

Changes in cognitive characteristics according to 3 intensity changes by 8 vibration frequencies (STROBE)

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Abstract

In this study, we attempted to observe changes in cognitive characteristics according to 3 intensity changes (Level 1: 0.25 gravity, Level 2: 0.38 gravity, Level 3: 1.3 gravity) at 8 vibration frequencies (10, 50, 100, 150, 200, 225, 250, 300 Hz).

The subjects were twelve male (22.1 ± 0.6 years old) and twelve female (21.5 ± 0.8 years old) healthy, right-handed adults with normal cognitive abilities. An experimental trial consisted of a stimulation phase (0.1 sec) in which a vibration stimulus was presented and a rest phase (6 sec) in which no vibration stimulus was presented. A selected stimulus was presented on the first knuckle of the right index finger 5 times (trials). Cognitive characteristics scores according to changes in intensity at each frequency were sampled using a subjective assessment sheet consisting of eighteen items ("ticklish," "shivery," "push," "convex," "thick," "numb," "slow," "fast," "shallow," "strike," "weak," "strong," "dense," "blunt," "heavy," "light," "stab," "no stimulus"). To identify the cognitive characteristics according to intensity changes by frequency, the 3 intensities were designated as variables, and a curve estimation regression analysis was performed.

At 10 Hz, cognitive characteristics of 'blunt' increased with the intensity, and 'weak' decreased. In 100 and 225 Hz, increase or decrease in intensity led to opposite cognitive characteristics ('weak-strong' in 100 and 225 Hz, 'light-heavy' in 225 Hz). In 100 and 225 Hz, as the intensity increased, expressions on the sense of surface such as 'blunt' were superior, and the shape of an object (thick) and dynamics (push) differed with the change in intensity. In addition, in 225 Hz, decrease in intensity led to increase in cognitive characteristics such as 'light' and 'shallow.' 'Fast' was unique in that it only appeared as the intensity increased at 300 Hz.

Abbreviation: SR = stochastic resonance.

Keywords: cognitive characteristics, frequency, intensity, vibration

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The datasets generated for this study are available on request to the corresponding author.

The protocol for the research project was approved by the Institutional Review Committee of Konkuk University, within which the work was undertaken, and it conforms to the provisions of the Declaration of Helsinki (7001355-201707-HR192).

The authors have no conflicts of interest to disclose.

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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1. Introduction

Recently, vibration stimulus has been used as a user interface in various areas such as mobile devices, automobiles, games, and medicine. In early studies on these areas, vibration stimuli were designed considering the most fundamental elements of frequency, amplitude, duration, and the location on the body where the stimulus is delivered. Through this, studies on methods of creating vibration feedback that can easily differentiate stimuli have been conducted. As the implementation of various effects such as waveform modulation and rhythm has become possible with the development of oscillator technology, various and rich vibration stimuli can be created.^[1,2]

Despite the possibility of presenting vibration stimuli using various parameters to that extent, studies related to specific tactile perceptions are lacking. One reason is that the words for various vibration stimuli perceived by individuals are very subjective, and the tactile characteristics of vibrations are difficult to clearly judge when changes in stimulus parameters increase. Accordingly, a basic study to systematically investigate the cognitive characteristics of various vibration parameters and apply them to different systems appears to be essential. Among vibration stimulus parameters, the most fundamental are frequency and intensity. Consequently, it is necessary to first set the range for these parameters, and then objectively and systematically analyze the tactile characteristics induced by the combination of these stimuli and their possible expressions by collecting tactile sense-related terms.

Our research team has systematically investigated subjective cognitive characteristics for vibration stimuli. A preliminary experiment was conducted by collecting a total of 235 words related to tactile sense, heat sense, pain sense, and myesthesia to create a subjective assessment form for various vibration stimuli, and a questionnaire was created to use in the main experiment. In addition, the following study was conducted to identify cognitive characteristics by presenting various vibration frequencies and intensities using a vibration stimulation system^[3] produced by our research team.

First, cognitive characteristics for nine frequencies (10, 50, 100, 150, 200, 225, 250, 275, and 300 Hz) at 1 intensity (1.8 gravity) were identified.^[4] Starting from 150–200 Hz, representative cognitive characteristics identified for low and high frequency tactile stimuli were “slow,” “convex,” and “thick” and “fast,” “shallow,” and “ticklish,” respectively. Based on the first study, the second study was conducted with varying stimulus intensities. Stimuli were presented at 3 different intensities (Level 1: 0.25 gravity, Level 2: 0.38 gravity, and Level 3: 1.3 gravity) at eight vibration frequencies (10, 50, 100, 150, 200, 225, 250, 300 Hz), and cognitive characteristics at each frequency at the 3 intensities were identified and reported.^[5] Depending on the intensity, differences in the cognitive characteristics “thick,” “blunt,” and “heavy” were identified at 100 to 150 Hz. For high frequency vibration stimuli at 200 to 300 Hz, changes in the cognitive characteristics “fast,” “shallow,” and “light” were observed depending on the intensity.

Based on the 2 previous studies, the present study attempted to observe changes in cognitive characteristics according to changes in intensity at different vibration frequencies using curve estimation regression analysis. This type of study’s significance is in observing frequency and intensity parameters—the most important parameters of vibration—from yet another perspective.

Based on the 2 previous studies, we believe that the cognitive characteristics according to intensity change per frequency can appear and that cognitive characteristics of each frequency by intensity will be clearly distinguished by the characteristics of the intensity.

That is, the present study attempted to observe changes in cognitive characteristics according to 3 intensity changes (Level 1: 0.25 gravity, Level 2: 0.38 gravity, Level 3: 1.3 gravity) at eight vibration frequencies (10, 50, 100, 150, 200, 225, 250, 300 Hz).

2. Methods

In the present study, vibration stimuli were presented at various frequencies and intensities using a self-developed vibrotactile stimulator.^[3–5] This system produces vibration using Lorentz’s force 2 electromagnetically generated by interactions between sinusoidal electrical signals sent through the solenoid coil, a coil of copper wire spirally wound, and an external magnetic field. Eight frequencies (10, 50, 100, 150, 200, 225, 250, 300 Hz) and 3 intensities (Level 1: 0.25 gravity, Level 2: 0.38 gravity, Level 3: 1.3 gravity) were selected from the range of frequencies (0–300 Hz) and intensities (0.25, 0.31, 0.38, 0.56, and 1.30 gravity, gravity: acceleration unit) presentable through the vibrotactile stimulator based on our research team’s previous study.^[5]

The selection of stimulus parameters was conducted on a total of ten subjects (5 male subjects: 22.5 ± 0.3 years old, 5 female

subjects: 21.3 ± 0.5 years old). In the case of frequency, the stimulus was presented to subject’s first knuckle of the right index finger in ascending and descending orders in 5 Hz intervals from 10 Hz to 300 Hz, and subjects were asked to determine if they could discriminate the frequencies. Eight frequencies that 70% or more of the ten subjects could discriminate were selected. In the case of intensity, the intensities of Levels 1 and 3 were set to the minimum (0.25 gravity) and maximum (1.3 gravity) intensities that could be presented through the vibrotactile stimulator. Vibration stimuli for Level 1 (0.25 gravity), one of the 3 intensities (0.31, 0.38, or 0.56 gravity) used to select intensity for Level 2, and vibration stimuli for Level 3 (1.3 gravity) were presented to subject’s first knuckle of the right index finger in ascending and descending orders, and 80% of the subjects were found to clearly discriminate Level 2 compared to Levels 1 and 3 when the intensity was 0.38 gravity. Stimuli were controlled using E-Prime software (Psychology Software Tools, Inc.). The area of the finger where the vibration stimuli were presented was $1.8 \times 1.8 \text{ cm}^2$.

The subjects were twelve male (22.1 ± 0.6 years old) and twelve female (21.5 ± 0.8 years old) healthy right-handed adults with normal cognitive abilities. The purpose and details of the experiment as well as restrictions for drugs and alcohol that could affect the experiment were fully explained to the subjects. All subjects were right handed as a result of the revised Edinburgh Reading Test.^[6] The protocol for the research project was approved by the Institutional Review Committee of Konkuk University, within which the work was undertaken, and it conforms to the provisions of the Declaration of Helsinki (7001355-201707-HR192).

For subjective evaluations, the questionnaire created in a previous study^[5] was used. The subjective evaluation form was composed of a total of eighteen items that included seventeen words (“ticklish,” “shivery,” “push,” “convex,” “thick,” “numb,” “slow,” “fast,” “shallow,” “strike,” “weak,” “strong,” “dense,” “blunt,” “heavy,” “light,” and “stab”) and one phrase (“no stimulus”). The evaluation used a 5-point scale, and the subjects were instructed to assign higher scores to the word that felt stronger (1: no feeling, 5: strong feeling).

As shown in Figure 1, the experimental trial consisted of a stimulation phase (0.1 sec) in which a vibration stimulus was presented and a rest phase (6 sec) in which no vibration stimulus was presented. To evaluate the cognitive characteristics, 1 of the eight frequencies and one of the 3 intensities were selected and repeatedly presented 5 times (trials). Once the stimulus presentation was completed, a subjective evaluation was performed. After a 5-minute break, the experiment was continued with the same frequency at a different intensity. Identical experiments were conducted for the other seven frequencies, and subjects were given a ten-minute break between experiments for each frequency to avoid adaptation. During the experiments, the eight frequencies and 3 intensities were randomly presented. All subjects wore a headset and closed their eyes during the experiments to exclude the influence of auditory and visual factors other than the vibration stimuli presented.

To sample cognitive characteristics according to intensity changes by frequency, the 3 intensities were designated as variables, and a curve estimation regression analysis with IBM Statistical Package for the Social Sciences statistics 25 was performed.

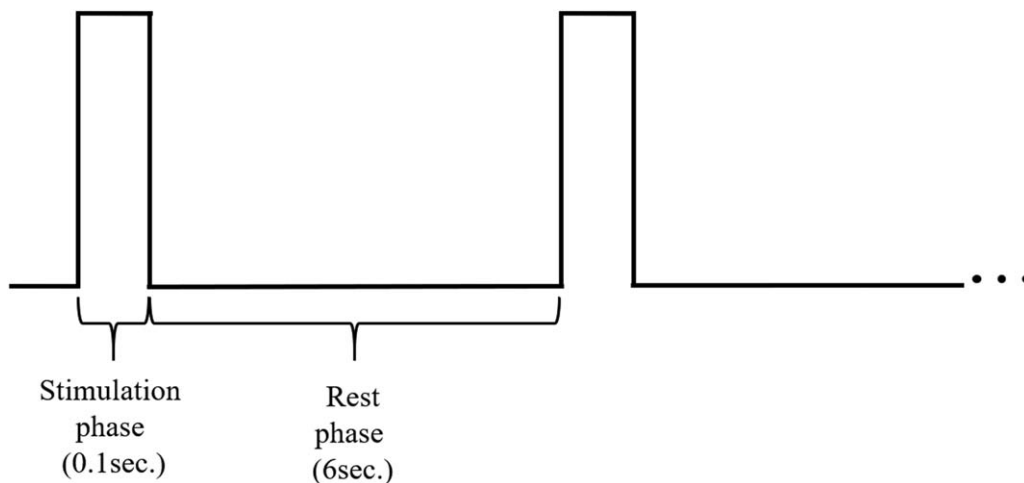


Figure 1. Vibration stimuli presentation device and experimental design.

3. Results

Words that showed significant changes according to the intensity at each frequency as a result of regression analysis (curve estimation) are presented in Table 1 and Figure 2 (A)–(G) (x = intensity, y = score). Changes in cognitive characteristics according to changes in intensity at each frequency were as follows.

- At 10Hz (low frequency), the cognitive characteristic “blunt” increased ($P=.004$), while the cognitive characteristic “weak” decreased ($P=.008$) when intensity increased.
- At 100Hz, the cognitive characteristic scores for “strong” ($P<.001$), “thick” ($P=.029$), “heavy” ($P<.001$), “blunt” ($P=.015$), and “push” ($P=.003$) increased when intensity increased. On the other hand, the cognitive characteristic score for “weak” decreased ($P=.003$).
- At 150Hz, the cognitive characteristic scores for “strong” ($P=.017$) and “push” ($P=.041$) increased when intensity increased.
- At 200Hz, the cognitive characteristic “strong” ($P=.024$) increased when intensity increased.

- At 225Hz, the cognitive characteristic scores for “strong” ($p<.001$), “thick” ($P=.024$), “heavy” ($P<.001$), “blunt” ($P=.028$), “push” ($P=.001$), and “shivery” ($P=.002$) increased when intensity increased. On the other hand, the cognitive characteristic scores for “light” ($P<.001$), “weak” ($P<.001$), and “shallow” ($p=.003$) decreased.
- At 250Hz, the cognitive characteristics “strong” ($P=.030$) and “shivery” ($P=.035$) increased when intensity increased.
- At 300Hz, the cognitive characteristic scores for “strong” ($P=.024$) and “fast” ($P=.025$) increased.

4. Discussion

Our research team previously conducted phased studies^[4,5] to identify cognitive characteristics according to the vibration stimuli of various intensities and frequencies. First, the cognitive characteristics of nine different frequencies were identified at one fixed intensity.^[4] Second, stimuli were presented in 3 different intensities at eight vibration frequencies, and cognitive character-

Table 1
Statistical analysis of changes in intensity according to frequencies (P-value).

	10 Hz	50 Hz	100 Hz	150 Hz	200 Hz	225 Hz	250 Hz	300 Hz
Ticklish	-	0.415	0.190	0.883	0.172	0.731	0.371	0.706
Shivery	0.310	0.541	0.061	0.143	0.373	0.002	0.035	0.303
Push	0.077	0.058	0.003	0.041	0.639	0.001	0.318	0.878
Convex	0.153	0.091	0.162	0.659	0.759	0.064	0.089	0.058
Thick	0.064	0.071	0.029	0.066	0.184	0.024	0.130	0.642
Numb	0.534	0.850	0.830	0.151	0.122	0.209	0.509	0.672
Slow	0.220	0.378	0.241	1.000	0.348	0.321	1.000	0.183
Fast	0.483	1.000	0.192	0.055	0.096	0.065	0.130	0.025
Shallow	0.396	0.343	0.095	0.143	0.906	0.003	0.392	0.920
Strike	0.587	0.412	0.325	0.156	0.235	0.091	0.075	0.129
Weak	0.008	0.247	0.003	0.433	0.517	$P<.001$	0.074	0.463
Strong	0.682	0.127	$P<.001$	0.017	0.024	$P<.001$	0.030	0.024
Dense	0.567	1.000	0.734	1.000	0.228	0.065	0.367	0.584
Blunt	0.004	0.239	0.015	0.135	0.372	0.028	0.227	0.616
Heavy	0.082	0.080	$P<.001$	0.221	0.800	$P<.001$	0.251	0.872
Light	0.491	0.281	0.056	0.345	0.772	$P<.001$	0.431	0.657
Stab	0.348	0.348	1.000	0.696	0.174	0.444	0.323	0.316

P-value: significance probability.

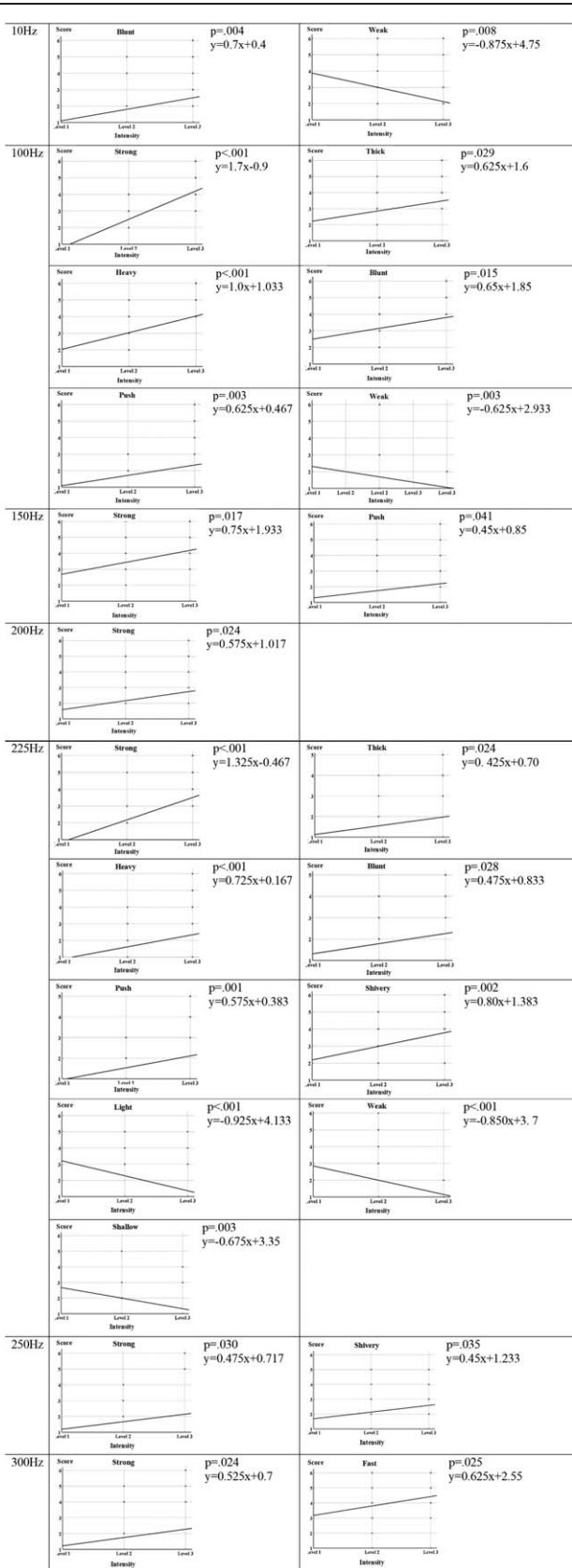


Figure 2. (A)–(G) The results of the curve estimation of the level of cognitive characteristics according to changes in the intensity of each frequency.

istics for each frequency at the 3 intensities were identified and reported.^[5] Based on the 2 previous studies, the third study was conducted to identify changes in cognitive characteristics that appear according to the 3 intensities for the eight different vibration frequencies.

At 10Hz, the cognitive characteristic “blunt” was stronger when the intensity increased. This cognitive characteristic was stronger when the intensity increased at 100 and 225Hz except, but not at 10Hz. The word “blunt” shows the shape or unevenness feeling of an object.

The cognitive level of “weak” increased when intensity decreased at frequencies of not only 10Hz but also 100Hz and 225Hz. The cognitive characteristic of “strong,” which contrasts to “weak,” increased when the intensity increased at 100 and 225Hz, unlike at 10Hz. The cognitive characteristics “weak” and “strong,” which are closely related to the perceived intensity of strength, clearly appeared only at applicable frequencies (100 and 225Hz) according to the increase and decrease of the intensity. In addition, the characteristic “strong” increased when the intensity increased in all frequencies 100Hz and higher. This is considered to be due to the fact that “strong” is the representative cognitive characteristic of the high frequency range as reported in previous studies.^[7–9]

In addition, the cognitive characteristics “thick” and “push” increased in common when intensity increased at 100 and 225 Hz. The word “thick” reflects an object’s shape characteristics while “push” reflects pressure sense or the dynamic characteristics of “push.”

At 225Hz, in addition to the strength intensity, object shape, and the dynamic characteristics of touch, the cognitive characteristic “light” decreased while “heavy” increased as the intensity increased. The words “light” and “heavy” are visual tactile sensations that are felt depending on shape and texture, and characteristics such as heaviness, lightness, smoothness, softness, and hardness have been reported to come under this category.^[10] In addition, the words “light” and “heavy” are characteristics representing weight, and they are reported to belong to the pressure sense category.^[10] Comparisons of cognitive characteristics at eight low to high frequencies by intensity showed that the cognitive characteristics of low and high intensities were mutually opposite to each other as “weak–strong” at 100Hz and “weak–strong” and “light–heavy” at 225 Hz.

At 225Hz, cognitive characteristics such as “shallow” were found to increase when the intensity decreased. The word “shallow” is a cognitive characteristic that expresses depth or height; similarly, it can express “light,” which represents the sense of weight even though the category is different. It appears to be a word that is expressed differently depending on the individual subjects’ method of expression or the category they feel.

Various tactile mechanoreceptors are densely distributed on the fingertips, and such receptors have been reported to respond to specific frequencies.^[11–13] Meissner corpuscles among mechanoreceptors respond to low frequency vibration stimuli (flutter) and are known to be particularly sensitive to 50Hz vibrations.^[13] In this experiment, various cognitive characteristics were expected to appear according to the increase and decrease of intensity at 50Hz, but no significant change in the cognitive characteristic was observed. Pacinian corpuscles respond to high frequency vibration stimuli and are known to be most sensitive at 225 Hz.^[11–13] For these reasons, various cognitive characteristics

were assumed at 225 Hz, and ultimately, contrasting cognitive characteristics of “weak–strong” and “light–heavy” appeared by changes in intensity at the high frequency vibration stimuli of 225 Hz. Further changes in various cognitive characteristics appeared depending on changes in intensity. Merkel’s cells among mechanoreceptors are known as receptors that sense slow movements and pressure stimuli, and 100 Hz stimuli are within the frequency range to which these cells respond.^[13] For this reason, changes in cognitive characteristics such as “push” and “heavy” appeared to occur.

At 225 and 250 Hz, the cognitive characteristic “shivery” became predominant with an increase in intensity. This appears to be the influence of Pacinian corpuscles among mechanoreceptors, which are sensitive to high frequency vibration stimuli. In particular, Pacinian corpuscles are most sensitive to 225–250 Hz vibration stimuli. That is, the cognitive characteristic “shivery,” which is a unique aspect of vibration stimuli, became predominant with an increase in intensity.

At 300 Hz, the cognitive characteristic “fast” was predominant as intensity increased. This cognitive characteristic did not appear at other frequencies, and it appears to be distinctive only at 300 Hz at which cognitive level was high as intensity increased.

Kim et al.^[14] and Gyeong et al.^[15] reported that not only frequencies but also intensities are necessary elements to change cognitive characteristics, and in high frequencies, the surface’s roughness and bumpiness increase while softness decreases. Comparison between previous studies and the present study is difficult due to differences in the range of presented frequencies, intensities, and words used in subjective evaluations. In the present study, words such as “bumpiness” and “softness” (surface characteristics) on which previous studies focused were not presented, but words such as “blunt” and “thick” that were judged to represent surface characteristics similar to previous studies showed that cognitive characteristics appeared largely when the intensity increased in the high frequency range of 100 and 225 Hz.

Recent studies have started to report that the finger’s tactile sensitivity increases when stochastic resonance (SR) is applied to normal and stroke patients.^[16–19] Stochastic resonance (SR) is a phenomenon in which an intermediate level of noise enhances the response of a nonlinear system to a weak input signal.^[20] Such SR phenomenon requires much attention in sensorimotor control. Trenado et al.^[19] and Manjarrez et al.^[18] explained the SR-type behavior by analyzing evoked potentials in the somatosensory area when mechanical tactile stimuli such as vibration were presented. As shown in this study, SR may have led to results clear enough to distinguish cognitive characteristics according to the intensity change by frequency. In the future, studies on finger’s tactile sensitivity according to various vibration parameters while considering SR-like phenomena may be necessary.

The present study identified cognitive characteristics that represent the stimuli’s intensity and strength by changing the intensity of vibration stimuli in the specific frequency range, and the results were generally predictable. When additional changes in specific frequencies and intensities were presented in a complex manner, however, various cognitive characteristics appeared. It was interesting that at specific frequencies (100, 225 Hz), contrasting cognitive characteristics (weak–strong at 100 and 225 Hz, light–heavy at 225 Hz) were observed when the intensity was increased or decreased, and at 10, 100, and 225 Hz, the feeling of unevenness that represents surface sensations such as “blunt” predominantly appeared as intensity increased. In

addition, at 225 Hz, cognitive characteristics such as “light” and “shallow” appeared to increase when the intensity decreased. The cognitive characteristic “fast” was a distinctive word that appeared when the intensity increased only at 300 Hz. In conclusion, changes in various cognitive characteristics according to changes in intensity at specific frequencies (100 and 225 Hz) at which the mechanoreceptors respond most sensitively compared to other frequencies were identified. Vibration stimuli are compound, not unitary, stimuli. Vibration stimuli can be presented as regular or irregular waveforms by various parameters of frequency, acceleration, and amplitude (intensity), and as such, they are felt as compound stimuli to humans. In addition, changes in additional parameters of vibration stimuli such as stimulus time, stimulus areas, stimulus pattern, and waveform modulations may induce more complex and diverse cognitive characteristics. If cognitive characteristics can be identified according to changes in these parameters in the future, it will be greatly helpful in implementing complex linguistic information directly to tactile sensation.

5. Limitations

First, eliciting various and accurate tactile properties through studies of not only the cognitive characteristics that appear when intensity and parameters change simultaneously, but also the changes in detailed stimulation intensity and frequency as well as the changes on stimulation duration, which is a very important parameter in neurophysiological experiments, is necessary. Second, studies that minimize the difference between the group of subjects that participated in stimulus parameter setting and those in this experiment, considering individual sensitivity thresholds for perception, are needed. For the reliability of the subjects’ perceptual experiences to various vibration stimuli, test-retest on the same subject with different time points seem necessary. Third, detailed research to identify cognitive characteristics in the frequency band around 50 Hz (the frequency band to which Meissner corpuscles respond sensitively) that did not appear in the present study is also needed. Although not easy, if it is possible to derive various tactile properties through studies with more detailed stimulus intensity and frequency changes in the future, it will be possible to provide basic information for realizing complex verbal information directly with sense of touch.

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