Size (η_p^2)
F	V*	$F(2, 38) = 5.602$, $p = 0.007$	0.228
	A*	$F(1, 19) = 27.79$, $p < 0.001$	0.594
Amp	V	$F(1, 19) = 2.466$, $p = 0.133$	0.115
	A*	$F(1, 19) = 54.82$, $p < 0.001$	0.743
E	V*	$F(1, 19) = 12.82$, $p < 0.001$	0.403
	A*	$F(1, 19) = 8.11$, $p = 0.001$	0.299
R	V	$F(1, 19) = 2.744$, $p = 0.114$	0.126
	A	$F(1, 19) = 0.655$, $p = 0.428$	0.033
D	V	$F(1, 38) = 0.148$, $p = 0.705$	0.008
	A	$F(1, 19) = 0.758$, $p = 0.395$	0.038
$F \times Amp$	V*	$F(2, 38) = 3.26$, $p = 0.049$	0.146
	A*	$F(2, 38) = 15.24$, $p < 0.001$	0.445
$F \times D$	V*	$F(2, 38) = 4.677$, $p = 0.015$	0.198
	A	$F(2, 38) = 0.937$, $p = 0.401$	0.047
$F \times R$	V	$F(2, 38) = 1.583$, $p = 0.219$	0.077
	A*	$F(2, 38) = 5.91$, $p = 0.006$	0.237
$E \times R$	V*	$F(1, 19) = 13.62$, $p = 0.002$	0.418
	A	$F(1, 19) = 0.193$, $p = 0.665$	0.010
$Amp \times$ $D \times R$	V*	$F(1, 19) = 5.599$, $p = 0.029$	0.228
	A	$F(1, 19) = 10.61$, $p < 0.001$	0.358
$F \times D \times$ $E \times R$	V	$F(2, 38) = 0.488$, $p = 0.618$	0.025
	A*	$F(1, 19) = 3.425$, $p = 0.043$	0.153

* Only main and significant interaction factors are shown.

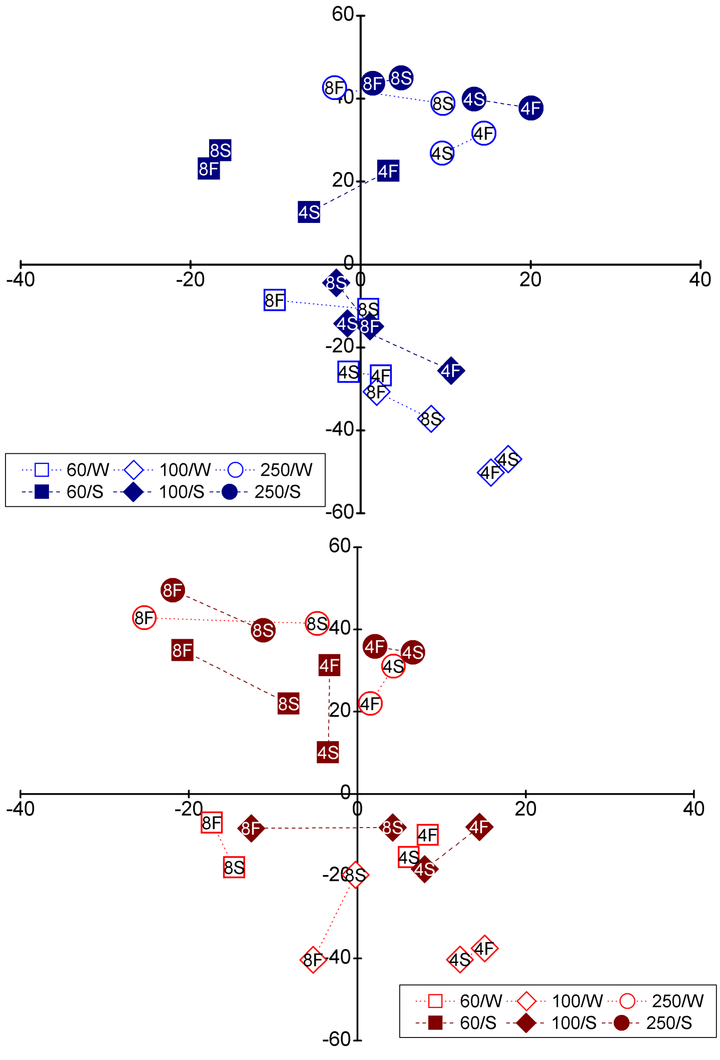


Figure 7.8: Emotional responses of the vibrotactile-thermal stimuli: vibrations with cooling stimuli (top) and warming stimuli (bottom). A number inside each data marker represents the extent (4 or 8 °C) and change rate (Slow; 2 °C/s or Fast; 4 °C/s).

stimuli were similar to those presented in [14]. Eight participants mentioned that a large extent of temperature change felt as negative. Other six mentioned that their coldness conveyed a positive feeling, while hotness conveyed a negative feeling, and another two said the opposite. One participant associated the extent of change with the arousal score. For vibrotactile stimuli, both amplitude and frequency are related to the arousal (17 of 20). Interestingly, seven participants assessed high-frequency vibrations as vibrant and active. Only one associate vibrotactile frequency with the valence score.

7.3.3 General Discussion

The experimental results provide guidelines for designing vibrotactile-thermal stimuli that convey desired emotional features. Table 7.3 summarizes the general guidelines for designing vibrotactile-thermal stimuli with a desired emotional property. For example, to elicit a positive and intense emotion, tactile stimuli should include high-frequency vibration and a rapid cooling stimulus. To present a weak and negative emotion, a low-frequency, smaller weak vibration and a warming stimuli with a large extent can be used.

We can find a general tendency that warming leads to negative response generally, and cooling induces a little positive response in the experimental results. Regardless of changing directions, the larger extent of temperature changes were assessed as negative, with a tendency of making the responses more intense in arousal. This is a similar tendency to those presented in [14]. However, tendencies that are inconsistent with the previous studies were also observed, which seem as context effects. The effect of vibrotactile frequency on the valence score was

Table 7.3: Summary of the factor effects on emotional responses

Parameter	Variable	Effects
Frequency	Valence	60 Hz is regarded as negative, while 100 Hz as positive.
	Arousal	100 Hz has the lowest, and increasing or decreasing frequency leads to higher arousal scores.
Amplitude	Valence	Stronger vibrations induce negative responses for low-frequency vibrations.
	Arousal	Stronger vibrations increases arousal ratings.
Direction	Valence	Cooling makes positive responses with high-frequency vibrations.
	Arousal	No significant effects.
Extent	Valence	A small temperature change regarded as positive, while a large extent of change regarded as negative
	Arousal	Larger extents of temperature perceived as more intense.
Rate	Valence	With a larger extent (8 °C), rapid change of temperature induces more negative response.
	Arousal	No significant effects.

significantly weakened, compared to those in vibrotactile emotional response experiment [13]. Instead, the effect of frequency on the arousal score was increased to a large extent. It seems that participants changed their criteria on each of vibrotactile or thermal stimuli for evaluation. As pieces of evidence, seven (out of 20) participants mentioned that high-frequency vibrations are perceived as 'active,' 'intense,' and 'alarming.' Three also mentioned that intense vibrations increased the arousal level, as well as intensify the emotion elicited by thermal stimuli. This might be explained the perceptual saliency difference between constant and dynamic temperature stimuli. For assessment of vibrotactile-thermal stimuli with dynamic temperature stimuli, participants seemed to consider both sensations to map the stimuli on the V-A space with their own criteria. In contrast, the constant stimuli are less salient compared to the dynamic stimuli when the participants got adapted, so participants had concentrated on vibrotactile stimuli more even though we asked to consider all the stimuli they felt. However, further evidence is needed; our future work will address this.

7.4 Conclusions

In this chapter, we have reported the emotional characteristics of vibrotactile-thermal stimuli. According to our results, constant-temperature thermal stimuli generally shift the emotional responses of vibrotactile stimuli while preserving the effects of the individual vibrotactile parameters of frequency, amplitude, and duration. The constant-temperature thermal stimuli also tend to intensify the emotions elicited by vibrotactile stimuli, but this requires further validation. Vibration with dynamic thermal stimuli showed a different tendency to those with constant stimuli. Vibrotactile parameters are generally associated with the arousal score, where thermal parameters are with the valence score. These results contribute to expanding our knowledge on the emotional features of tactile stimuli and their better uses in interaction design by providing more holistic haptic experiences to users.

Part IV

Applications of Perceptual and Affective Characteristics of Tactile Stimuli

8. Vibrotactile Authoring Based on Adjectival Expressions and Their Ratings

In this chapter, we introduced and evaluate an authoring method using adjectives. The authoring of vibrotactile stimuli has been investigated for decades. Such authoring tools are mainly focused on easy manipulation of physical parameters to design a desired vibration. Graphical methods [94, 92, 93], or a metaphor of musical score [96] have been suggested for easier use. However, for end-users, who have lack of knowledge, finding a desired vibration is not easy even using such tools. Especially, for complex vibrations, most of the end-users are unaware of on the perceptual effects of parameters. This make the designing task more difficult.

Thus, we constituted *adjectival spaces* that quantifies and suggests the subjective quality of sensation of a vibration to the users, utilizing the results of previous chapters. An adjectival space is a Cartesian space with adjectival axes. Each adjectival axis consists of two adjectives which are antonyms of each other, and presents the the degree of a certain sensation quality that could be expressed by the adjective. For example, an axis of "light–heavy" presents the perceived weight of a vibration.

The remainder of this chapter contains as follows: First, we introduce our authoring tool in Sec. 8.1, and we evaluated the usability of the method and tool by comparing the performance with a traditional method in Sec. 8.2. The sections of discussions and conclusions follow the experiment sections.

8.1 Adjective Space and Vibrotactile Authoring Tool

In this section, we introduce our vibrotactile authoring tool. First, we built adjectival spaces for authoring from the results of the adjectival rating experiments (Chapter 5). The spaces visualize the relative levels of subjective characteristics on a Cartesian space, to enable users to select desired levels. Then, we designed user interfaces for intuitive authoring of vibrotactile stimuli by non-expert users.

8.1.1 Establishing Adjectival Spaces

Here, we first defined "*adjectival spaces*" for authoring vibrotactile stimuli. An adjectival space consists of one or two axes of adjectives that stand for perceptual characteristics of vibrotactile stimuli. An adjectival axis in the space presents a continuous change of feeling of vibrotactile stimuli, divided by predetermined levels. The levels would be presented by explanations (e.g., very soft, somewhat hard, etc.), or numerical values. For example, an adjectival axis of "soft – hard" can present a continuous change of feeling of softness to hardness. The distance between levels and number of levels are predetermined in the authoring space data. If space consists of two axes, they are allocated and presented orthogonally. As results, in one-axis (1D) case, the grids would be allocated horizontally, so it appears as a long bar. In 2D case, a Cartesian space consists of check-pattern grids would be presented.

Building appropriate adjectival spaces is the most important task of this

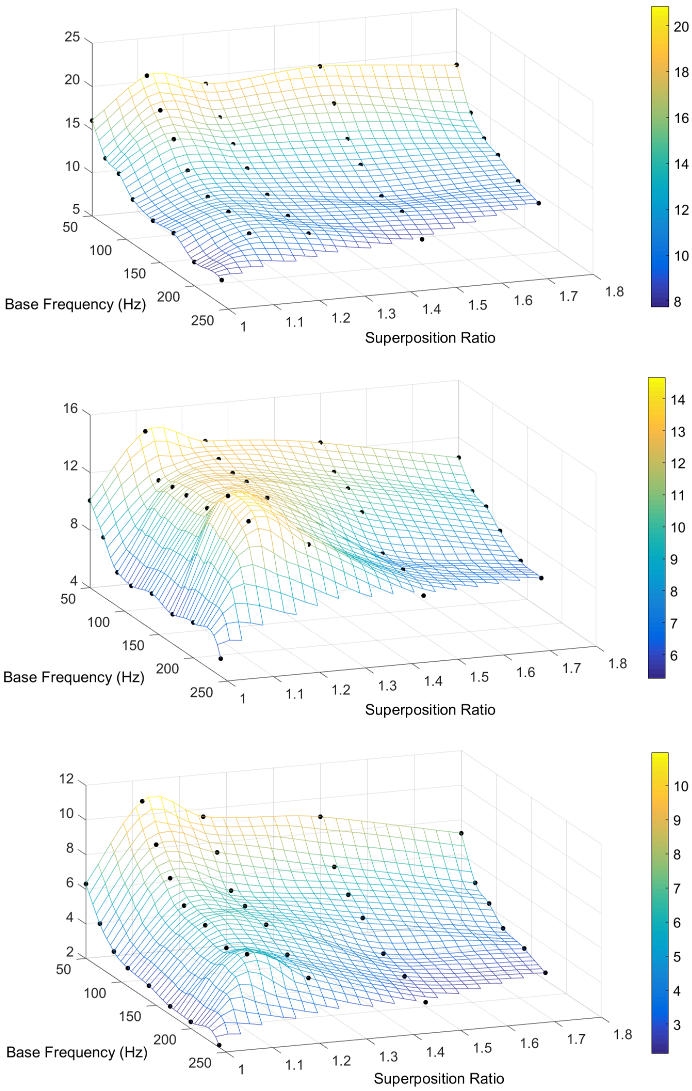


Figure 8.1: The adjectival ratings of vibrations corresponding to the grids of the 2D adjectival space (revisited; from Chapter 5.)

study. For this, we tried to compose an intuitive and easy-to-use authoring space. Trivially, the authoring space can be composed by any adjectival rating scores with desired adjectival sets, but we started from our adjectival rating results described in Chapter 5. We evaluated perceptual heaviness, roughness, and bumpiness of single sinusoids and superimposed vibrations. Both the heaviness and roughness ratings were highly correlated to the frequency, but roughness was largely affected by the superposition ratio (Fig. 8.1). The heaviness and roughness ratings did not share salient subjective qualities of sensations if we did not use single low-frequency vibrations, so they could be considered as perceptually orthogonal in parts. The tendency of the bumpiness rating contains both tendency of roughness and heaviness. Therefore, we constitute a 2D adjectival space using the heaviness and the roughness axes, and a 1D adjectival space using the bumpiness axis.

Then, we calculated the ratio of the maximum and the minimum values of subjective scores. They would indicate the expressibility of vibrotactile sensation in user's perspective, as well as the possibility of authoring in a wider region of perceptual domains. The bumpiness ratings (bumpy–even) showed the largest ratio (5.1; the maximum rating of 10.47 and minimum of 2.145). The ratio of the heaviness (heavy–light) and the roughness (rough–smooth) were 2.7 and 2.8.

We tried to utilize the concept of perceptual transparency [95] on the subjective sensations, so we built authoring spaces by the following way, using the results of Chapter 5. Regarding the intensity of stimuli, we matched the perceived intensity to the same level (strong: perceived intensity of 10), using the perceived intensity model that we derived in our previous study. For superimposed vibrations, the amplitude of each component was decided by the square sum (Pythagorean summation) raw, in Chapter 3. Users can select a grid in the space to select the designated level of subjective characteristics.

First, for the 1D adjectival space, perceived bumpiness B was fitted by two functions. Since the impact of the superposition ratio is greater than that of frequency to the discriminability [116, 28], we tried to change the frequency first, and then we used the superposed vibrations. *Freq* and *Ratio* indicate the frequency and the frequency ratio of superposition.

$$B = \frac{464.1}{Freq + 22.554}, Ratio = 1.0 \quad (1.5 \leq B \leq 5.9)$$
$$B = \frac{1409.9}{Freq + 87.701}, Ratio = 1.12 \quad (5.9 \leq B \leq 10.2)$$

Then, for the 2D adjectival space, we matched the vibrotactile parameters of frequency and superposition ratio on each grid point to find the 'best fit' surface. Each grid point has the heaviness and the roughness rating scores, and the corresponding physical parameters were selected using the inverse relationship of the results. We calculated the optimal interpolation point if there is no point to satisfy the two adjectival ratings simultaneously, to minimizes the mode errors of adjectival ratings. Also, to avoid an abrupt change of sensation, the interpolation was done using the values of neighboring cells first. We also calculated and visualized the physical parameters and the model errors for the 2D space, and this method worked well for most cases. The fitting error of a cell was the sum of differences between the two desired adjectival rating scores and the estimated adjectival ratings of the matched vibration (Fig. 8.2).

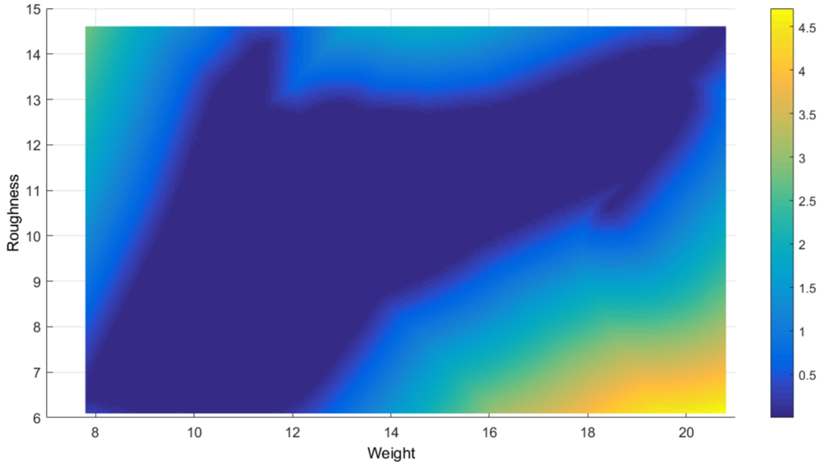


Figure 8.2: The 2D adjectival space composed in this study. Blue region (small error) was the authoring space. Regions whose error exceeds 1.0 were truncated and not provided to the users to prevent distortion.

To avoid extrapolation, we disabled the cells with a fitting error exceeding 1.0. For example, "light" feeling would be highly correlated to "smooth," which are mostly observed in high-frequency vibrations, since the tendencies of the two adjectival scores are similar in the high-frequency region. Therefore, consequently, some regions "light and rough" and "heavy and smooth" cannot be found in the rating scores. In addition, this would be well matched with a Cartesian space with two orthogonal axes, which is one of the easiest and intuitive interface for authoring.

The resultant authoring spaces and the corresponding physical parameters are presented in Fig. 8.3 and 8.4

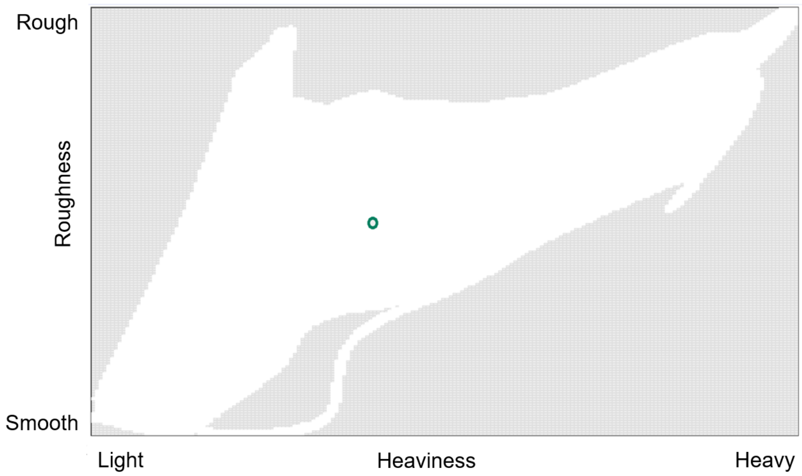


Figure 8.3: The established 2D and 1D adjectival spaces.

8.1.2 I/O of Authoring Tool

Input

The authoring tool loads the authoring space data which was described and built above. The data includes the name of each dimension, minimum value and interval between levels, and verbal descriptions. Then, to utilize the perceptually-transparent vibrotactile rendering [95], as well as to support a wide variety of vibrotactile actuators, the tool loads the actuator calibration data, as an independent input. The calibration data consists of a set of relationships between voltage and vibrotactile output acceleration under a certain frequency.

Output

The authoring tool presents the vibration during authoring, as well as the meta-data of vibrations that composed by the users. For playing vibrations,

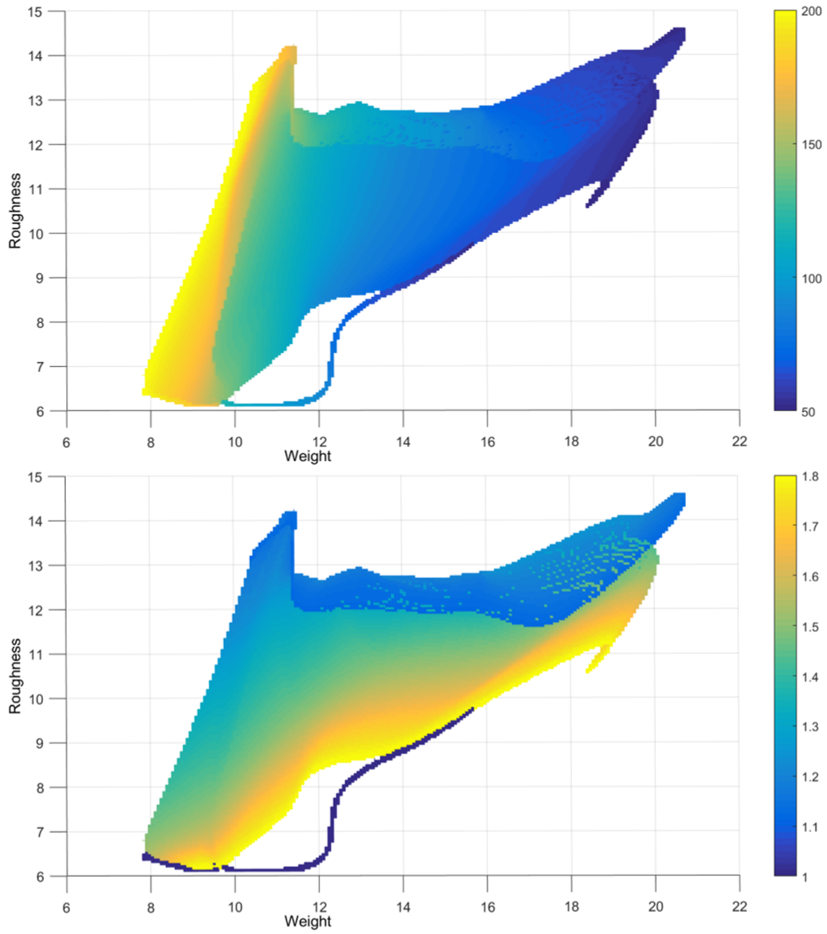


Figure 8.4: The physical parameters of vibrations corresponding to the grids of the 2D adjectival space.

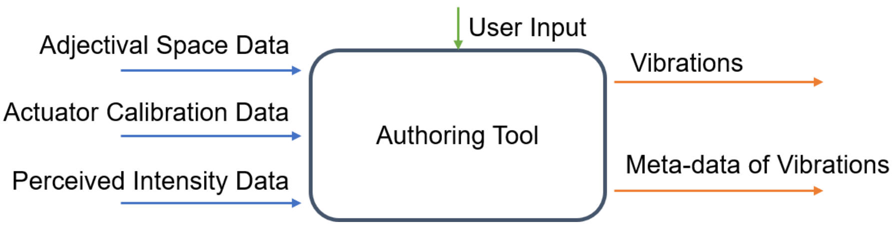


Figure 8.5: I/O scheme of the adjectival authoring tool.

```
[Number of Vib.] [Dur. (s)] [ISI] [Intensity]
F1 F2 A1 A2 (for first vibration)
...
F1 F2 A1 A2 (for n-th vibration)
EOF
```

we supported two options. First, if the option "vibrate when click" is enabled, vibration will be presented to the connected actuator when a user clicked a spot in the space. Second, when the user clicks the button "play the vibrations," vibration will be presented. The authoring tool refers the actuator calibration data to find the applying voltage, then the vibration signal is generated with the parameters of the authoring space.

To record the vibrotactile stimuli that produced by users, we support a meta-file output that writes the parameters of vibrations only. The following is the format for meta-file of vibrations. Since we supported only the single sinusoid and dual-frequency superimposed vibrations for authoring, we designed the format of the output file of vibrotactile meta-data as simple as possible. F1, F2 means component frequencies of a superimposed vibration, and A1 and A2 are corresponding physical amplitudes in g[1] scale. In case of single vibrations, F2 and A2 would be zeros. This format spends only a little storage capacity but requires the calibration data and signal generation part in implementation. Complex waveform data is not needed. In case of a single vibration, F2 and A2 will be zero to eliminate the second frequency component. Currently, we did not consider complex pattern authoring such as vibrations with complex rhythm, or

[1]gravity acceleration unit, $\simeq 9.8m/s^2$

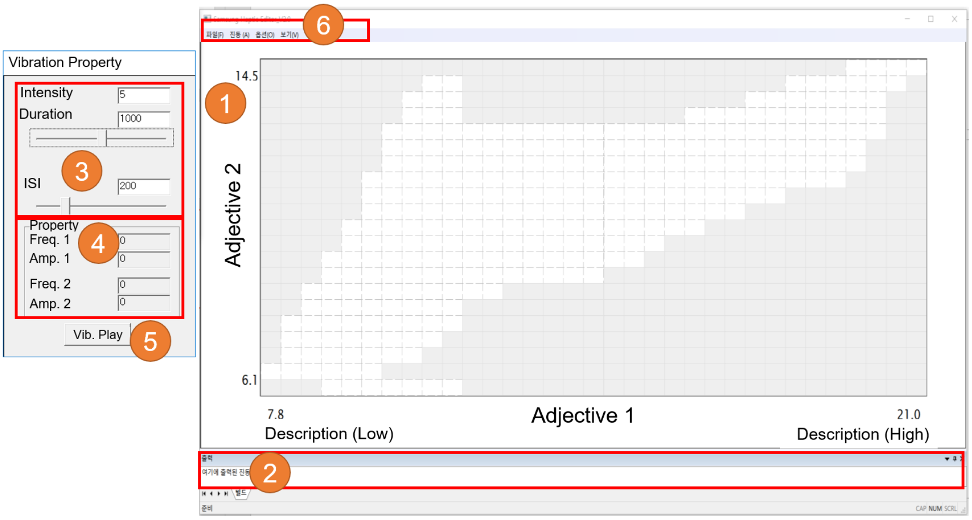


Figure 8.6: Graphical user interface of authoring tool.

time-varying amplitudes.

Fig. 8.5 describes the overall I/O scheme of the authoring tool.

8.1.3 Graphical User Interface

Fig. 8.6 shows the user interface. We used the MFC (Microsoft Foundation Classes) library, but any of GUI programming languages can implement the features. We supported following features in this tool:

1. Main authoring space: presents an adjectival space for authoring. Users can select a grid to find a vibration with desired levels of subjective sensations.

2. Logging window: records the user's and program's action.

3. Properties window: Intensity, duration, and inter-stimulus interval (ISI) adjustment.

4. Physical properties such as frequency and amplitudes would be presented in this region.

5. Vibration play button: play the composed vibration when clicked.

6. Menus for file I/O, toggle grid view and vibration on/off when click the space.

Fig. 8.7 shows the use examples of the authoring tool. Users can make a single vibration or a series of vibrations in the perceptual domain, shown in Fig. 8.7.

8.2 Usability Evaluation Experiment

In this section, we evaluated the usability of authoring methods by a user experiment that compares the task performances of participants. For comparison, we implemented an editor with a *frequency space*, which maps two frequency components into the coordinates (x, y) of a Cartesian space. This is widely used scheme in computer graphics and audio engineering tools (i.e., color pickers).

Our research hypotheses are focused on the efficiency of authoring a vibrotactile stimulus with a desirable subjective quality. Specifically, the hypotheses are: 1) Adjectival spaces would allow users to find an appropriate vibrotactile stimuli more quickly. 2) Participants would spend more time if the complexity of the space is increased. 3) The authoring results from adjectival spaces would reflect the users' intention more appropriately.

The subjective quality of sensation is affected by all of the physical parame-

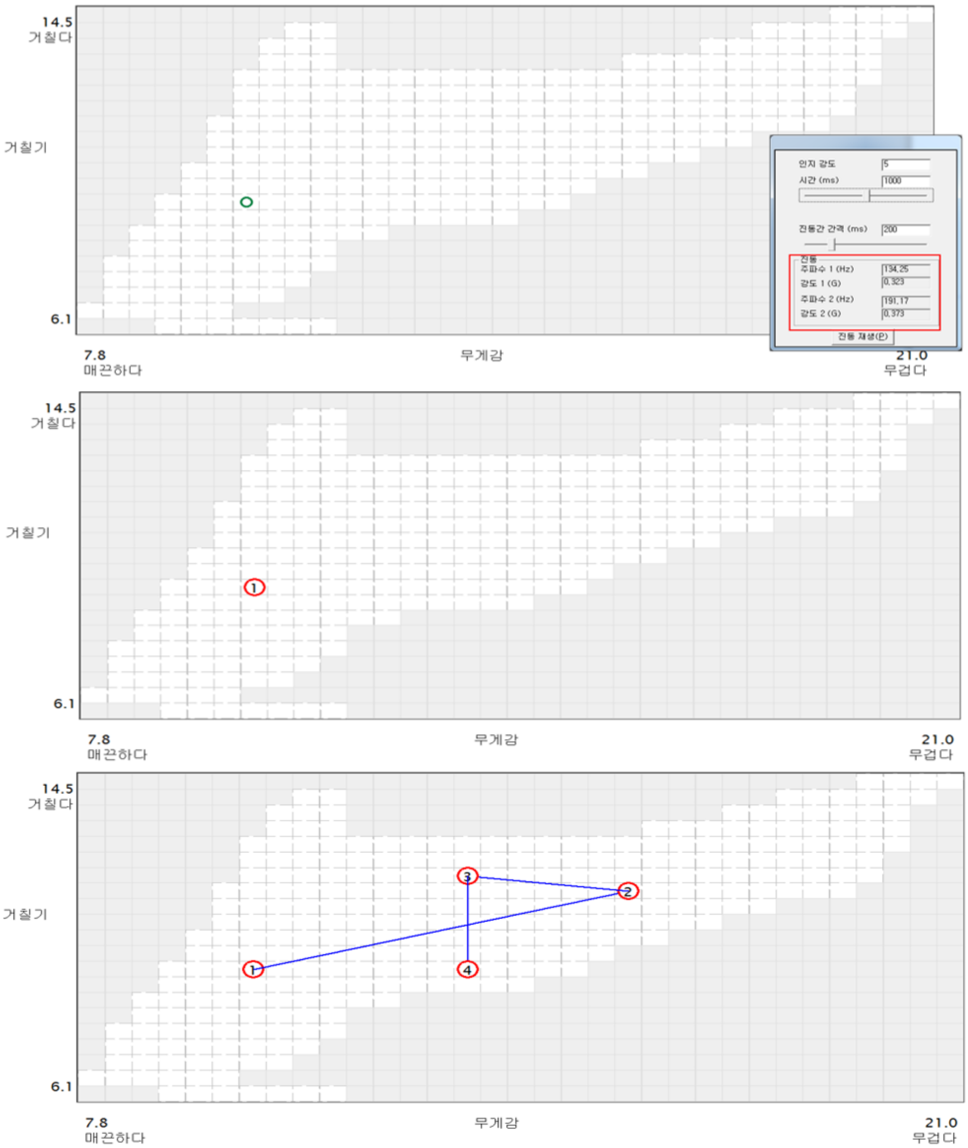


Figure 8.7: The use scenario example of the authoring tool.

ters such as frequency, amplitude, and superposition frequency ratio. Among the parameters, however, the amplitude of vibration is directly related to the perceived intensity, and be easily manipulated by the users' intentions. Therefore, in this experiment, we did not contain the tasks that manipulate the vibration amplitude in this experiment. Instead, we focused on the frequency components of vibrations.

8.2.1 Participants

20 university students (18 - 31 years old, average of 22.8, 4 female) participated to this experiment. Nobody reported known sensory disorders. They received 10,000 KRW ($\simeq$10 USD) after the experiment.

8.2.2 Apparatus

A mechanical shaker (Brüel & Kjær; model 4809) with a power amplifier (Brüel & Kjær; model 2719) produced all vibrotactile stimuli used in the experiments. The shaker is a voice-coil actuator with a very wide frequency bandwidth (DC to 18 kHz) and high linearity. A rectangular aluminum plate ($16\times16\times0.6$cm; 550 grams) was attached to the mini-shaker using a bar-type aluminum bracket. Participants were asked to lay their left hand on the enclosure with comfortable posture while their index finger. A two-level separable table was designed to hide the shaker. The shaker was hidden in a table, and the part of the aluminum plate was revealed on top of the table (Fig. 5.2). To block the propagation of the acoustic vibration which generated from the shaker, anti-vibration pads were used underneath the table legs. A computer-controlled DAQ (National Instruments; model USB-6251) was used to produce vibrotactile stimuli. Custom experimental programs were used for the experiments. Calibration of the shaker was conducted by using the method described in [119] for every 10 Hz, range from 50 Hz to 350 Hz. The values between the measured frequencies and amplitudes were interpolated.

8.2.3 Tasks and Procedures

For authoring, we implemented an MFC-based authoring program. The user interfaces and authoring spaces are described in Fig. 8.8. We composed four large authoring spaces for the authoring experiment to allow the users' decisions of miscellaneous changes of sensation, as well as precise authoring. Two of them were one-dimensional, and the other two were two-dimensional spaces. The 1D adjectival space consists of 186 parallel cells corresponding to the levels of perceived bumpiness ("even–bumpy"), and the 1D frequency space consists of 180 cells that map the frequency of single-frequency sinusoidal vibrations. The 2D adjectival space has 186 $\times$ 171 grids generated from the values of perceived heaviness ("light–heavy") and roughness ("smooth–rough") axes. Unpopulated areas in the corners (i.e., cannot be presented by the model) were disabled in the grids. The 2D frequency space has 181 $\times$ 181 grids, from 50 Hz to 230 Hz for two frequency components. Since the frequency space has a symmetry axis of $y = x$, we also notified that to users and asked to use either upper or lower region of the $y = x$ line for authoring.

The experiment consists of three phases; two authoring phases, and one comparison phase. In the first phase, we asked participants to perceive a reference

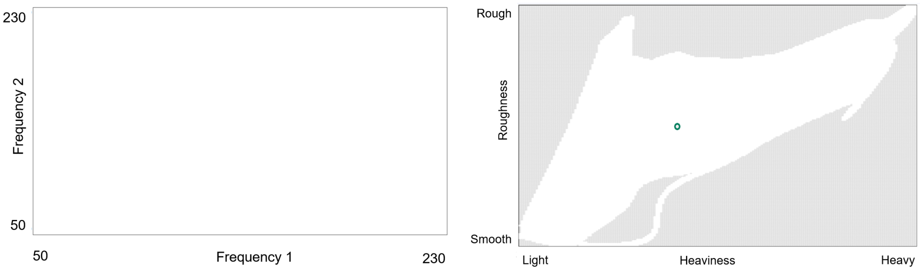


Figure 8.8: Two authoring methods used in the experiment. Frequency space (top) and adjectival space (middle).

vibration each trial and asked them to make the most similar one as they can as possible, in terms of subjective sensations that felt by the participants. Since this experiment aims to compare the effectiveness of authoring, we gave a time limit of 30 s for each trial. We asked the participant to save the file and finish the task immediately when the time taken by the user reaches 30 s, in each trial. For each of four spaces (1D and 2D, adjectival and frequency space), four trials were conducted. The presenting order of the four spaces was random. The reference vibration was selected randomly in the space for each trial. In total, participants went through 16 trials. Participants can perceive the reference vibration as they want during the task within the time limit.

In the second phase, we gave participants descriptions for authoring, and asked them to make the most appropriate vibration on their own criteria. Contrary to the task of the first phase, we did not set a time limit for a task, but the completion time of each trial was measured for further analysis. Participants were allowed to explore the space and perceive the vibration as they want. Eight descriptions (four for 1D, and the other four for 2D spaces) for two different type of spaces were provided to each participant, in random presenting order. 16 trials were done by a participant. Participants produced eight vibrations using adjectival space and frequency space, respectively. Table 8.1 summarizes the eight target sensations.

The last phase consists of comparison tasks. In each trial, participants were asked to compare two vibrations made by themselves, from the same description (total 8 pairs, Table 8.1). They perceived two vibrations, one from adjectival space and the other one from frequency space were presented in a random order. The presenting order of descriptions was random, and participants were unaware of spaces that the vibrations came from. After that, they were asked to vote which vibration is more appropriate for the description. Eight comparison trials went through for a participant.

After the experiment, we conducted a post-experimental survey. We asked intuitiveness, easiness, learnability, and preference of each space (1D and 2D, adjectival and frequency) in 0-100 scales. Participants were encouraged to write their opinion about the authoring spaces in free-form writing. The whole experimental procedure took about 45 minutes for each participant.

8.2.4 Metrics and Data Analysis

In the first phase, we measured the task completion time and the percentage frequency error to the target vibration for each task. In case of dual-frequency superimposed vibrations, we measured the percentage frequency error of the base frequency of superimposed vibrations, and the percentage superposition ratio errors. In the second phase, we measured the task completion time only, and

Table 8.1: Target stimuli and descriptions used in the user experiment.

Space	Descriptions
1D Space	Brisk and dynamic sensation
	Heavy and rough sensation
	Vibration bell on cell phone
	Engine of a vehicle
2D Space	Dense and fast sensation
	Soft and dark sensation
	A mosquito
	Boiling water

lastly, the number of votes for each comparison trials were counted.

For calculating the task completion times and frequency errors, arithmetic mean across participants were used. Also, we conducted pairwise t-tests to find a statistically significant difference between the adjectival and the frequency space. Lastly, the number of votes were aggregated across all the participants (totally 160 votes, 80 from 1D and 80 from 2D spaces). We ran a binomial test to find the statistical significance.

8.3 Results

8.3.1 Phase I. Tasks Using Target Vibrations

First of all, we compared the task completion times. Results showed that all the participants spent much less time when using 1D spaces. For 2D spaces, participants tended to use the full time of 30 s to search and select, while considerable numbers of trials of 1D spaces were finished within 20 s. This is a natural result, since the space consists of vibrations

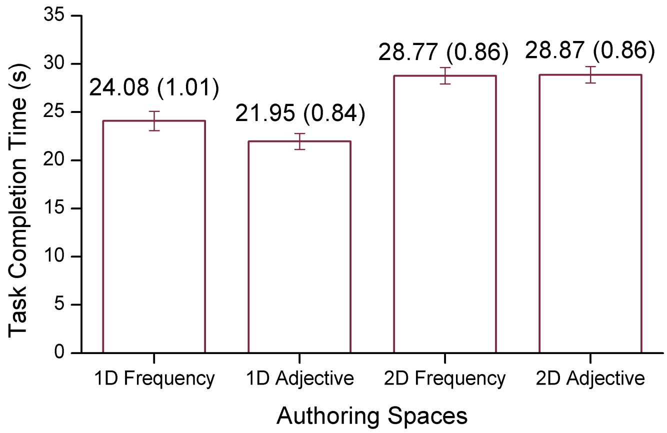


Figure 8.9: Task completion time in phase I (Top: 1D, bottom: 2D spaces).

However, the results of pairwise t-tests showed that there were no significant difference between two methods, on both 1D and 2D spaces ($t(158) = 1.62$, $p = 0.107$ for 1D, and $t(158) = -0.082$, $p = 0.934$ for 2D). This is due to the large deviation of task completion times (8.37 to 54.8 s, including the procedure for saving the work and moving to the next trial), caused by the individual proficiency difference of computer interfaces. Some participants used shortcut keys efficiently, but other some did not use. Also, different style of authoring affect the task completion time; some participants tended to use the full amount of 30 s, to select vibrations very carefully, while some other participants tended to select quickly.

We also measured the percentage frequency errors between target vibration and participants' results. On 1D spaces, participants find nearer vibrations to targets using the frequency space than the adjectival space ($t(158) = 2.10$, $p = 0.038$). The average percentage error of frequency between the targets and the participants' choices was 6.8% (8.95 Hz) on the frequency space and 10.9% (11.7 Hz) on the adjectival spaces. However, both two are below the vibrotactile discrimination threshold (about 15–20 % of reference), so participants seem to find almost same vibrations to the targets within a short time.

On 2D spaces, the average percentage errors of base frequency on the two spaces were increased; 28.1% in the frequency space, and 22.0% in the adjectival space. The frequency error on the frequency space is higher than that of adjectival spaces, but it was not statistically significant ($t(158) = 0.71$, $p = 0.478$). The average percentage error of the superposition ratio was statistically different; 54.2% in the frequency space, and 12.8% in the adjectival space. The ratio error in the frequency space is significantly higher than that of the adjectival space ($t(158) = 5.46$, $p < 0.001$). The accuracy of authoring on the adjectival space is better than that of the frequency space when authoring was done in 2D spaces. The amount of squared-root sum errors were 39.08 Hz and 35.14 Hz on the frequency and the adjectival space, respectively.

We counted the numbers of trials whose percentage error of the (base) frequency exceeds 50%, which could be regarded as "totally missed." On 1D spaces, the errors in 1 (in 1D; of 80) and 31 (in 2D) trials exceeds. In the adjectival space, the errors in 14 (in 1D) and 34 (in 2D) trials exceeds them. We also counted the numbers of trials in 2D spaces whose ratio error exceeds 0.5. In the frequency space, 29 (of 80) trials exceeds, while only two trials exceed the ratio error of 0.5 in the adjectival spaces. That means, the participants occasionally failed to find the target vibrations within a short time, especially in the 2D frequency spaces.

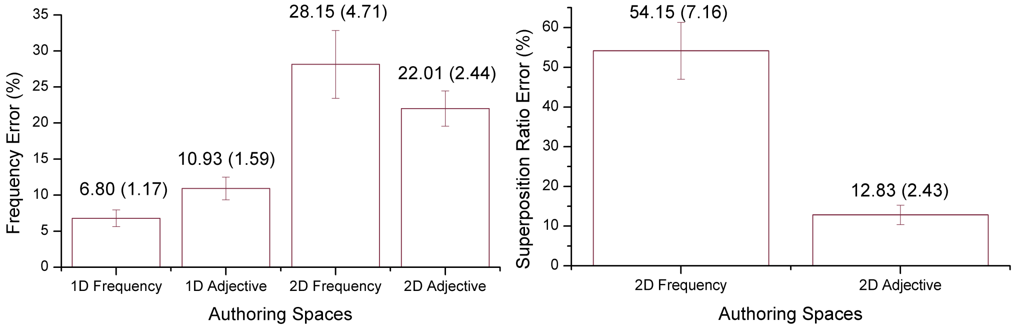


Figure 8.10: Average frequency difference between target vibrations and users' results.

In the 2D adjectival space, participants showed relatively better performances in terms of those errors; relatively small errors and a small number of "totally missed" trials. Histograms of errors were shown in Fig. 8.11.

The results can be summarized as 1) For the target-finding task on 1D spaces, there were no significant differences of task performance between two authoring methods. It seems that the performance relied on the users' individual proficiency to a large extent, rather than the authoring space configurations. 2) However, in 2D cases, the participants showed better performance in the adjectival space than the frequency space. 3) When the number of parameters of vibrations increases, the adjectival space would be better for usability.

8.3.2 Phase II. Tasks Using Verbal Descriptions

We compared the task completion time, and the results are shown in 8.12. A pairwise t-test showed that there were no significant difference in the task completion time between the adjectival and the frequency space, both 1D and 2D ($t(158) = 0.169$, $p = 0.866$, and $t(158) = 0.912$, $p = 0.363$ in 1D and 2D, respec-

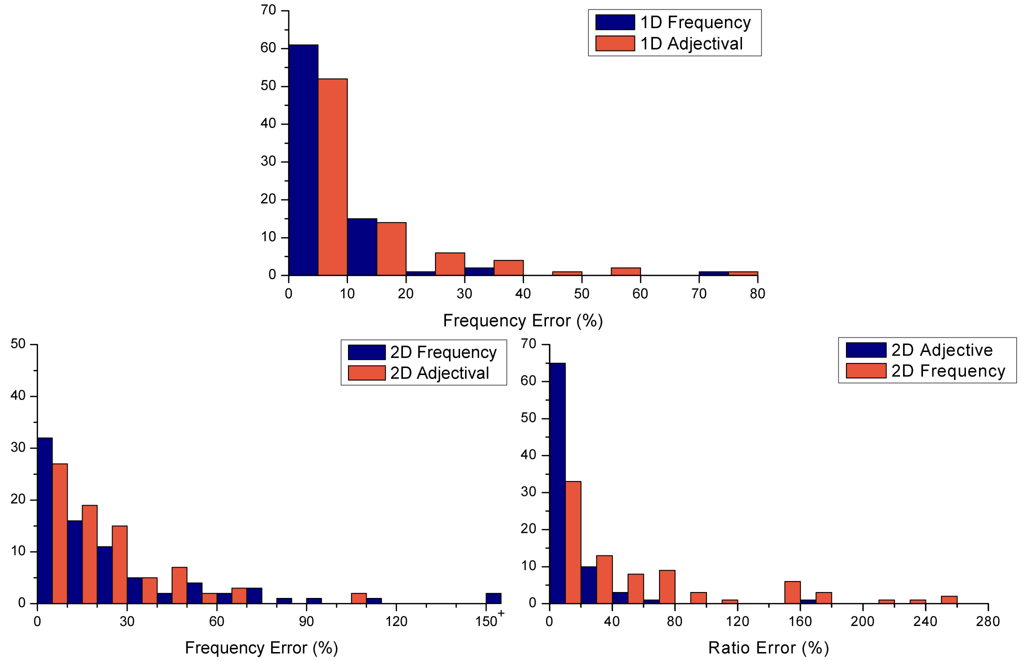


Figure 8.11: Histograms of the percentage error in the 1D (top) and 2D spaces (bottom; left: frequency, right: ratio error).

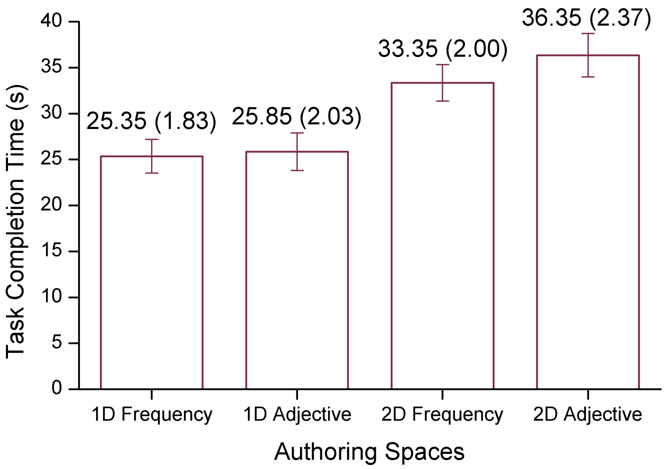


Figure 8.12: The task completion time for the authoring in phase II.

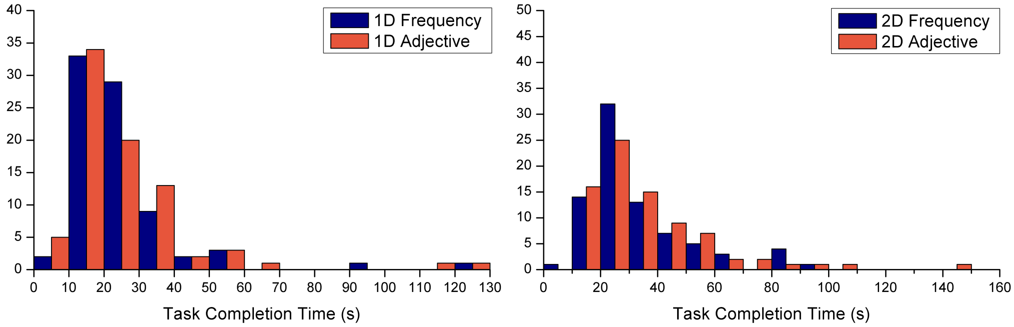


Figure 8.13: Histograms of the percentage error in the 1D and 2D spaces.

tively). On 1D spaces, the participants spent almost same time for authoring, but participants spent a bit more time in the adjectival space (36.3 s) than the frequency space (33.3 s) in 2D spaces. A large deviation of the task completion time in individual trials was observed. The shortest was 6.03 s, and the longest was 142.73 s. Fig. 8.13 shows the histogram of the task completion time results, in the 1D and 2D spaces.

8.3.3 Phase III. Comparison of Vibrations from Frequency Space and Adjectival Space

Fig. 8.14 shows and compares the numbers of votes in the comparison stage. The participants asked to evaluate and select 'better' one, (i.e., more adequate) for the given description, among two vibrations generated by participants themselves in the second phase. Eight comparison trials went through for a participant, therefore 160 votes were collected. For vibrations generated from 1D spaces, the vibrations from the frequency space were selected in 36 trials, while those from the adjectival space were selected in the other 44 trials In 2D spaces, the vibrations from the frequency space were selected 31 times, while those from the adjectival space were selected 49 times. We conducted a Cochran-Mantel-Haenszel test for comparing the results from 1D and 2D spaces, and the statistics indicated that there were no differences between two groups ($\xi_{CMH} = 0.399 \sim \chi^2$, $p = 0.53$), so we pooled the results from the 1D and the 2D spaces. The binomial test showed that the results from the adjectival spaces were selected more frequently, that means the authoring results from the adjectival space is better than that of the frequency spaces. ($B(93, 160, H_0 : P(x) = 0.5)$, results in $H_1 : P(x) \neq 0.5$. $p = 0.0477$).

8.3.4 Qualitative Results

For each method, participants evaluated perceived easiness, intuitiveness, learnability, and preference in 0-100 scales. Fig. 8.15 compares the scores of the frequency and the adjectival spaces. The t-statistics showed that there were no differences between the 1D frequency and 1D adjectival spaces, in terms of all the

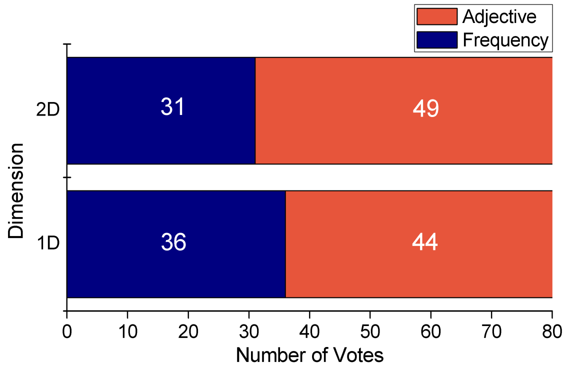


Figure 8.14: The results of participants' comparison task. Numbers are the number of votes.

subjective scores. ($t(38) = 0.199, -0.220, 1.048, 0.036$, $p = 0.84, 0.83, 0.30, 0.97$ for perceived easiness, intuitiveness, learnability, and preference, respectively.) However, in 2D spaces, participants evaluated the adjectival space was easier than the frequency space ($t(38) = -2.45$, $p = 0.018$) and they prefer the adjectival space a bit (tendency value; $t(38) = -1.69$, $p = 0.099$).

In the post-experiment survey, participant answered that the two methods are not essentially different when the spaces were 1D. Some participants mentioned that the mapping of x-coordinate and the change of the sensation in the 1D space is very easy and intuitive. They pointed out that adjectival axes sometimes need to be trained to understand. It seems that participants are easily manipulate the parameter to find the desired sensation when only one parameter was given.

In 2D space, however, most of the participants evaluated the frequency space as not intuitive neither easy. Participants said that they had difficulties to find the relation between the change of sensation and the x and y coordinates, in the

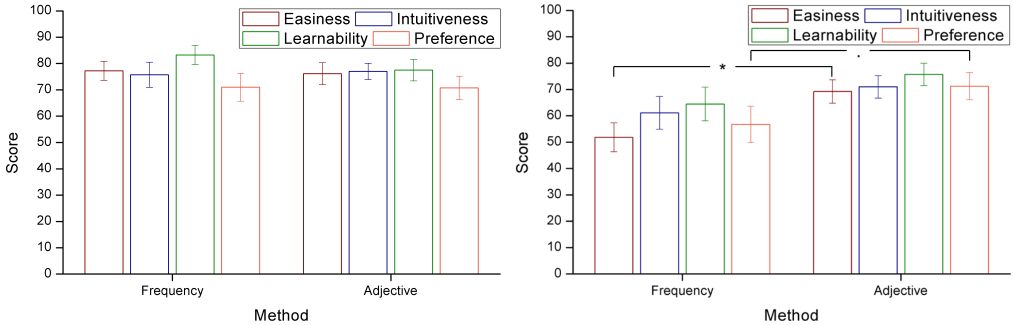


Figure 8.15: The participants' subjective rating of easiness, intuitiveness, learnability, and preference. Left: 1D, right: 2D spaces. Asterisks: statistically significant ($p < 0.05$), dots: tendency values ($p < 0.1$)

2D frequency space. The adjectival 2D space is relatively preferred by them since it provides two adjectival axes which could be guides of subjective sensations and participants utilized them to find the desired vibrations.

8.4 Discussion

8.4.1 Comparison of Authoring Methods

We hypothesized that the adjectival space would allow users to find a desired vibrotactile stimuli more quickly, and the authoring results from adjectival spaces would reflect the users' intention more appropriately. Therefore, we compared the two measures of the time factor and the accuracy (error) factor.

First, the task completion times were similar in both the target-finding task and the authoring task using given descriptions. In 1D authoring, the task completion time on the adjectival space and the frequency space was not significantly different, but it shows a tendency that authoring on the adjectival space took less time slightly. However, interestingly the participants spent more time on 2D adjectival space than the 2D frequency space. This is contrary to our hypothesis of quicker target finding.

In the post-experimental survey, most of the participants complained that they did not find the relation between the coordinates and the change of sensation in the 2D frequency space. During the experiment, they seemed to click the space randomly and chose the best among the searching, or even giving up in some trials. Thus, the task completion time got shorter. In contrast, with adjectival space, which provides a structured, concise representation of the subjective quality of sensation, participants tended to select the vibration more carefully. Also, participants seemed to utilize the adjectival expressions to finding their targets on the space. Thus, the total time consumption increased in the 2D adjectival space.

Second, in terms of the accuracy, the dimensions of the space affect the quality of the authoring. In the 1D space, the frequency space authoring showed a smaller frequency error than that of the adjectival space authoring. Since there was only one parameter that can be manipulated in the user interface, it seems that the participants accepted the frequency, which was presented in numbers in the space more intuitively. The participants got used to the frequency and found the relationship between frequency and the change of the quality of sensations. In contrast, the adjectival expression of bumpiness was less intuitive for the participants. Some of them mentioned that it needs time for understanding what the expressions meant.

However, in the 2D spaces, the adjective-based authoring outperformed the frequency-based authoring. This can be proven by the errors of target-finding (the experimental phase I), and the results of the comparison task (phase III). In phase III, participants evaluated the vibrations from adjectival spaces is more appropriate for the same descriptions. In the results of phase I, the superposition ratio error was small in the 2D adjectival spaces (12.83% on average), compared to that of the 2D frequency spaces (54.15%) (See Fig. 8.11). The large ratio error in the 2D frequency space would be an apparent disadvantage of the space since even a subtle change of superposition ratio would cause a different sensation [29, 28], even though there are no significant differences on frequency errors between the two methods. Participants often pointed out the difficulty of finding the relation between the coordinates and the change of sensations.

The subjective scores also reflect this. The easiness score of the 2D frequency space is rather low (51.85), compared to that of the 2D adjectival spaces (69.25). Also, due to this, participants preferred the adjectival space for authoring, rather than the frequency space.

In overall, the adjectival space took a bit less time but produce slightly more error, and vice versa, if only one frequency component was manipulated. However, in 2D authoring, the frequency space authoring showed a clear drawback of intuitiveness, and authoring on the adjectival space can produce better results in terms of accuracy. We could not say about the time-saving of the 2D adjectival space literally, but considering the large error on the 2D frequency space, the 2D adjectival space could reduce the time for finding the desired vibration on the space.

8.4.2 Expertness Factor on Authoring

The results came from 20 university students who are fresh to the vibrations. Since they have no backgrounds, they merely relied on the numbers and expressions and tried to match the sensation that they perceived. If the users have some background knowledge, the results would be different. In other words, the expertness of users can affect the results. For example, the expert group is aware of the relation between frequency and subjective smoothness, intrusiveness, or other subjective qualities. Thus, the expert users may prefer manipulating the physical parameter directly, which is the same way that current haptic designers do. However, still the advantages of the adjectival space exist for the experts. For example, manipulating a subtle change of sensation would be a difficult task even for the experts, but the grids on the adjectival space could help them. Recruiting the experts or training the users before experiment would help to understand this, as well as to assess the learnability of the adjectival spaces.

8.4.3 Ways to Improve The Adjectival Space Authoring

Though we supported to manipulate the intensity and duration factors, the experiment aims the frequency component, rather than rhythmic or amplitude components. Providing slider bars with adjectival indicators for manipulating the amplitude and duration would be helpful for supporting more design parameters. However, such components of vibrotactile icons are also important for building a large tactile icon set [42]. To aid this, supporting rhythmic component [96], amplitude variation like crescendo or decrescendo [134] are useful options.

In addition, like [99], providing samples, verbal expressions and visualization would be helpful for the users to find their desired vibrations. Providing affective features of tactile icons [13] can also contribute understanding of the users. Although the ability of tactile waveform discrimination is not very sensitive, the editing of waveform would be considered as a minor option to produce a subtle, delicate change of sensations.

Combining those methods to the adjectival authoring space would be our future work.

8.5 Conclusions

In this chapter, we introduced the adjectival space that consists of adjectival axes based on perception experiments, and suggested a vibrotactile authoring method that uses the adjectival spaces. Based on the results of adjectival ratings of vibrations, we composed a 1D and a 2D adjectival space for vibrotactile authoring. The usability experiment showed that the adjectival space is intuitive and useful when two or more frequency parameters exist. Future work would be expanding the editor to provide rhythmic and amplitude-varying components, and supporting multi-channel authoring.

9. Emotion Augmentation Using Tactile Stimuli

As an application of the perceptual and affective characteristics, we suggest the concept of emotion augmentation using tactile stimuli. The term *augmented reality* means an enhanced environment by virtual components, based on a real environment. Similarly, here, we *augment* emotional features of a context by adding some tactile stimuli. This can enhance or translate the original emotion of the context. Fig. 9.1 describes the concept. Both thermal and vibrotactile stimuli, which we have investigated their properties already, are used in this study.

Studies on affective characteristics of haptic stimuli have been done. Salminen et al. [21] investigated the emotional effects of thermal stimuli. They asked participants to assess the perceived degrees of pleasantness, dominance, arousal, and approachability as emotional metrics. Recently, Seifi et al. introduced a framework to design vibrations with desired affective properties [77]. They first investigated the emotional characteristics of vibrations with a large-scale experiment (10,080 ratings). They found several expressions that can attribute vibrotactile emotional properties such as agitation, liveness, and strangeness. Wilson et al. mapped the emotional responses of thermal stimuli into V-A space [78], and they also suggested and evaluated the multimodal icons to cover a wide range of V-A space [112] Halvey et al. conducted an experiment with a similar approach

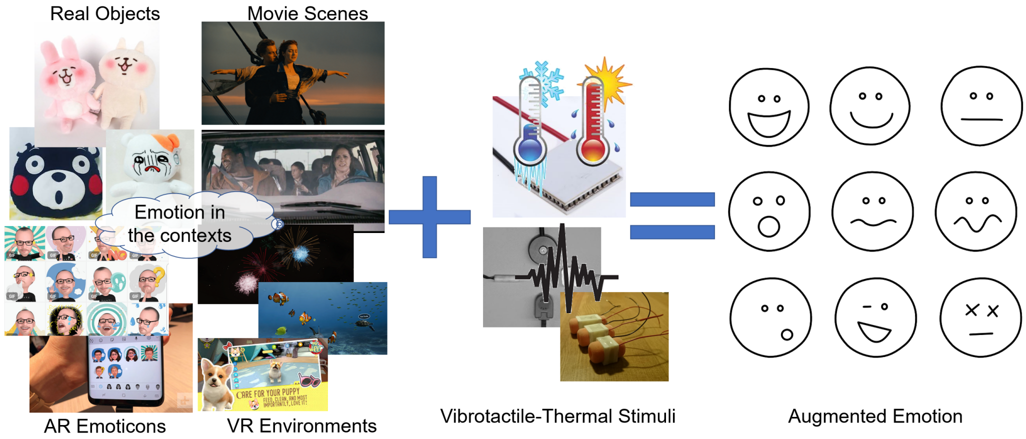


Figure 9.1: The concept of augmented emotion by tactile stimuli.

to our work using thermal stimuli [145]. They presented thermal stimulation with audiovisual contents and assessed the emotion elicited by the multimodal stimuli. The results indicated that the existence of thermal stimuli makes different emotional responses of users, although perceiving them needs a relatively long time.

In this chapter, we tried to apply the concept of emotion augmentation to short-time interactions. As the first target application, we selected emojis in mobile devices. We augmented emojis that have strong emotional messages with vibrotactile and thermal stimuli. The valence and arousal scores of the augmented emojis would be compared to those of non-augmented ones.

9.1 Method

9.1.1 Apparatus

We used a commercial smart phone (Google, Nexus 5; 130 g, 138 x 69 x 8.6 mm, 5.0” screen) to present the stimuli and instructions. Since we used visual emojis in this experiment, smart phones are the best platform to provide both visual and tactile stimuli for improving the user experience for communication. We assembled a vibrotactile-thermal tactile display consists of a Peltier module and a vibrotactile actuator and attached to the back panel of the smart phone, shown in Fig. 9.2. A Peltier module (4.5 cm $\times$ 4.5 cm) for thermal stimulation was attached onto a rectangular heat sink. For temperature control, we designed a closed-loop PD controller for the Peltier module. A thermistor (LM35DZ; Texas Instruments) was attached to the Peltier module and calibrated using an infrared thermometer (LaserSight, Optris). A wide-band vibrotactile actuator (TactileLabs, Haptuator Mark II) was also attached to the back panel of the phone (Fig. 1) to provide vibrations. The same procedures were conducted to calibrate these actuators, described in Section 7.

The two actuators were connected to a PC through a data acquisition card (PCI-6251, National Instruments). A custom Android application was installed and used for evaluating the emotional responses of the visuo-tactile stimuli. The application sends the tactile stimuli information to the PC, and the PC controls the hardware to present the corresponding stimuli. The smart phone and the PC were connected via Bluetooth communication.

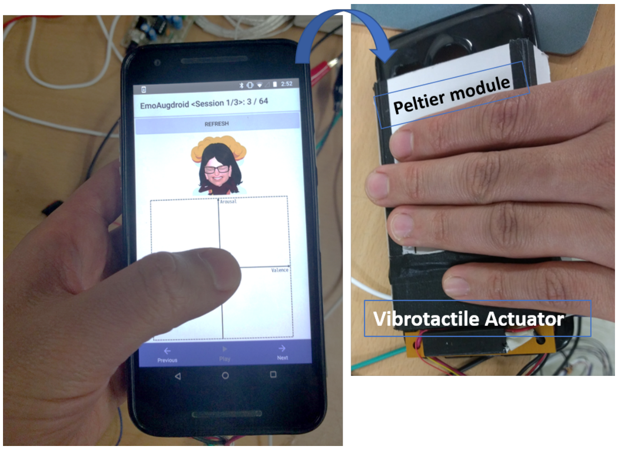


Figure 9.2: Apparatus used in this study.

9.1.2 Participants

Forty (20 male, 20 female, 18-35, average 23 years old) university students and staffs participated in this experiment. Nobody reported any known sensory disabilities or diseases. We divided them equally into two groups. Twenty (10 male and 10 female) of them assessed the vibrotactile-augmented emojis (described in the next section) and the other twenty assessed the thermal-augmented emojis.

9.1.3 Stimuli

As visual stimuli, we used the feature called "AR emoji," embedded in a recent mobile device (Galaxy S9, Samsung Electronics). This feature uses a picture of the user's face and automatically generates a character who resembles the user, and a set of 36 animated emojis using the character. A member of our group volunteered to be the model of the emojis. The original AR emojis

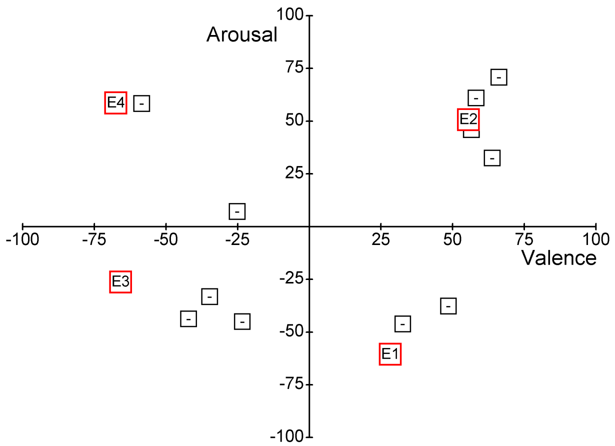


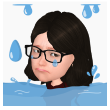
Figure 9.3: Pilot results: emotional responses of emojis. E1-E4 (marked as red squares) are selected and used in the main experiment.

are provided in GIF animation format, but we extracted the still cut of them instead of using themselves. This is to prevent excessive immersion into the visual animation effects without loss of their emotional meaning.

To select the emoji using for this experiment, we selected 15 emojis which has strong emotional meanings. Then, to extract the most representative emojis for each quadrant of the V-A space, we conducted a pilot experiment that assesses the emotional responses of the icons with 20 university students. As results, we extracted the four emojis. We added a "blank" condition, to establish a baseline for assessing the emotional responses. Figure 9.3 shows the result of the pilot experiment, and Table 9.1 describes them.

For vibrotactile stimuli, we used four stimuli using two amplitudes (weak and strong) and two frequencies (100 and 250 Hz). The amplitude level for each vibration was determined by a pilot experiment using the method of adjustment,

Table 9.1: Emojis used in this experiment.

Code	Emoji	Emotion
E1		Calm
E2		Joy
E3		Sad
E4		Angry

to find the point that perceived as equal intensity. The vibrotactile accelerations of 100 Hz were 0.2 and 0.4 g for weak and strong amplitude levels, and those of 250 Hz were 0.5 and 0.8 g, respectively. In addition, we added "no vibration" condition, which is regarded as the baseline of emotional responses. Thus, five conditions were used for vibrotactile stimuli.

As thermal stimuli, we excluded the change rate factor in this experiment since it does not have a strong effect on the emotional responses of users, as seen in Chapter 7. Therefore, two directions (D; cooling and warming) and two extents (E; 4 °C, 8 °C) were used as thermal parameters. Thus, we used four thermal stimuli in the experiment. Similar to the vibrotactile stimuli, we added "no thermal stimuli" condition for the baseline, results in five conditions of thermal stimuli. For the main experiment, we constituted two sets of augmented emojis. A set of 25 vibrotactile-augmented emojis from the five visual and the five vibrotactile stimuli were given to the group of 20 participants, and another set of 25 thermal-augmented emojis from the five visual and the five thermal stimuli were given to the group of the other 20 participants.

9.1.4 Procedure

Prior to the experiment, the experimenter explained the concepts associated with valence and arousal to each participant using a written script. The script also included some examples of valence and arousal scores for emotion-related words such as exciting, restful, and lazy. The participant was allowed to ask any questions in this period to have a clear understanding. We also notified them that the stimuli set contain visual stimuli, thermal stimuli, and visuo-tactile stimuli. The participant then signed on an informed consent form and started the experiment.

The participants' task was to rate the valence and arousal of tactile icons after perceiving them. They held the smart phone shown in Figure 9.2 with their non-dominant hand and touching the Peltier module. The experimental program on the smart phone provided a "play" button that allowed participants to see and feel the same tactile icon repeatedly. Then, they entered valence and arousal scores by touching on a point in the 2D V-A space displayed on the touchscreen of the phone. The V-A space consisted of a horizontal line for valence and a vertical line for arousal, both 5.5-cm long, with their crossing point as the origin. They used their dominant hand to control the graphical user interface. Then, the horizontal and vertical positions of the response point were converted to valence and arousal scores, each from -100 to 100, for data analysis.

This direct reporting method is often used in computer-based experiments for emotion estimation owing to its efficiency [135].

Each session included the whole set of augmented emojis. The order of the stimuli was random. After completing each session, the participant took a break of 2 min and then started the next session. This procedure provided three V-A scores for each tactile icon per participant. The participants wore noise-cancelling headphones during the experiment to block external noise. They were allowed to take a rest whenever necessary. All the participants finished the experiment in 30 minutes.

9.1.5 Data Analysis

We collected three V-A scores for each stimulus. The data of the first session were regarded as training and excluded from data analysis. The V-A scores of the other two sessions were averaged using the arithmetic mean across the 20 participants. The data were not normalized to preserve individual variances and biases.

9.2 Results

9.2.1 Effects of Tactile Stimuli on Augmenting Emotion

Figure 9.4 shows the overall distributions of emotional responses. The left panel is the results from vibrotactile augmentation, and the right panel is from thermal augmentation. Smaller markers indicate the responses of augmented emojis, and larger markers indicate those of single tactile stimuli and non-augmented

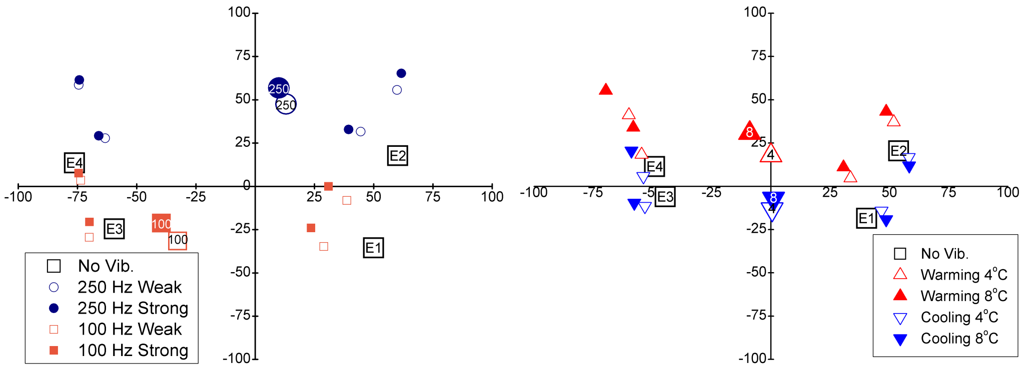


Figure 9.4: Emotional responses of mean points of each emoticons and vibrotactile stimuli (larger markers with numbers).

emojis. The emotional responses of E1-E4 are similar to that of the pilot experiment.

Regarding the responses of vibrations, 100 Hz vibrations are assessed as negative and a bit weak, while those of 250 Hz as positive and intense. The effect of amplitude on the response seems weak; the differences between weak and strong vibrations are quite small. In 100 Hz, moreover, the arousal score of the stronger vibration was lower than that of the weak vibration.

Responses of thermal stimuli showed that warming slightly increased the arousal score while cooling decreased it. Warming with a large extent (8 °C) leads to a small decrease in the valence score. However, the extent of augmentation seems to be small.

We investigated the augmentation effects of vibrations in depth. Fig. 9.5 shows the results of emojis E1 (calm) and E2 (joy) — positive emojis. Two main tendencies we found. First, Providing 250 Hz vibrations increase the arousal scores of emojis but not rarely affect the valence score. Second, 100 Hz vibrations

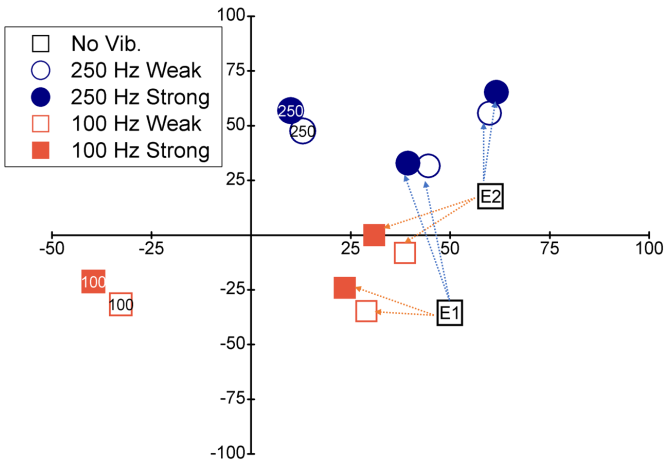


Figure 9.5: Emotional responses of vibrotactile-augmented emojis from E1 (calm) and E2 (joy). Arrows indicate the direction of emotion augmentation.

decrease the valence score, but rarely affect the arousal score. It seems that the emotional properties of vibrations considerably affect the emotion elicited by positive emojis.

Fig. 9.6 shows the results of emoji E3 (sad) and E4 (angry) — negative emojis. The augmentation property of 250 Hz vibrations remained as same as that of E1 and E2; 250 Hz vibrations increase the arousal scores to a large extent. Augmentation with 100 Hz seems to have a limited effect, both on the valence and arousal scores. It seems that the emojis E3 and E4 have strong emotional attributes of negativeness; 100 Hz vibrations did not have any effects on the criteria of the participants.

The results of augmentation are presented in Figure 9.7 and 9.8. We observed three tendencies: 1) warming stimuli increases arousal and decreases valence for all emojis regardless of the temperature change extent, 2) cooling stimuli

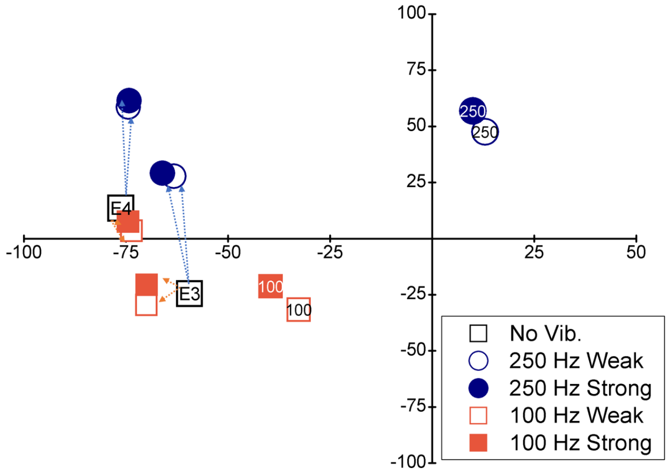


Figure 9.6: Emotional responses of vibrotactile-augmented emojis from E3 (sad) and E4 (angry).

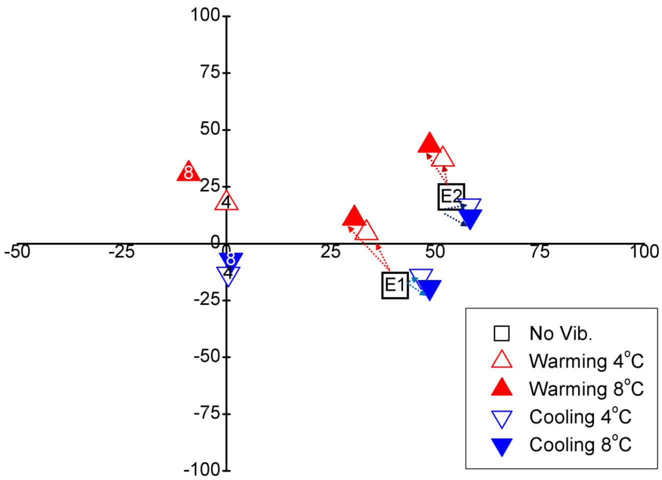


Figure 9.7: Emotional responses of thermally augmented emojis from E1 (calm) and E2 (joy).

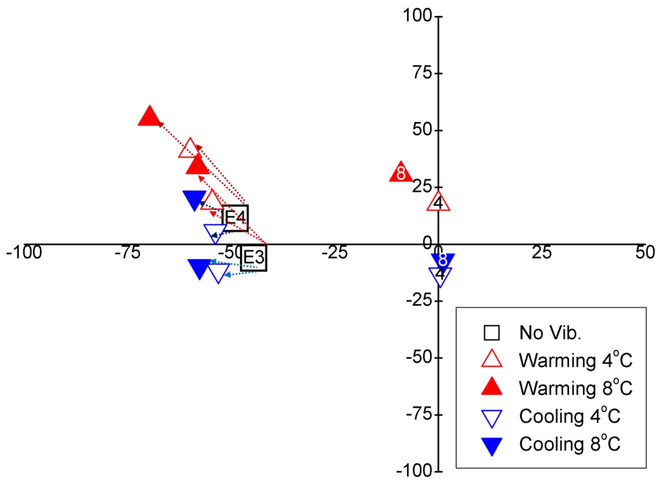


Figure 9.8: Emotional responses of thermally augmented emojis from E3 (sad) and E4 (angry).

intensify the valence ratings without changing the arousal level, and 3) such effects appeared more saliently on negative emojis (E3 and E4).

To examine the significance of the factor effects, we conducted a two-way ANOVA. All the factors have significant effects on both the valence and arousal scores. The significance of the emoji factor seems natural since we used four different emojis that represents the four quadrants of the V-A space. Thus, we did not investigate further for this factor.

As seen above, the effect of vibrotactile stimuli on the emotional responses depends on the frequency. High-frequency vibrations increased the arousal score, while low-frequency vibrations decreased the valence score. The significance of the factor *Vibration* on both valence and arousal with large effect sizes(η_p^2) confirm this. Thermal stimuli also have significant effects on both valence and arousal, but the effect sizes are smaller than those of vibrations. Also, the in-

Table 9.2: ANOVA results of the emotional responses of vibrotactile-augmented emojis.

Factor	Dependent Variable	Statistics	Effect Size(η_p^2)
Emoji	Valence*	$F(4, 76) = 117.6$, $p < .0001$	0.8609
	Arousal*	$F(4, 76) = 10.56$, $p < .0001$	0.3573
Vibration	Valence*	$F(4, 76) = 14.57$, $p < .0001$	0.4340
	Arousal*	$F(4, 76) = 65.52$, $p < .0001$	0.7752
Emoji × Vibrations	Valence*	F(16, 304) = 6.278, $p < .0001$	0.2483
	Arousal*	$F(16, 304) = 3.115$, $p < .0001$	0.1409

Table 9.3: ANOVA results of the emotional responses of thermally-augmented emojis.

Factor	Dependent Variable	Statistics	Effect Size(η_p^2)
Emoji	Valence*	$F(4, 76) = 103.0$, $p < .0001$	0.8442
	Arousal*	$F(4, 76) = 12.7$, $p < .0001$	0.4006
Thermal	Valence*	$F(4, 76) = 2.734$, $p = .0349$	0.1257
	Arousal*	$F(4, 76) = 8.399$, $p < .0001$	0.3065
Emoji × Thermal	Valence*	F(16, 304) = 1.933, $p = .0174$	0.0923
	Arousal	$F(16, 304) = 1.187$, $p = .277$	0.0588

teraction between $Emoji$ and $Thermal$ can explain the tendency 3) we observed in thermal stimuli. We conducted a Tukey's HSD test to verify this, and the results confirmed all the tendencies presented above. As expected, the tactile stimuli were classified into two significantly different groups, both in as seen in Figure 9.9.

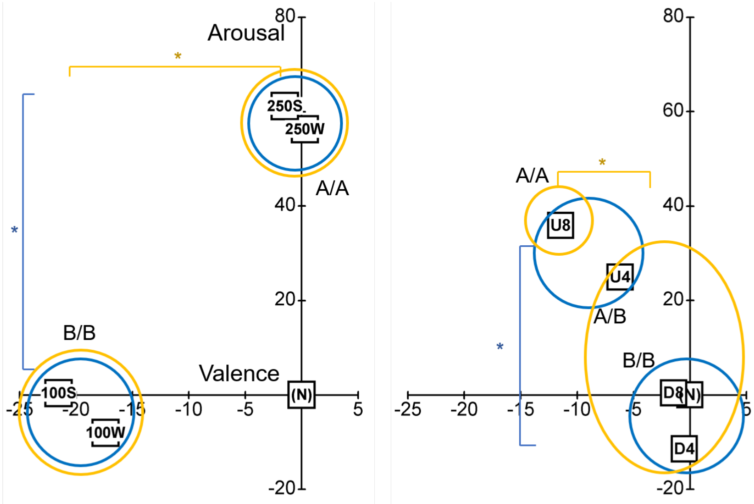


Figure 9.9: Tukey's HSD post-hoc analyses of the emotional responses of augmented emojis (Left: vibrotactile, Right: thermal). (N) means no tactile stimuli condition, which is regarded as local origin in this plot.

9.2.2 Post-experimental Questionnaire

Vibrotactile Augmentation

10 out of 20 participants mentioned that they perceived different emotion to the visual emoji when they perceived augmented emojis. To be specific, seven (of 10) pointed out that the emoji E1 (calm) interpreted as negative emojis such as *suppressing her anger* and *upset*, when the emoji was augmented with high-frequency, strong vibrations. Other one mentioned that he felt *bearing her gloom* when he perceived E1 with a weak low-frequency vibration, while the other two said that the emoji E3 (sad) perceived as *cry for anger* when augmented with a high-frequency vibration. Another six said that vibration could emphasize the emotion when augmented with *congruent* vibrations which have similar emo-

tional properties (i.e., the levels of valence-arousal scores) to the given visual stimulus. The other four did not feel any significant effects on their emotion. These responses are quite consistent with the tendencies which we found in the V-A space.

Thermal Augmentation

Seven out of 20 participants said that they perceived different emotion from the original meaning in augmented emojis. All the six of them mentioned the negative aspect of the warming stimuli, and two of them said the cooling stimuli have an effect of intensifying the valence score. For example, they described E1 (calm) with warming as *overcoming mental stress*, or *angry*, and E2 with cooling as *immersed in her serene*. Other five said that thermal stimuli modulated the intensity of perceived emotion; adding thermal stimuli provides intense emotional experiences. The others said that thermal stimuli have rarely affected their emotions.

Individual Variance

As similar to the other emotion-related experiments, we observed large individual variances. Since each participant has different ideas, experiences, and perspectives, such large variance seems natural. However, averaging all the data over participants may eliminate the dimidiate tendencies. For example, regarding 8 °C cooling, more than a half of participants assessed it as positive, but a considerable number of participants evaluated it as negative due to an excessive coldness.

9.3 Discussion

9.3.1 Direction of Augmentation

As seen in results, we found that adding vibrotactile stimuli induces: 1) a shift of the valence score to the negative direction or 2) increased arousal score. Adding thermal stimuli induces: 1) increased arousal score, or 2) intensified valence scores that appeared more saliently in negative emojis. The effect of augmentation appeared more clear in the negative sides in V-A space, in both vibrotactile and thermal stimuli. Shifting toward the positive direction of valence was rarely appeared, as well as that to decrease arousal scores.

This would be from the nature of augmentation with artificial stimuli. In [13], we evaluated the emotional responses of various vibrotactile stimuli. The most positive valence score was around +30 in a -100 to 100 scale. That may suggest the nature of vibrations, that induces negative feeling. For thermal stimuli, similarly, their maximum positiveness rating was about +20, as seen in Chapter 7. Currently, it is difficult to find a widely-applicable solution to augment emotion toward the positive direction.

Since no stimuli can elicit a strong positive emotion, augmentation toward positive direction might need a different type of tactile stimulus. It could be another tactile modality, or high-level designed stimuli such as rhythmic vibrations or up-and-down patterns of temperature change. We also can utilize the individual criteria of users to achieve it, though it can be used to a limited extent. For example, E1 (calm) and E3 (sad) with warming stimuli were interpreted as “angry” for some participants, while E2 (joy) with cooling as “excited.” Regarding vibrations, some participants assessed 250 Hz as very positive, while the other some assessed it as very negative. Investigation towards this direction would be our future work.

Increased arousal can be explained as the redundancy of information. Tactile stimuli have emotional meaning, as visual icons. Thus, participants exposed to more emotional information when they perceive augmented emojis. Consequently, they assessed the augmented emojis to have stronger meanings, resulted in higher arousal scores of augmented emojis.

9.3.2 Difference between Thermal and Vibrotactile Augmentation of Emotion

10 out of 20 participants who assessed the vibrotactile-augmented emojis said that they felt somewhat different emotions due to the vibration effects. Interestingly, six participants said that vibration could emphasize the emotion when augmented with *congruent* vibrations which have similar emotional properties (i.e., the levels of valence-arousal scores) to the given visual stimulus. The participants seem to reproduce the emotional meaning of emojis with the metaphors elicited by vibrations. Also, it seems that they had firm criteria on the vibrotactile stimuli for assessment of emotion. For them, when the emotional characteristics of visual and tactile stimuli matched well, participants felt a stronger emotional meaning and vice versa. This is a similar tendency presented in our previous study on crossmodal congruency based on the emotional responses [75]. A smaller distance between two stimuli in the V-A space led to a higher congruency score.

However, those who assessed thermally-augmented emojis did not mention such congruency. Instead, they said more about atmosphere, circumstance, and mood, with specific examples of emojis. For example, a participant described E1 (calm) with cooling as “deeply meditating,” while E1 with warming as “suppressing her anger.” Most of such examples are about the association between the negativeness and warming stimuli, while a small number related the cooling stimuli to the positiveness. Regardless of changing directions, a large extent of temperature change increased arousal–participants associated such stimuli with “alarmed” or “stressed.” It seems that thermal stimuli might attribute some circumstances or nuisances to the emojis.

9.4 Conclusion

In this chapter, we suggested the concept of emotion augmentation using tactile stimuli and conducted an experiment with emojis that contains strong emotional messages. The results of the experiment with two groups, each with 20 participants showed that a considerable change in the valence and the arousal scores when tactile stimuli are presented with emojis. General tendencies we observed are: 1) high-frequency vibrations increased arousal, while low-frequency vibrations decreased valence, 2) warming stimuli increased arousal and decreased valence for both positive and negative emojis while cooling stimuli intensify valence ratings. In the post-experimental survey, a considerable number of participants mentioned that sometimes they felt different emotional meanings from the original ones by adding tactile stimuli. Some participants also pointed out that adding (*emotionally congruent*) tactile stimuli enhance the original emotional meaning elicited by emojis and vice versa. Conducting a large-scale experiment with diverse stimuli to gather more clues for augmenting emotions would be our future work.

Part V

Conclusion

10. Conclusion

In this research, we studied perceptual and affective characteristics of complex tactile stimuli and suggested their applications. In our perception study, three perception studies of superimposed vibrations were conducted. First, the perceived intensity of superimposed vibration was investigated. Findings are 1) the perceived intensity of vibration is proportional to its skin-absorbed power, and based on this, 2) the Pythagorean summation ($I_1^2 + I_2^2 = I_S^2$) can be used for estimating the perceived intensity of superimposed vibrations. Second, we investigated the perceived consonance, borrowing from the concept of the musical chord. The results indicate that participants robustly evaluate the consonance of superimposed vibrations with different frequencies, like musical chords. The role of the beat frequency is important in the vibrotactile consonance perception. Third, we investigated the verbal expressions of vibrotactile stimuli, to understand the expressions of the subjective quality of vibrotactile sensations. We conducted a large-scale survey that seeks adequate expressions for the vibrotactile sensations with a large number of participants. The results indicated: 1) Metaphoric expressions of heaviness and thickness (extent) were frequently used to describe the single frequency vibrations' sensation. 2) Dual-frequency superimposed vibrations were largely described by expressions of speed (slow–fast), density (sparse—dense), and bumpiness of spatial structure (bumpy—even), that bear more physical meanings. 3) Expressions of roughness and bumpiness were highly associated with the low-frequency components of vibrations, especially acoustic beats of superimposed vibrations. We picked three adjectival expressions of heaviness, roughness, and bumpiness, and find magnitude functions that explain the relations between physical parameters such as frequency, amplitude, and superposition ratio and the degree (magnitude) of subjective qualities. These results would expand our knowledge of vibrotactile perception, as well as utilized directly to the vibrotactile authoring using adjectival expressions.

The affective characteristics of complex tactile stimuli were also investigated. We investigated emotional responses of vibrotactile and vibrotactile-thermal complex stimuli using wide ranges of physical parameters. The four parameters of amplitude, carrier frequency, duration, and envelope frequency showed clear relationships to the valence and arousal of vibrotactile stimuli. Thermal stimuli generally shift the emotional responses of vibrotactile stimuli while preserving the effects of the individual vibrotactile parameters of frequency, amplitude, and duration. However, responses of vibrotactile stimuli with varying temperatures showed different tendencies. Vibrotactile parameters such as frequency and amplitude have considerable effects on arousal, while less on valence. Thermal parameters such as direction (cooling/warming) and extent of temperature change are closely related to valence rating, but rarely related arousal. Based on these results, we established useful design guidelines for the complex tactile stimuli with desired emotional features.

As applications, we suggested the vibrotactile authoring and the concept of emotion augmentation using tactile stimuli. First, we introduced the adjectival space that consists of adjectival axes based on the results of perception studies and suggested an authoring method that uses the adjectival spaces. The usability experiment showed that the adjectival space is intuitive and useful when two or more frequency parameters exist. Second, we suggested the concept called *emotional augmentation*, means adding haptic stimuli to convert or enhance the existing emotional contents. We validated this framework by a user experiment with some emojis which have strong emotional meanings. Experimental results indicate that 1) high-frequency vibrations increased arousal, while low-frequency vibrations decreased valence, 2) warming stimuli increased arousal and decreased valence for both positive and negative emojis while cooling stimuli intensify valence ratings. In the post-hoc survey, a considerable number of participants mentioned that sometimes they felt different emotional meanings from the original ones by adding tactile stimuli. Participants also pointed out that adding vibrotactile stimuli which have similar emotional responses (*emotionally congruent stimuli*) generally enhance the original emotional meaning elicited by emojis and vice versa; supports the valence-arousal rating results. These results can confirm the usefulness of perceptual parameters in applications of vibrotactile stimuli, as well as the emotional effects of complex tactile stimuli.

요 약 문

촉감 자극은 모바일 기기, 웨어러블 기기 등 다양한 인간-컴퓨터 상호작용에 응용되고 있으나, 그 역할은 비교적 단순한 의미 혹은 정보 전달에 그치고 있다. 이러한 문제를 해결하기 위하여 다양한 형태의 촉감을 제공하는 액츄에이터가 개발되었으며, 복잡한 형태의 진동을 효율적으로 사용자에게 전달하기 위한 기법들이 연구되는 등 많은 진전이 있었으나, 이들 다양하고 복잡한 형태의 촉감들은 아직까지 그 인지적 및 감성적 특성에 대한 연구가 이루어지지 않은 바 실제 활용된 사례가 매우 드물다. 이와 더불어, 촉감이 가지는 그 특유의 감성적 특성이 있음에도 불구하고 이와 관련된 연구 또한 아직까지 매우 미흡한 실정이다. 따라서, 본 연구에서는 이러한 문제를 해결하기 위하여 촉감 자극, 그 중에서도 중첩 진동자극을 이용한 진동촉감 및 열 촉감의 복합 촉감 자극들에 대하여 그 인지 및 감성적인 특성을 조사하고, 복합 촉감 자극의 활용 가능성을 알아보기 위한 응용 사례를 제시하였다.

인지적 특성으로는 기존에 잘 알려져 있지 않은 중첩 진동 자극의 인지 강도와 정성적인 특성들에 대한 조사를 수행하였다. 피부에 흡수되는 진동 에너지의 추정치를 기반으로, 개별 주파수 성분의 인지 강도의 삼각 합(피타고리안 합)을 이용한 중첩 진동의 인지 강도 추정 방법을 제안하고 이를 실험을 통하여 검증하였다. 정성적 특성으로는 우선 중첩 진동의 협화도 음악의 화음 개념을 바탕으로, 인지적인 어울림의 척도인 협화도 개념을 진동에 적용하여 진동 화음의 어울림 정도를 조사하였다. 그 결과 협화도는 진동 주파수 및 주파수의 중첩비 ($f_1 : f_2$)의 함수 형태로 나타낼 수 있었으며, '고르다', '부드럽다', '깨끗하다' 등의 형용사 표현과 관련이

있었다. 이를 시작으로, 우리는 정성적 특성을 잘 나타낼 수 있는 표현 및 어휘에 주목하여, 대규모의 설문조사를 수행하여 진동 촉감의 정성적인 느낌을 표현하기 적합한 어휘를 도출하였다. 조사 결과 단일 주파수 사인파 진동의 느낌은 무게감(가벼움–무거움) 및 두께감(얇음–두꺼움)으로, 중첩 진동의 경우는 속도(느림–빠름), 밀도(듬성듬성함–빽빽함), 굴곡감(울퉁불퉁함–평평함)과 관련된 어휘로 주로 표현되었으며, 특히 중첩 진동의 경우는 물리적인 의미보다 비유적으로 활용되는 것을 볼 수 있었다. 또한, 거칠기 및 굴곡감은 중첩 진동의 맥놀이(beat)와 같은 저주파수 성분을 표현하는 데 자주 사용되었다. 이들 결과를 바탕으로, 무게감, 거칠기, 굴곡감의 세 가지 어휘를 대상으로 진동의 물리적 특성에 따라 정성적 특성, 즉 느낌이 어떻게 변화하는지를 수치적으로 알아보기 위한 강도 추정 실험을 수행하였다. 강도 추정 실험 결과 주파수가 높아지고, 강도가 약해질수록 무게감, 거칠기, 굴곡감이 모두 감소, 즉 가볍고, 매끈하며, 평평하게 느껴지며, 낮은 주파수 및 강한 진동은 그 반대의 양상을 보였다. 중첩 진동의 중첩비는 1을 약간 상회하는 (1.1–1.3) 구간에서 거칠기와 굴곡감을 큰 폭으로 상승시키는 것을 확인할 수 있었다.

촉감 자극의 감성적 특성 또한 조사하였다. 감성의 정량적 표현에 널리 쓰이는 Russell의 Circumplex model을 사용하여, Valence와 Arousal 두 개의 파라미터로 진동 및 열자극의 감성적 특성을 사용자 실험을 통하여 조사하였다. 그 결과, 진동의 주파수, 강도, 길이 및 엔벨로프(envelope) 모두 두 가지 감성 파라미터에 유의미한 영향을 줌을 확인할 수 있었으며, 대표적으로 주파수가 높아질수록 Valence가 증가하고, 강도가 강해지고 길이가 길어질 수록 Arousal이 증가하며, 엔벨로프 주파수가 증가하면 Valence가 감소하였다. 또한, 상온 자극의 온도에 따라 Valence 및 Arousal, 즉 감성 반응 결과가 이동하는 것을 볼 수 있었는데, 특히 고온 자극의 경우

부정적이고 강렬한 (negative valence, high arousal) 방향으로 이동하는 것을 관찰할 수 있었다. 그러나, 뜨거워지거나 차가워지는 등 온도가 변화하는 자극과 진동을 동시에 제공하는 경우에는 감성 반응의 경향이 상당히 달라지는 것을 확인할 수 있었다. 온도 변화 열자극과 진동이 동시에 주어지는 경우, 진동의 주파수 및 강도는 모두 Arousal의 변화를 가져왔으며, valence에 미치는 영향은 크게 줄어들었다.

복합 촉감 자극의 활용 가능성을 알아보기 위해, 위 연구 결과를 활용하는 응용 연구 또한 진행하였다. 우선, 형용사 표현을 이용하여 정성적인 특성의 정도를 수치화한 실험 결과를 바탕으로 '형용사 공간' 및 이를 이용한 진동 저작 방법을 제안하고, 기존의 주파수 등 파라미터를 직접 조절하는 저작 방식과 사용성을 비교하였다. 그 결과 파라미터의 개수가 2개 이상인 복잡한 형태의 진동을 저작함에 있어서 형용사 공간을 이용한 저작이 결과물 및 사용자 선호 측면에서 기존 방법보다 더 우수함을 보임을 확인하였다. 마지막으로, 촉감 자극의 감성적 응용 사례로 촉감을 이용하여 기존의 콘텐츠에 존재하는 감성적인 의미를 변화시키는 감성 증강(emotion augmentation)의 개념을 제안하고, 실험을 통하여 그 가능성을 확인하였다. 실험에서는 감정적인 의미를 강하게 나타내는 시각 이모티콘들을 대상으로, 진동과 열촉감 자극을 더하여 감각적으로 증강시켰을 때 사용자들이 느끼는 감성이 어떻게 바뀌는지 조사하였다. 실험 결과, 1) 고주파 진동은 arousal만을 증가시키고 저주파 진동은 valence만을 감소시키며, 2) 온열감(warming)은 전반적으로 arousal 증가, valence 감소를 보였다. 또한, 냉감(cooling) 자극은 이모티콘의 긍정/부정의 정도를 강화하는 모습 또한 발견할 수 있었다. 이들 결과를 통하여, 촉감을 통하여 시각 등의 콘텐츠에 존재하는 감정을 어느 정도 변화시킬 수 있음을 확인할 수 있었다. 실험 후 설문조사 결과, 다수의 피실험자들은 촉감이 더해짐으로써 이모티콘의

본래 의미와는 다른 감정을 느낄 수 있었다고 응답하였으며, 또한 일부 피실험자는 촉감과 이모티콘의 감성적 특성이 잘 어울릴 경우 감정의 폭을 증대시켜주며, 그렇지 않을 경우 그 반대라는 응답을 하였다.

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Publications

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