Audio-Tactile Integration: Concurrent Audio Feedback Can Shift Vibrotactile Frequency Perception

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Abstract. We hypothesize that cross-modal integration can shift the haptic perception of vibrotactile frequency in the presence of concurrent audio stimuli. The feasibility and extent of this hypothesis are examined in two psychophysical experiments. The first experiment focuses on the core hypothesis, comparing purely vibrotactile feedback against vibrotactile feedback accompanied by audio stimuli of various frequencies. In the second experiment, we quantify the difference in vibrotactile perception that users perceive in the presence of concurrent audio feedback. The results show that concurrent low-frequency aural stimulation has a significant effect on the perception of high-frequency vibrations.

Keywords: Cross-modal integration · Psychophysics · Vibrotactile.

1 Introduction

In the field of haptic perception, delivering versatile and realistic haptic texture experiences remains a difficult task. This difficulty is heightened by the inherent limitations of the hardware used in the delivery of tactile feedback. However, an intriguing principle of human perception is its susceptibility to illusion and deception. Capitalizing on this principle, the current paper proposes a novel approach to extending the tactile sensation range via cross-modal integration.

Cross-modal interaction is a complex perceptual phenomenon that involves the integration of sensory information from different modalities, leading to a perception that is different from the sum of its parts [6]. This interaction is not just linearly additive but involves complex transformations and integrations that can alter the perception of individual sensory inputs [2].

Among the sensory modalities, vision, hearing, and haptics play a significant role in our perception of the world. Vision is considered the dominant sense in humans, but it can be influenced by other sensory modalities. For instance, the McGurk effect demonstrates how auditory information can alter the perception of visual speech [20]. Hearing, or auditory perception, allows us to perceive events that are not directly within our line of sight [5]. It is well-documented that auditory stimuli can change the perception of visual stimuli [1]. Haptic perception, which involves the sense of touch and proprioception, provides us with direct information about the physical properties of objects, such as texture, temperature, and weight. Haptic feedback can, thereby, significantly improve the perception of virtual objects, making them feel more realistic [19].

The interaction between these sensory modalities can occur at various levels, including in perception and cognition. At the perceptual level, one sensory modality can enhance, suppress, or alter the perception of another, a phenomenon often referred to as sensory dominance [24]. At the cognitive level, the integration of sensory information can influence attention, memory, and decision-making processes [11]. For example, multisensory stimuli can capture attention more effectively than unisensory stimuli, a phenomenon known as multisensory enhancement [16].

Based on the principle of multisensory enhancement, the current study focuses on the interaction between auditory and tactile modalities, with a particular emphasis on the effects on tactile perception in the presence of auditory stimuli [26]. This interaction is particularly interesting as both the auditory and tactile senses are sensitive to the same physical property, that is, mechanical pressure in the form of oscillations. This correlation can support integrative interactions at various levels along the sensory pathways, from the most peripheral stages [25] to the cortical association areas of the central nervous system [4, 8].

This understanding forms the basis of our experiments, where we aim to investigate the use of sound to manipulate the perceived frequency of vibrations. We hypothesize that *overlaying haptic rendering with a concurrent audio rendering at a different frequency can modulate haptic sensations.* Psychophysical experiments are conducted to test this hypothesis and to understand its extent and limitations. The design of the experiments and analyses of the results are driven by two research questions. The first research question (RQ1) is whether the users can identify the mismatch in haptic frequencies with and without the presence of concurrent audio stimuli. The second research question (RQ2) asks about the amount of distortion caused by the overriding audio stimuli, that is, how much the audio frequency distorts the perception of the vibrotactile frequency and at what level users can identify them as different sensations.

2 Related Work

In this section, we examine how audio-tactile integration can enhance perceptual experiences. We also explore how audio feedback impacts tactile perception.

2.1 Audio-Tactile Integration

Studies have shown that the integration of audio and tactile feedback, due to their similar characteristics, can affect performance in various tasks. A study by Guest et al. [15] explored audio-tactile interaction in the perception of roughness. They found that the presence of concurrent auditory feedback can enhance the tactile perception of roughness. Similarly, Bernard et al. [3] demonstrated that roughness in auditory systems showed similar trends to roughness in tactile systems, suggesting a unified mechanism across these sensory experiences. Their work supports the idea of a shared strategy for interpreting complex stimuli, emphasizing the depth of our sensory system's integration. For the visually impaired, assistive technologies have been developed, where wearable devices utilize both sound and vibrations to provide critical spatial information [10].

Similarly, vehicle safety systems utilize a blend of beeps and seat or steering wheel vibrations to provide real-time safety alerts to drivers [27].

Wilson et al. found that identical or closely aligned frequencies for combined auditory and vibrotactile stimuli resulted in maximum detection rates [30]. Another study investigated the use of audio-driven tactile feedback in audio mixing applications. It aimed to provide a more immersive understanding of the audio being manipulated [21].

2.2 Effect of Audio on Tactile Perception

Audio feedback has been documented to influence various tactile perception. This includes the absolute threshold for tactile perception [31], temporal resolution between tactile events [13], spatial localization of tactile stimuli [22], and the perceived frequency of vibrotactile feedback [18].

A study by Yau et al. suggested that auditory stimuli can interfere with tactile perception when their frequencies are similar [31]. Other studies have shown that the presence of concurrent auditory cues can modulate the perception of tactile stimuli. Zampini et al. used two separate studies to show that the perception of food texture and everyday objects can be modulated by changing the frequency or amplitude of the accompanying audio stimuli [32, 33].

The aforementioned studies highlight the significant interplay between audio and tactile perception. In the current study, we strive to understand the role of audio frequency in changing the perception of tactile frequency. Such an effect can aid in designing broader bandwidth sensations with limited hardware.

3 Experiment 1: Effect of Concurrent Audio on Vibrotactile Frequency Perception

This experiment aims to identify the impact of concurrent audio feedback on the perception of vibrotactile signals. In line with RQ1, it ascertains the perceived dissimilarity of vibrations with and without a concurrent audio signal.

The experiment examines how the tactile and auditory systems process frequency information. While both systems are sensitive to frequency, they interpret it differently. In the tactile system, mechanoreceptors in the skin translate vibrations into neural activity, resulting in tactile sensations. In contrast, the auditory system converts sound waves into neural signals in the cochlea, leading to the perception of sound. The underlying hypothesis is that the auditory system's higher sensitivity and complex neural encoding might influence tactile frequency perception. We expect that this interaction could make low-frequency vibrations perceived as higher frequency when accompanied by high-frequency sounds. In contrast, a low-frequency sound signal might not be able to influence a higher-frequency vibration, as the lower frequencies are readily identifiable.

3.1 Participants

A total of 20 participants were recruited to take part in the experiment (15 male, 5 female). They were all right-hand dominant and their ages were from 21 to 52 years old (mean 29.2 years). They reported no disabilities that would affect the outcome of the experiment. Informed consent was granted by all participants before the experiment. The participants were rewarded with 15 USD (14 Euro) worth of gifts after the experiment. The experiment was approved by the Institutional Review Board.

The sample size for this study was determined using a power analysis, conducted based on the following parameters:

- Effect size: The effect size was estimated based on the just noticeable difference (JND) for haptic frequency perception in humans. JND was used as a measure because an effect lower than the JND would most likely not be perceived by the users. Previous research has suggested that the JND for the haptic perception of frequencies is between 17% and 30% [9, 23]. For this study, an effect size of 30% was assumed, which is the upper limit of the JND. This accounts for greater individual variations making our analysis robust against Type II errors (missing a true effect). Essentially, by planning for a broader range of perceptual responses, we improve our chances of capturing differences in how users experience haptic feedback. Opting for the upper limit of the JND, rather than the lower end, allows us to better accommodate and understand tactile perception.
- Standard deviation: We used the standard deviation of JND as the standard deviation for calculating the sample size. JND is the minimum change in frequency detectable by an individual, which correlates with the ability to perceive differences in tactile stimuli. Given our focus on evaluating variations in the perception of frequency dissimilarity, the variability in JND offers a practical approximation of the expected variability in dissimilarity perception. The assumption is that the standard deviations of JND will align with the diversity in perceiving frequency dissimilarities. The literature reports the standard deviation of JND between 8.6% and 13% [23]. As a precaution, a standard deviation of 15% was considered for this study. It should be noted that a higher standard deviation would result in a smaller value for Cohen's d [7]; Cohen's d is calculated as the difference between means (effect size) divided by the standard deviation. The smaller the value of Cohen's d, the more challenging it is to detect the effect, given the same sample size and experimental conditions.
- Power: A power of 0.95 was chosen, which means that if there is a true effect, the study would have a 95% chance of detecting it.
- Significance level: A significance level of 0.01 was chosen, which means that the probability of falsely rejecting the null hypothesis (i.e., of finding a significant effect when there is none) is 1%.

The formula used for sample size estimation [12] is:

$$N = \frac{4\sigma^2 (Z_{\alpha/2} + Z_\beta)^2}{D^2} \tag{1}$$

where $Z_{\alpha/2}$ is the critical value of the normal distribution at $\alpha/2$ (for a confidence level of 99%, α is 0.01 and the critical value is 2.576), Z_β is the critical value of the Normal distribution at β (for a power of 0.95, β is 0.05 and the critical value is 1.64), D is the effect size, and σ is the standard deviation. Using these parameters, the required sample size was calculated to be 17.77 participants. As a precaution, 20 participants were recruited. This sample size ensures that the study is adequately powered to detect the assumed effect.

3.2 Materials

The experiment was facilitated through an application designed using Matlab R2023a on a laptop computer (ASUS Zephyrus G15). The interface and the experimental setup are provided in Fig. 1. It had buttons for playing the reference and comparison stimuli and a text box for entering their perceived dissimilarity.

A voice coil actuator (VP216, Acouve lab) was used to generate the vibrotactile signals, attached to the back of a 3D-printed phone. The phone was used as an interface for delivering vibrations as it is the most commonly used device in our daily interactions. The audio signals were played using headphones (Jabra Evolve2 85 MS Stereo). Both signals were relayed through the same pre-amplifier (Scarlett 6i6 by Focusrite) to ensure concurrent delivery.

Actuator Frequency Response It is well known that most actuators have a non-linear response to different frequencies. The frequency response under a standard load is usually provided by the manufacturer. However, the frequency response under specific experimental conditions might differ from the one provided by the manufacturer. Therefore, we calculated the frequency response of the VP216 actuator under our experimental conditions. The purpose of providing the actuator response is to enable reproducibility of the results.

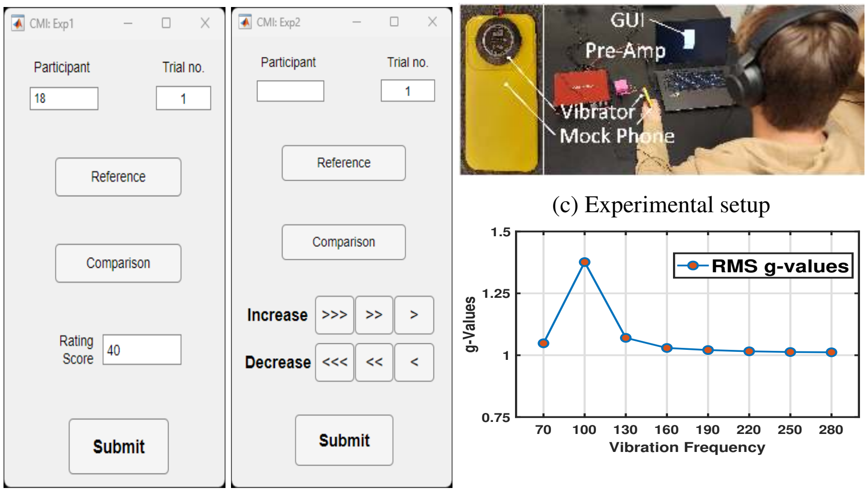
The actuator was mounted on the 3D-printed phone and held by a user. An accelerometer (GY-521, MPU 6050) was attached to the phone using zip-ties. Data from the accelerometer was collected by an Arduino Uno, which was serially connected to a computer. A MATLAB program collected data from the Arduino for five seconds.

The frequency response of the actuator was recorded for the eight frequencies mentioned in Sect. 3.3. Values were recorded three times and averaged out. The frequency response of the actuator is provided in Fig. 1d in root-mean-squared (rms) g-values.

3.3 Stimuli

The stimuli for this experiment consisted of vibrotactile-only signals and combined vibrotactile and audio signals. Their frequencies ranged from 70 Hz to 280 Hz, with an interval of 30 Hz, resulting in a total of 8 signals (70, 100, 130, 160, 190, 220, 250, 280 Hz).

For each vibrotactile signal, a set of combined stimuli was created by pairing the vibrotactile with audio signals ranging from 70 Hz to 280 Hz, with an interval of 30 Hz. This resulted in 8 combined stimuli for each vibrotactile signal and a total of 64 comparisons for all the vibrotactile signals, as shown in Table 1. All the vibrotactile and audio signals were pure sine waves. The audio signal strength was kept consistent at a 40-phon curve of equal subjective intensity [17] to ensure that the participants had frequency cues as the only available discriminatory criterion. The strength of the signals were 71.02, 64.37, 59.95, 56.70, 54.14, 52.39, and 48.98 dB SPL, respectively. The



CMI: Exp1

Participant: 18

Trial no.: 1

Rating Score: 40

CMI: Exp2

Participant:

Trial no.: 1

(c) Experimental setup

(a) Exp 1 GUI (b) Exp 2 GUI (d) Frequency Response of VP216

Fig. 1: GUIs for experiments 1 (a) and 2 (b), the experimental setup (c), and (d) the frequency response for VP216 actuator in experimental conditions.

vibrotactile signals in each trial had the same frequency and, consequently the same perceived intensity.

3.4 Method

The experiment involved delivering a vibrotactile signal at a specific frequency and comparing it against the same vibrotactile signal along with a concurrent audio signal. The null hypothesis (H0) for this experiment is that the perceived frequency of the vibrotactile stimulus is the same whether it is presented alone or with a concurrent audio signal. The alternate hypothesis (H1) is that the perceived frequency of the vibrotactile stimulus is different when it is presented with a concurrent audio signal.

In each trial, participants were presented with a pair of stimuli: a vibrotactile signal and a combined vibrotactile and audio signal. The vibrotactile signal served as the reference stimulus, while the combined signal was the comparison.

The experiment used a within-subject design. The order of the trials was randomized and counterbalanced. Magnitude estimation without modulus was used for rating to exclude any user bias during averaging that may arise due to interpersonal differences in scaling [29, 34].

3.5 Procedure

The experiment was conducted in a quiet, controlled environment to minimize external auditory or tactile distractions. Participants were seated and given the mock smartphone with a voice-coil actuator attached to it. They held the mock smartphone in their left

No.	Reference	Comparison	
	Vibrotactile-only Frequency (Hz)	Combined Signal (Hz)	
		Vibrotactile	Audio
1	70	70	70 100 130 160 190 220 250 280
2	100	100	70 100 130 160 190 220 250 280
3	130	130	70 100 130 160 190 220 250 280
4	160	160	70 100 130 160 190 220 250 280
5	190	190	70 100 130 160 190 220 250 280
6	220	220	70 100 130 160 190 220 250 280
7	250	250	70 100 130 160 190 220 250 280
8	280	280	70 100 130 160 190 220 250 280

Table 1: Pairing of vibrotactile and audio frequencies for Experiment 1 trials. This table illustrates the combinations of vibrotactile-only and combined vibrotactile and audio frequencies. Each row represents a unique vibrotactile frequency as a reference, paired with a corresponding set of combined stimuli as comparisons. The vibrotactile portion of the combined stimuli remains the same as the vibrotactile-only stimuli, while the audio portion changes in each trial.

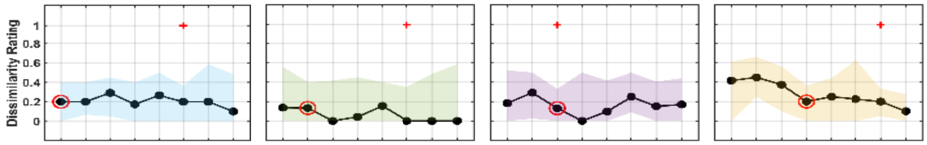
hand and interacted with the application using their right hand. They wore headphones throughout the experiment. Participants were asked to focus on the frequency of the vibrotactile sensation and compare the reference and comparison stimuli. The instructions were: *"You will be rating the perceived dissimilarity between the frequencies of the reference and comparison. Do not focus on the audio signal. If you feel they are the same, you will record a value of Zero. Otherwise, you will assign a value to this difference. There is no upper limit to the difference value."* Participants provided a rating depending on the difference between the stimuli. They were instructed to keep their scale consistent. Each participant rated all the combinations resulting in a total of 64 trials (8 comparisons for each of the 8 vibrotactile signals). The experiment took 23 minutes on average. Breaks were provided as needed to prevent fatigue.

3.6 Results and Discussion

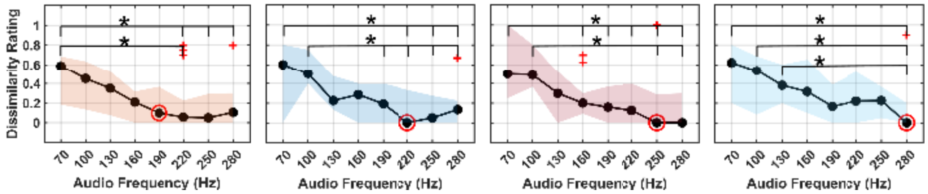
The objective of the data analysis was to understand the perceived differences between the combined vibrotactile and audio stimuli in comparison to their respective vibrotactile signal references. The ratings were normalized between zero and one and averaged across all participants. Shapiro-Wilk test showed a non-normal distribution, therefore, the Kruskal-Wallis test was used to check for statistical significance.

The introduction of audio stimuli affected the perception of vibrotactile of varying frequencies, thus rejecting the null hypothesis. The Kruskal-Wallis test showed that vibrotactile at frequencies 190 Hz, 220 Hz, 250 Hz, and 280 Hz displayed significant differences when paired with concurrent audio of varying frequencies ($H(7) = 31.74$, $H(7) = 35.27$, $H(7) = 35.85$, and $H(7) = 28.78$, respectively, all p-values < 0.001). Tukey's HSD test showed multiple significant pairs, as shown in Fig. 2.

Initially, we expected that high-frequency audio might influence the perception of low-frequency vibrotaction. Contrary to this expectation, the results showed that a



(a) 70 Hz (b) 100 Hz (c) 130 Hz (d) 160 Hz



(e) 190 Hz (f) 220 Hz (g) 250 Hz (h) 280 Hz

Fig. 2: Each subplot shows the perceived dissimilarity in vibrotactile frequencies under the influence of a concurrent audio signal. The x-axis indicates the audio frequencies, while the y-axis quantifies the median perceived difference between the vibrotactile-only signal and the combined vibrotactile-audio signal. The shaded areas show the 75^{th} and 25^{th} percentile, the red o shows the reference vibrotactile frequency, and the red + shows the outliers. * p-values < 0.001

high-frequency vibrotactile signal when paired with a concurrent low-frequency audio signal was perceived as significantly different from the same high-frequency vibrotactile signal delivered without audio. This result was further corroborated by the Kruskal-Wallis test from the perspective of audio signals. It was surprising to discover that low-frequency audio, specifically at 70 and 130 Hz (H(7) = 19.32, 18.75 $p < 0.01$), had a pronounced effect on the perception of vibrations, while 220 Hz audio also showed statistical significance at H(7) = 16.45, $p < 0.05$.

These results showed that there exists a difference in the perception of vibrotactile signals when accompanied by audio stimuli. The magnitude of this difference, however, was not studied. A second experiment was designed to identify the magnitude of the frequencies that had significant differences.

4 Experiment 2: Shifting of Vibrotactile Frequency Perception

This experiment quantifies the perceived difference in vibrotactile signals with and without concurrent audio stimuli for RQ2. Participants adjust a vibrotactile signal to match a combined vibrotactile and audio signal, measuring the frequency shift caused by the audio signal.

4.1 Participants

A total of 16 participants were recruited for the experiment (12 male, 4 female). All were right-handed and their ages were from 23 to 52 years (mean 27.6 years). Some participants were part of experiment 1. They reported no disabilities that would affect the experiment. Informed consent was granted by all participants. They were rewarded with 15 USD (14 Euro) worth of gifts after the experiment. The experiment was approved by the Institutional Review Board.

The sample size of 16 was calculated using equation 1 with an effect size of 30, a standard deviation of 15, a power value of 0.90, and a significance value of 0.01. The power value was reduced from 0.95 for the first experiment but kept higher than the widely accepted value of 0.8 [12]. These calculations resulted in a sample size of 14.88 participants, which we rounded off to 16 as a precaution.

4.2 Materials

The materials in this experiment were the same as in the first experiment. A new application was developed for this experiment, as shown in Fig. 1. The application had buttons for playing the reference and comparison stimuli. The frequency of the comparison stimuli could be increased or decreased using another set of buttons. Buttons were provided for three levels of increments or decrements. The three levels were 30 Hz, 10 Hz, and 2Hz.

4.3 Stimuli

The vibrotactile stimuli used in this experiment were at frequencies of 190 Hz, 220 Hz, 250 Hz, and 280 Hz. The audio stimuli were ranging from 70 Hz to 280 Hz with a step size of 30 Hz. A total of 32 stimuli pairs were presented to the participants; eight combined vibrotactile and audio stimuli for each vibrotactile stimulus, as shown in Table 2. The strength and generation mechanism of the stimuli were the same as in the first experiment.

No.	Reference		Comparison
	Vibrotactile and Audio Frequency (Hz)		Vibrotactile-only Frequency (Hz)
	Vibrotactile	Audio	
1	190	70 100 130 160 190 220 250 280	190
2	220	70 100 130 160 190 220 250 280	220
3	250	70 100 130 160 190 220 250 280	250
4	280	70 100 130 160 190 220 250 280	280

Table 2: Pairing of vibrotactile and audio frequencies for Experiment 2 trials. This table illustrates the combinations of vibrotactile-only and combined vibrotactile and audio frequencies. Each row represents combined stimuli as a reference, paired with corresponding vibration-only stimuli.

4.4 Method and Procedure

Participants were presented with a combined vibrotactile and audio signal as a reference, followed by a vibrotactile signal as a comparison. The reference stimulus varied by combining different audio frequencies with the vibrotactile frequencies carried over from Experiment 1. The comparison stimulus had the same frequency as the vibrotactile component of the combined signal. The experiment had a within-subject design. The trials were randomized and counterbalanced. The comparisons were carried out using the method of limits.

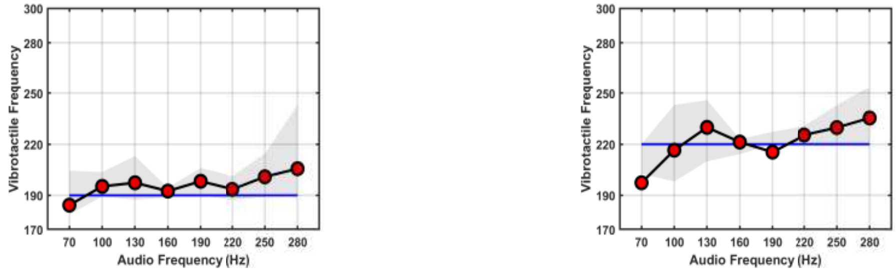
The experimental setup for this experiment was the same as the first experiment. Participants were presented with a combined vibrotactile and audio signal, followed by a vibrotactile signal having the same frequency as the vibrotactile component of the combined signal. The instructions to participants were: *"Adjust the frequency of the comparison signal until its perceived frequency matches the frequency of the reference signal. Do not focus on the audio signal. If you feel the perceived frequencies are the same, go to the next trial. If you feel they are different, increase or decrease the frequency of the comparison stimulus until you feel it matches the frequency of the reference signal."* The experiment took 21 minutes on average. Participants were allowed to take short breaks if needed.

4.5 Results and Discussion

The perceived frequency shift for each vibrotactile frequency was achieved by comparing the initial and final frequencies for each trial. The Shapiro-Wilk test showed a non-normal distribution, therefore, the Kruskal-Wallis test was employed to ascertain the significance of the shift in frequency perception, as shown in Fig. 3. The Kruskal-Wallis test showed that 220, 250, and 280 Hz vibrotactile frequencies showed a statistically significant shift when combined with audio signals (H(7) = 18, H(7) = 20.18, H(7) = 16.07, with $p < 0.05$), whereas, the 190 Hz vibrotactile signal did not produce a significant shift in the presence of audio signals.

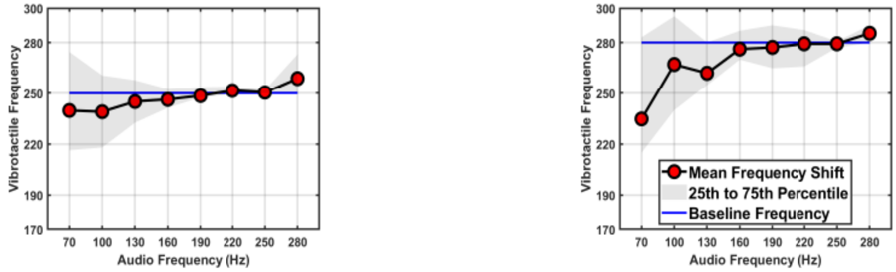
The vibrotactile signals at 220 Hz were affected by lower and higher audio stimuli almost equally. The trend line in Fig. 3b shows that the 70 Hz audio stimulus shifted the perceived frequency down to 194 Hz, and audio at 280 Hz shifted the perceived frequency up to 237 Hz. A similar trend was seen for vibrotactile signals at 250 Hz. The vibrotactile signals at 280 Hz were shifted with an increasing magnitude as the frequency of the audio stimulus decreased. Most significantly, the vibrotactile signals at 280 Hz were perceived as equivalent to 229 Hz when a 70 Hz audio stimulus was played concurrently. These shifts are equal to or greater than the JND for frequency discrimination according to [9, 23], suggesting that the shift in perception is significant.

We explored whether some participants showed a larger shift than others, and if the magnitude of shifts stayed consistent. Figure 4a shows that the absolute magnitude of the perceived shift is consistent across most participants. Participants 4 and 11 showed a higher shift as compared to others. Participant 8 showed an elevated mean shift only for vibrotactile signal at 190 Hz, and relatively low shifts for all others. This is shown in the mean shift being very low.



(a) 190 Hz baseline frequency

(b) 220 Hz baseline frequency



(c) 250 Hz baseline frequency

(d) 280 Hz baseline frequency

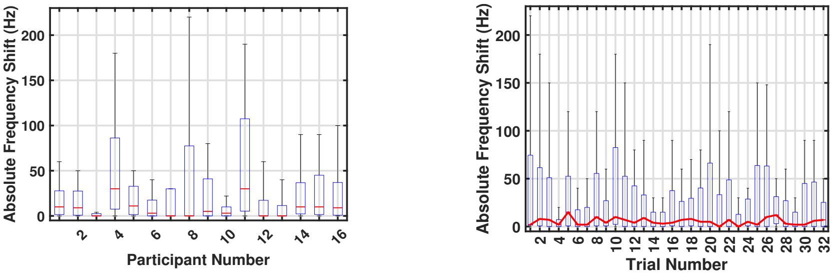
Fig. 3: The subplots show the baseline vibrotactile frequency and the shifts in perceived vibrotactile frequency as a result of concurrent audio stimuli.

We analyzed whether participants' perceived frequency shift of the vibrotactile signal varied over time, indicating adaptation to audio stimuli as the experiment progressed. Figure 4b shows the shift across trials, independent of frequency in each trial. A repeated measures analysis using the Friedman test showed no significant differences in these shifts (p-value > 0.05), indicating stable perception throughout the experiment without adaptation to the audio stimuli.

The key takeaways from this experiment are: vibrotactile frequencies above 200 Hz are affected more in the presence of concurrent audio stimuli. The higher the difference between vibrotactile and audio stimuli, the higher the perceived shift in frequency. The effect on tactile perception is consistent and doesn't change with repeated exposure.

5 General Discussion

The theory of Supramodality [14] states that our brain is designed not around separate sensory modalities but around tasks that often require multiple senses. In our experiments, the task was the perception of vibrotactile stimuli, but the introduction of audio stimuli transformed this singular sensory task into a multisensory one. The brain then attempted to reconcile and integrate the information from both the tactile and auditory domains. This integrative process is shown in our results as the shifts in perceived vibrotactile frequencies when audio stimuli are present. The findings of Crommett et al.



(a) The absolute magnitude of perceived frequency shift for each participant.

(b) The magnitude of perceived frequency shift in each trial of the experiment.

Fig. 4: The magnitude of shift for participants is the average of the shifts in all the trials. The magnitude of the shift in trials is calculated by averaging all the trials, irrespective of which frequency appeared in that trial.

[8], where auditory adaptation was shown to improve tactile frequency discrimination, align with this theory. Their research indicates that the same neural pathways may be responsible for tactile frequencies and auditory cues, highlighting that certain brain functions are universal and do not operate on any single sensory system.

It was interesting that some participants reported perceiving an increased intensity of vibrations despite the intensity being the same. The principle of Multisensory Integration [28] suggests that the brain integrates information from various modalities to form a coherent representation of the environment. This can lead to one modality dominating or altering the perception of another.

Figures 2 and 3 illustrate that frequency perception remained largely unchanged when the frequencies of audio and vibrotactile signals closely matched. These findings are in line with prior studies [30, 31], where adjacent audio stimuli were found to enhance perceptual detection thresholds.

We selected the frequency range from 70 to 280 Hz for our investigation based on two reasons. First, it is the most sensitive band for tactile perception. Second, this range encapsulates the operational frequencies of vibration motors commonly found in smartphones. These devices typically utilize either Linear Resonant Actuators (LRAs) or Eccentric Rotating Mass (ERM) motors. ERM motors generally operate at lower frequencies (60 to 200 Hz), while LRA motors are designed to resonate at higher frequencies (140 to 300 Hz). Our study explored the possibility of expanding the perceptual range of one motor type to simulate the characteristics of the other. Although our results did not fully achieve this bidirectional transformation, we observed a significant perceptual shift in one direction. The effect of frequency in combination with intensity [30] can be used to cause larger shifts in perceived frequency, and effectively map a larger area of perception using limited hardware.

This finding may have tangible implications for designing broader haptic feedback in devices with a limited vibration frequency range. It suggests potential applications in designing more effective multisensory interfaces, where auditory cues can be deliberately paired with tactile feedback to modulate user perception, enhancing the user experience.

In both experiments, we equalized the intensity of the audio stimuli to control for perceived loudness. However, a similar equalization was not applied to the vibrotactile stimuli. In the first experiment, equalization of vibration intensity was deemed unnecessary since each trial compared the perception of the same vibration frequency (only the audio frequency changed), thus eliminating intensity as a variable. In the second experiment, although equalization of vibrotactile intensity was not performed, we expected minimal influence of intensity on the results due to the relatively close comparison frequencies. Both the frequencies started as similar, and the participants changed the comparison frequency to match the reference frequency. Additionally, Fig. 1d shows that the frequency response of the actuator is almost flat in the frequency range used in experiment two (190 Hz to 280 Hz). The flat response shows that the vibration intensity was not affected by the actuator response. However, the results show that in some cases the comparison frequency was changed significantly which would introduce a significant effect of intensity. We acknowledge that the potential for even minor differences in intensity might impact perceived frequency, and future studies would benefit from incorporating intensity equalization to refine the accuracy of the findings.

Given the constraints of our study, including limited time and resources, we opted for a single-trial approach per condition. Our analysis using the Friedman test indicated no significant adaptation effect to auditory stimuli, suggesting stable perception across trials. This outcome supports the reliability of our findings, despite the single-trial design. The study provides important initial insights into the effects of concurrent auditory stimuli on tactile perception, particularly the significant frequency shifts observed in vibrations above 200 Hz.

Future research can delve deeper into the underlying neural mechanisms that drive these auditory-tactile interactions. Moreover, the influence of other factors like amplitude, duration, or temporal patterns of both auditory and tactile stimuli can be explored to get a more comprehensive understanding.

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