Translating Music to Touch: Exploring Tactile Perception of Pitch, Roughness, and Pleasantness

Jeremy Marozeau, Alice Taylor, Sacha Novozhilova, Mario Prsa and Daniel Huber

***Abstract*—Music is a rich multisensory experience, yet individuals with hearing impairments often lack access to this important aspect of culture. As tactile technologies advance, there is growing interest in whether musical information can be conveyed through vibration. This study investigates how core dimensions of auditory music perception, pitch, roughness, and pleasantness, can be translated into the tactile domain. Participants were asked to rate these perceptual dimensions in response to sinusoidal and complex waveforms, including amplitude-modulated signals, sawtooth, and missing fundamental stimuli. Perceived pitch showed a systematic relationship with stimulus frequency for most participants, suggesting that tactile devices could effectively convey melodic patterns. The sawtooth waveform emerged as particularly effective for representing pitch changes, underscoring the role of rapid temporal transitions in tactile pitch encoding. Roughness ratings were negatively correlated with pleasantness, mirroring well-established findings in auditory perception. Waveforms with sudden temporal changes or rapid amplitude modulations were consistently judged as less pleasant. Taken together, these findings indicate that tactile systems can effectively convey melodic structure and emotional tone, laying the groundwork for musical touch interfaces. Importantly, our results highlight the crucial role of the fast temporal envelope rather than the temporal fine structure, in shaping vibrotactile perception. Consistent with this interpretation, our data provide evidence for a tactile analog of the auditory missing fundamental phenomenon, reinforcing the idea that tactile pitch perception primarily relies on envelope periodicity rather than the presence of specific frequency components.**

***Index Terms*—Tactile, Auditory, Music, Pitch, Roughness, Psychophysics, Haptic.**

I. Introduction

Can music be perceived through skin vibration? For the millions of people with hearing loss who are excluded from the auditory experience of music, haptic technologies offer a potential solution into this essential form of human expression. However, a key question remains: how much of music's richness can truly survive the translation of sound to touch? These questions have gained interest in recent years with the development of new devices aimed at helping hearing impaired people experience music through tactile stimuli [1]–[5]. Sound and tactile vibrations are inherently linked as both involve the transmission of mechanical waves. It makes the sense of touch a natural medium for conveying musical qualities when auditory processing is impaired [6], [7].

Music is a complex auditory signal that depends on multiple physical parameters such as frequency, intensity, and spectral envelope. These parameters are fundamental in shaping perceptual dimensions, such as pitch, loudness, and timbre, which are low level aspects of music perception. Beyond these basic attributes, higher level perceptual dimensions, including pleasantness, roughness, dissonance, and valence, play critical roles in shaping the emotional and aesthetic experience of music [8]–[10]. For example, pitch height and pitch strength contribute to melody perception, while roughness and dissonance are essential to create tension and resolution, two key elements of musical expression [9], [10]. Translating these auditory features into tactile experiences requires an understanding of how vibration affects the perceptual and emotional aspects of touch.

Although the use of vibration to convey music is not new, an optimal solution has yet to emerge. Devices designed to translate music into tactile feedback often face challenges in replicating the complexity of auditory signals, particularly in capturing subtle changes in pitch, timbre, or dissonance [11]. In addition, tactile perception operates on a narrower frequency range and relies on different mechanisms compared to auditory perception, raising questions about how effectively tactile stimuli can capture the full spectrum of musical information. While hearing relies on mechanotransduction by a uniform population of hair cells in the cochlea, which decompose sound into frequency components [12], touch depends on a diverse set of specialized mechanoreceptors distributed across the skin, such as Pacinian and Meissner corpuscles, each tuned to different aspects of vibration and pressure [13]. This fundamental difference in sensory pathway complicates the translation of auditory features into tactile formats.

Here, we investigate how much musical information can be conveyed through a tactile vibration alone using a single actuator. Specifically, we focus on how tactile stimuli can represent three key musical dimensions: pitch, roughness, and pleasantness. First, participants were asked to judge the perceived frequency of sinusoidal and complex vibrations to evaluate the tactile equivalent of pitch perception. Second, they rated the roughness of the same complex stimuli to explore whether vibration can encode qualities related to consonance and dissonance. Finally, they evaluated the pleasantness of the stimuli to examine how tactile signals influence emotional and aesthetic responses and if it is negatively correlated with roughness. These experiments aimed to capture both low level perceptual attributes and higher level affective responses,

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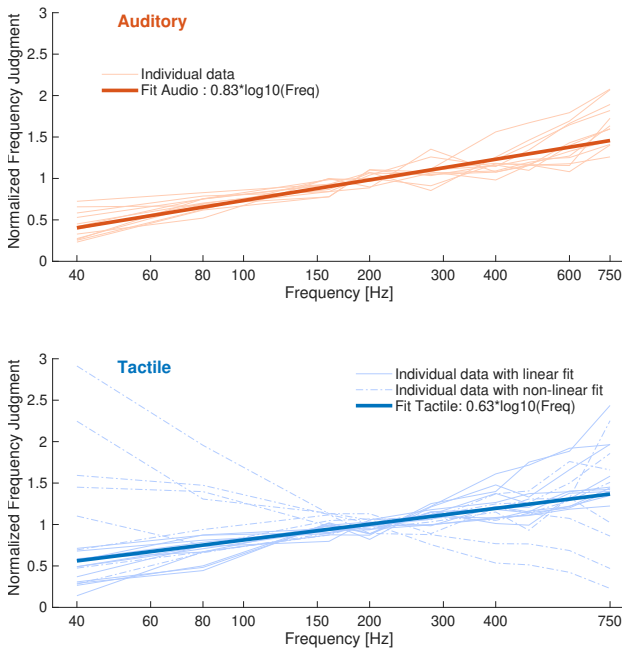

Fig. 1. Perceived frequency judgments for sinusoidal stimuli across all participants. The upper panel displays individual responses for auditory stimuli (thin lines). The lower panel presents individual responses for tactile stimuli, where participants best fit by a positive linear regression are shown with thin continuous lines, while those best fit by other models are represented with thin dashed lines. The overall linear fit for both stimuli are depicted with thick lines.

providing a comprehensive understanding of the tactile representation of musical information.

Our findings contribute to the development of tactile devices capable of providing meaningful musical experiences to people who cannot rely on hearing, while also advancing our understanding of the similarities and differences between auditory and tactile perception.

II. Results

A. Vibrotactile pitch induced by a sinusoidal stimulus

Pitch perception, the ability to discern whether a musical note is high or low, plays a central role in music appreciation and is closely linked to sound frequency. In a first experiment, we explored how variations in frequency were perceived in both auditory and tactile domains by directly asking participants to evaluate perceived frequency using a simple sinusoidal stimulus, ranging from 40 to 750 Hz. We tested two groups of participants: one received sinusoidal vibrations applied to the hand, while the other listened to identical frequencies through headphones. Participants rated the "perceived frequency" of each stimulus on a self defined scale, explicitly defined as the repetition speed of an oscillation. Amplitudes were calibrated beforehand to ensure equal perceptual intensity across modalities matched in perceived intensity to a 280 Hz reference played at a comfortable level (see Method, section V).

For auditory stimuli, perceived frequency judgments increased linearly with the logarithm of stimulus frequency for all participants, showing minimal inter individual variability (Figure 1, top panel). A linear fit to these judgments, akin to the Mel scale [14], yielded a slope of 0.83 with $df = 7$, $p < 0.001$, $R^2 = 69\%$, reflecting strong sensitivity to frequency changes.

Tactile stimuli produced a similar but significantly weaker linear relationship, (slope $= 0.63$, $F(1, 284) = 17.9$, $p < 0.001$), indicating reduced sensitivity to frequency variations (Figure 1, bottom panel). To explore these inter individual differences, we fitted both linear and quadratic models to each participant's responses and conducted ANOVAs to determine the most appropriate fit. The significance level α was adjusted for multiple comparisons using 0.5 divided by the number of participants per condition. All auditory responses best fit a positive linear model, with slopes ranging from 0.43 to 1.23, see Methods. Tactile responses were varied: 13 out of 20 participants exhibited a positive linear fit (continuous lines, figure 1), four favored a quadratic fit, two showed no clear relationship, null model, and one participant demonstrated a negative linear relationship, (dashed lines, figure 1).

Among participants with a positive linear fit in the tactile condition, the mean slope was not statistically different compared to the auditory condition, slope 0.72, linear mixed effects model ($F(1, 221) > 0.05$, $p < 0.5$). These findings suggest that, although tactile frequency perception can align with auditory pitch perception, this relationship is generally weaker and less consistent. The underlying reasons for these different behaviors remain unclear. We examined variables such as gender, musical expertise, age, and familiarity with tactile tasks, but none provided a significant explanation.

B. Vibrotactile pitch induced by a complex stimulus

The first experiment examined pitch perception using simple sinusoidal vibrations, which contain energy at a single frequency and no harmonics. In contrast, musical notes typically involve complex waveforms with harmonic structures, where energy is present at integer multiples of a fundamental frequency, F_0.

It is important to distinguish between waveform, periodicity, and F_0. The waveform refers to the signal's shape over time and determines the presence and relative strength of harmonics. Periodicity describes how often the waveform repeats in the temporal domain and is quantified by the inverse of F_0. For example, a sine wave contains only one frequency component, whereas a sawtooth waveform consists of numerous harmonics with amplitudes decreasing proportionally. Both can share the same periodicity but differ in harmonic structure. Additionally, the acoustic waveform can be decomposed into two complementary aspects: the temporal fine structure, which represents the rapid fluctuations within each waveform cycle, and the fast envelope, which corresponds to the instantaneous amplitude of the waveform obtained using the Hilbert transform [15]. While the fine structure captures cycle by cycle phase information, the fast envelope describes the instantaneous amplitude variations that strongly influence perceptual characteristics, including speech and timbre.

Auditory pitch perception involves two dimensions: pitch chroma, primarily influenced by periodicity and linked to note identity, and tone height, influenced mainly by spectral

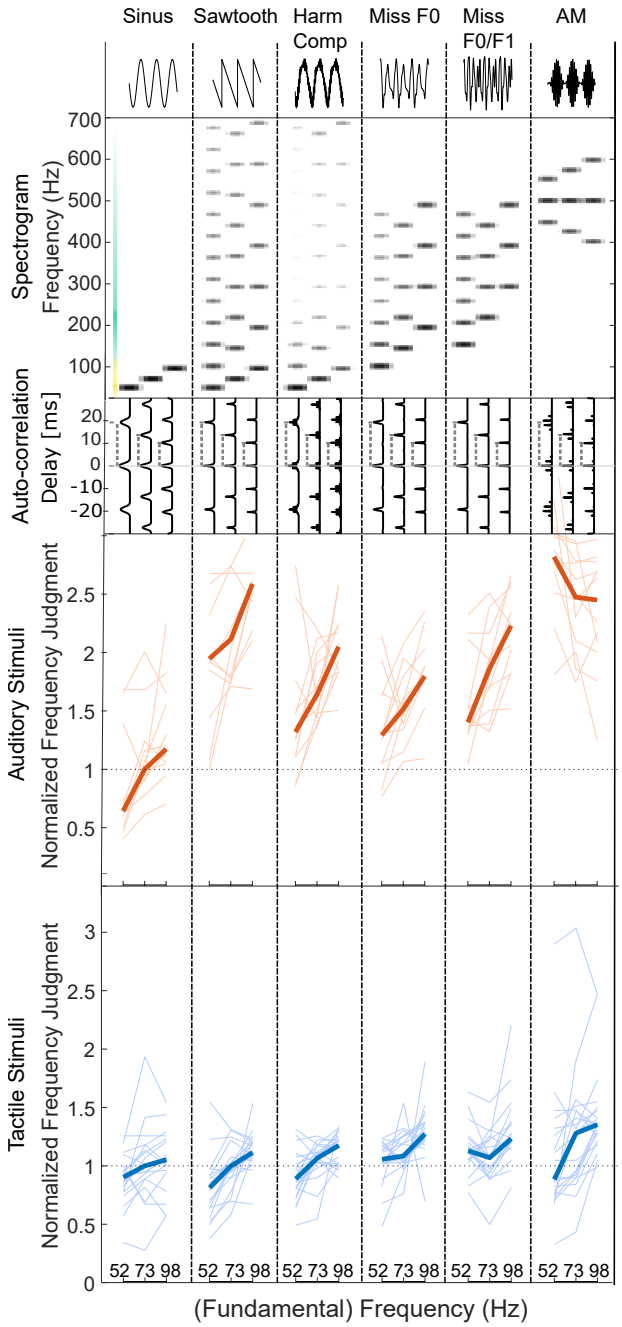

Fig. 2. Figure 2 Physical representation and perceptual judgment of the 18 stimuli grouped by waveform and fundamental frequency F_0. The Top row represent three repetitions of each waveform in the temporal domaine. The second row displays spectrograms illustrating the frequency composition of each stimulus. The vertical color gradients on the left depict the sensitivity ranges of Pacinian corpuscles, green, and Meissner corpuscles, yellow. The third row shows the autocorrelation of each stimuli, showing that despite their large difference in spectral envelope, they share the same periodicity. The fourth row shows normalized perceived frequency judgments for auditory stimuli, orange, while the last row represents tactile stimuli, blue. Thin lines indicate individual participant responses, thick lines represent the median judgments across participants.

content and associated with the perceived octave or register. For instance, an harmonic complex with strong high frequency components can be perceived sometimes as one octave higher than a sine wave, despite sharing the same periodicity [16].

Here, we investigate how these auditory dimensions translate into tactile perception. Specifically, we hypothesized that tactile pitch perception would be predominantly driven by periodicity, with minimal influence from harmonic structure, or waveform.

To test this, we presented participants with 18 stimuli combining six different waveforms and three fundamental frequencies, 52, 73, and 98 Hz. The sinusoidal waveform served as a baseline. We included a sawtooth waveform, selected for its sharp temporal onset, to test whether such transients enhance tactile pitch perception, see Figure 2. To isolate the role of harmonic structure from temporal sharpness, we also included a harmonic complex waveform with harmonics attenuated by 3 dB per octave and randomized in phase, resulting in a smoother waveform.

Additionally, we tested whether tactile pitch perception could occur without direct energy at the fundamental frequency, analogous to the auditory missing fundamental effect [16], [17]. Two waveforms were created: Missing F_0, lacking energy at the fundamental frequency, and Missing F_0/F_1, lacking energy at both the fundamental frequency and the first harmonic. If tactile pitch relies primarily on waveform periodicity, participants should still perceive pitch clearly even when the energy at the fundamental frequency is absent.

We also introduced an amplitude modulated, AM, waveform with a 500 Hz carrier frequency and modulation frequencies at the same frequency that the F_0 of the other stimuli, 52, 73, and 98 Hz. We included this AM stimulus because it provides clear spectral energy centered around the carrier frequency. By testing this waveform, we aimed to investigate if strong spectral energy at higher frequencies, distinctly above the fundamental, can influence tactile pitch perception.

Participants judged the perceived frequency of these complex stimuli, illustrated in Figure 2. Despite individual variations, the median judgments generally increased with frequency for both auditory and tactile stimuli, except for the AM auditory stimuli. Waveform type notably influenced auditory pitch perception, consistently resulting in higher pitch judgments for complex stimuli compared to sinusoidal stimuli of identical periodicity. This effect, known as the octave error, likely arises from greater energy in higher harmonics, influencing the perceived tone height [16].

A two way repeated measures ANOVA on auditory stimuli showed significant main effects of Waveform, $F(5, 55) = 9.82$, $p < 0.0001$, $R^2 = 37\%$, and Frequency, $F(2, 22) = 9.93$, $p = 0.0008$, $R^2 = 3\%$, with a significant interaction, $F(10, 100) = 6.60$, $p < 0.0001$, $R^2 = 3.2\%$. Post hoc Bonferroni analyses revealed that sinusoidal stimuli were judged significantly lower than the harmonic complex, $p = 0.0003$, Missing F_0, $p = 0.0088$, Missing F_0/F_1, $p = 0.0012$, and AM, $p = 0.0002$. Additionally, AM stimuli were judged significantly higher than harmonic complex, $p = 0.0212$, Missing F_0, $p = 0.0007$, and Missing F_0/F_1, $p = 0.0035$. Missing F_0 and Missing F_0/F_1 also differed significantly, $p = 0.0127$.

A similar two way repeated measures ANOVA for tactile stimuli showed significant main effects of Waveform, $F(5, 95) = 4.27$, $p = 0.0014$, $R^2 = 11\%$, and Frequency, $F(2, 38) = 38.37$, $p < 0.0001$, $R^2 = 10\%$, with a significant

interaction, $F(10, 190) = 2.17$, $p = 0.02$, $R^2 = 2\%$. Post hoc Bonferroni analyses showed that sinusoidal stimuli were judged significantly lower than Missing F_0, $p = 0.0355$. Sawtooth stimuli were judged significantly lower than Missing F_0, $p = 0.0032$, and Missing F_0/F_1, $p = 0.0029$. Additionally, harmonic complex stimuli were judged significantly lower than Missing F_0, $p = 0.0256$. Notably, the sinusoidal stimuli were not significantly lower than Missing F_0/F_1, in accordance with the effect of the missing fundamental in tactile perception.

Comparing the auditory and tactile ANOVAs via effect sizes, R^2, we observed that auditory pitch perception was primarily driven by Waveform, harmonic structure, explaining 37% of variance, compared to only 3% for frequency. In contrast, tactile pitch perception showed similar modest influences from Waveform and Frequency, periodicity of the waveform, each accounting for about 10% of variance.

We hypothesized that waveforms with a sharp rise, such as the sawtooth, should lead to a more salient perception of vibrotactile pitch. To test this, we compared the effect of Frequency on the sinusoidal and sawtooth stimuli using a planned contrast analysis, see Methods. Frequency indeed had a significantly stronger effect, that is a steeper slope, on the sawtooth stimulus compared to the sinusoidal stimulus, $p = 0.0239$, supporting our hypothesis.

C. Perception of Roughness

Beyond pitch, music conveys affective qualities like tension and dissonance, often characterized by roughness. In the auditory domain, roughness emerges from rapid amplitude modulations produced by interactions between unresolved harmonics. Auditory roughness perception, as computationally modeled by Zwicker and Fastl [18], depends less on F_0 and more on the density and spacing of partials in higher frequency regions. Based on an implementation of this model, see Methods, on our stimuli, the sawtooth waveform is predicted to generate the greatest roughness, due to its rich harmonic structure with pronounced high frequency content.

In the tactile domain, models of roughness perception under single point stationary stimulation are less established. The duplex theory, proposed by Bensmaia [19], suggests distinct mechanisms underlying tactile texture perception. Coarse textures, elements greater than 100 μm, are encoded spatially through slowly adapting type I afferents, whereas finer textures, less than 100 μm, are primarily mediated by rapidly adapting afferents, particularly Pacinian corpuscles. Pacinian corpuscles are highly sensitive to high frequency vibrations, optimally around 250 Hz, suggesting frequency as an important factor for finer textures. Research has proposed two main coding theories for fine texture: an intensity based code and a temporal, frequency based, code [19]. Specifically, it has been suggested that tactile roughness perception could result from a weighted sum of the stimulus spectrum by the Pacinian corpuscle's sensitivity profile around 250 Hz, with higher frequencies receiving greater weighting. Thus, waveforms with strong high frequency content, like sawtooth and amplitude modulation, AM, are predicted to be perceived as rougher. Additionally, the irregularity of waveforms and sharp spatial deviations, as measured by the Hurst coefficient [20], have been proposed as critical factors contributing to roughness perception, further supporting the prediction that sawtooth and AM waveforms would be perceived as particularly rough. To test these predictions, participants were asked to rate the roughness of vibrotactile and auditory stimuli previously used in the perceived frequency task.

Consistent waveform effects emerged across both modalities, Figure 3, left panels. For the auditory stimuli, a two way repeated measures ANOVA revealed a significant main effect of Waveform, $F(5, 55) = 18.49$, $p < 0.0001$, $R^2 = 52\%$, and Frequency, $F(2, 22) = 43.11$, $p < 0.0001$, $R^2 = 2\%$, but no significant interaction, $F(10, 110) = 1.59$, $p = 0.1174$. Post hoc pairwise comparisons, Bonferroni corrected, showed that the sawtooth stimulus was rated significantly rougher than the sinusoid, $p = 0.0200$, Missing F_0, $p = 0.0034$, Missing F_0/F_1, $p = 0.0059$, and AM, $p = 0.0070$, as predicted by the model. In addition, the harmonic complex was rated rougher than the sinusoid, $p = 0.0426$, AM, $p = 0.0097$, and both Missing F_0 conditions, $p = 0.0004$ and $p = 0.0017$. As expected, F_0 had only a minor influence on roughness perception.

For the tactile stimuli, a significant main effect of Waveform was found, $F(5, 95) = 22.14$, $p < 0.0001$, $R^2 = 28\%$, along with a weak and significant interaction with Frequency, $F(10, 190) = 2.95$, $p = 0.0018$, $R^2 = 3\%$, but no main effect of Frequency alone, $F(2, 38) = 1.77$, $p = 0.1835$. Post hoc comparisons revealed that AM stimuli were perceived as significantly rougher than all other waveforms, all $p < 0.01$, including the sawtooth, $p = 0.0466$. The sawtooth waveform was rated rougher than the sinusoid and harmonic complex, but smoother than the AM. The harmonic complex was judged smoother than both the Missing F_0/F_1, $p = 0.0055$, and sawtooth, $p = 0.0008$, and the sinusoidal waveform was consistently rated as the smoothest, significantly smoother than Missing F_0/F_1, $p = 0.0067$, and sawtooth, $p < 0.0001$.

The AM waveform was perceived as significantly rougher than all stimuli. This emphasizes the critical role of waveform irregularities in the perception of tactile roughness. In addition, the sawtooth was rated as the second roughest. Rather than frequency content alone, tactile roughness appears particularly sensitive to disruptions of regularity and sharp temporal fluctuations. This aligns with existing theories proposing that temporal waveform irregularity and abrupt amplitude transients, rather than harmonic density per se, dominate tactile roughness perception under single point stationary stimulation [20].

We conclude that tactile roughness can be systematically controlled by modifying the vibration waveform, with minimal influence from frequency. If we aim to use vibration to convey musical emotion, we must examine whether tactile roughness contributes to feelings of unpleasantness, as has been observed in the auditory domain [21]. In the next experiment, we tested whether tactile roughness is negatively correlated with tactile pleasantness.

D. Experiment 4: Perception of Pleasantness

In this experiment, we tested whether stimuli that were judged as rough would also be perceived as less pleasant.

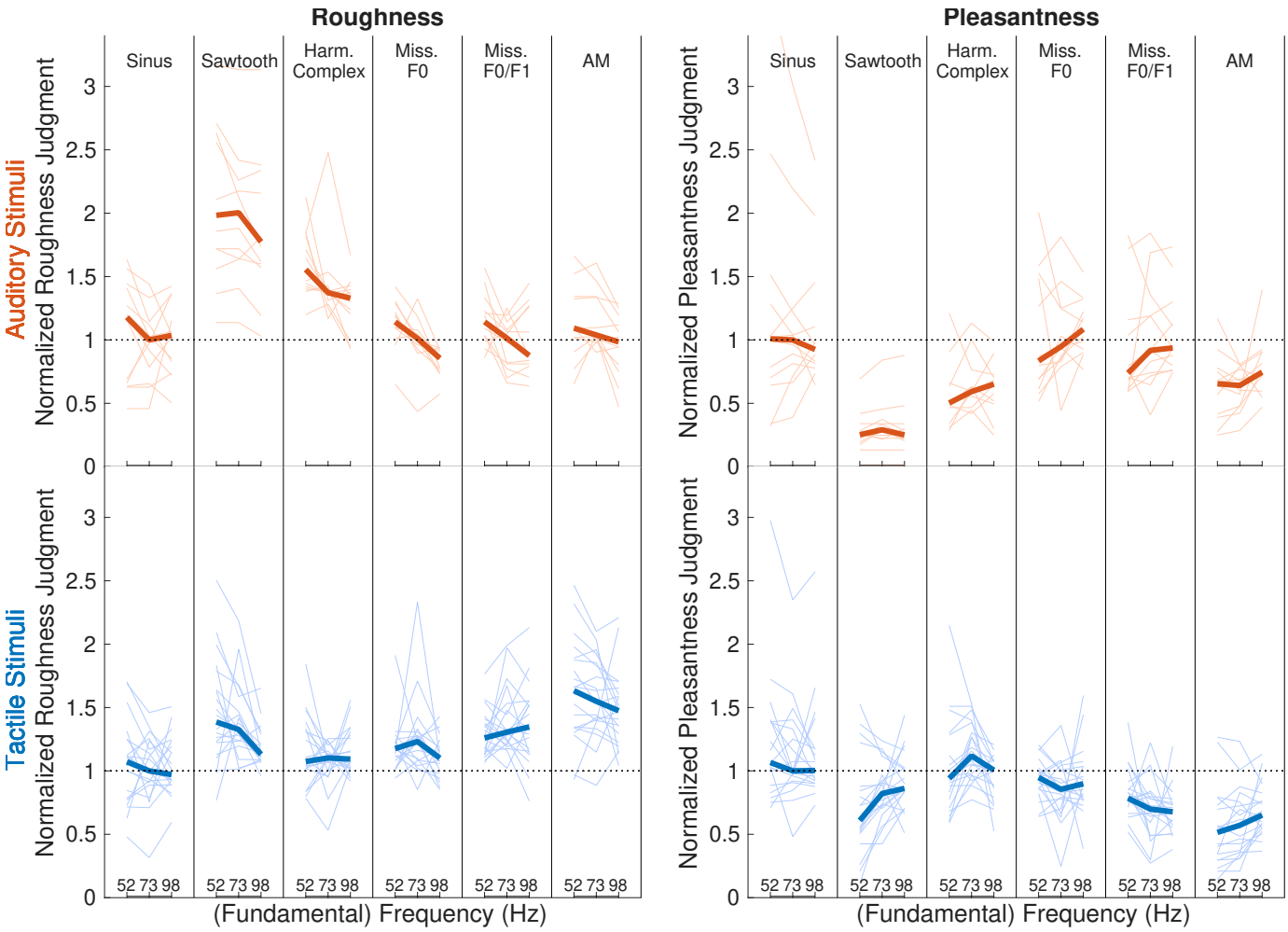

Fig. 3. Left panel: roughness ratings. Right panel: pleasantness ratings. Normalized roughness and pleasantness ratings are shown for six waveform types: sinusoidal, sawtooth, harmonic complex, Missing F_0, Missing F_0/F_1, and AM, at three base frequencies (52, 73, and 98 Hz), for auditory stimuli (upper panels, orange) and tactile stimuli (lower panels, blue). Thin lines indicate individual participant responses, thick lines represent the median judgments across participants.

This is a phenomenon well established in the auditory domain, where increased roughness is typically associated with dissonance and decreased pleasantness [21]. Verrillo et al. [22] similarly reported a negative correlation between roughness and pleasantness in tactile perception using various sandpapers. We hypothesized that, as in audition, participants' judgments of roughness and pleasantness would be negatively correlated for both auditory and tactile modalities. To test this, we asked participants to rate the pleasantness of the same vibrotactile and auditory stimuli used in the previous experiments.

Rating of pleasantness of the complex stimuli revealed a significant effect of the waveform, especially for auditory stimuli, Figure 3, right panel. For auditory stimuli, an ANOVA indicates a significant effect of Waveform on pleasantness judgments, $F(5, 55) = 9.54$, $p < 0.0001$, $R^2 = 37\%$, while there was no main effect of Frequency, $F(2, 22) = 0.66$, $p = 0.5276$, nor interaction effect between Waveform and Frequency, $F(10, 110) = 0.93$, $p = 0.5093$. Post hoc analyses further reveal that participants rated the sawtooth waveform as significantly less pleasant than all the other waveforms, sinusoidal, $p = 0.041$, harmonic complex, $p = 0.0013$, Missing F_0, $p = 0.0011$, Missing F_0/F_1, $p = 0.003$, and AM, $p = 0.0074$. The harmonic complex was judged as less pleasant than the Missing F_0, $p = 0.0016$. Interestingly, within the other waveforms, AM was judged as less pleasant than both Missing F_0, $p = 0.0186$ and $p = 0.033$.

For tactile stimuli, the ANOVA also shows a significant influence of Waveform on pleasantness, $F(5, 95) = 15.15$, $p < 0.0001$, $R^2 = 29\%$, and a significant, though weaker, interaction effect with Frequency, $F(10, 190) = 3.93$, $p < 0.0001$, $R^2 = 4\%$, while Frequency alone does not significantly impact pleasantness ratings, $F(2, 38) = 0.02$, $p = 0.9779$. Notably, the AM tactile stimulus received significantly lower pleasantness ratings compared to sinusoidal, $p = 0.0017$, sawtooth, $p = 0.0327$, harmonic complex, $p < 0.0001$, and Missing F_0, $p = 0.0004$ stimuli. The sawtooth waveform was judged as less pleasant than the harmonic complex, $p = 0.0247$. As for the audio stimuli, the two tactile stimuli that were judged as more rough, were also judged less pleasant. Additionally, Missing F_0/F_1 was rated as less pleasant than the sinusoidal, $p = 0.0117$, harmonic complex, $p = 0.0002$, and Missing F_0, $p = 0.0009$.

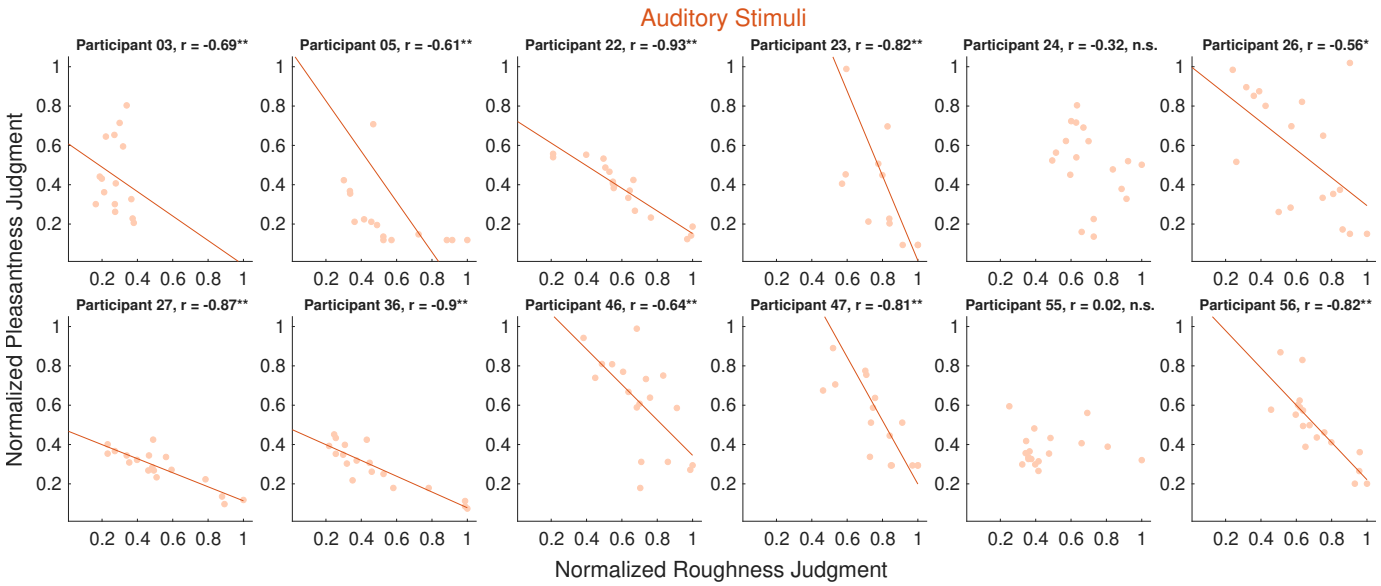

Fig. 4. Correlation between roughness and pleasantness ratings for auditory stimuli. Each panel shows the data of an individual participant. Dots represent single stimulus ratings, and straight lines indicate significant regression fits.

Because judgments of pleasantness are highly individual, we examined the relationship between roughness and pleasantness at the level of each participant. For each person, we computed the correlation between their roughness and pleasantness ratings across the full set of stimuli. Correlations were calculated over the 27 stimuli, yielding 26 degrees of freedom.

For the auditory stimuli, a significant negative correlation, $p < 0.05$, was observed in 10 out of 12 participants, and for the tactile stimuli, in 12 out of 20 participants, see Figures 4 and 5. All significant correlations were negative, except for P46 with the tactile stimuli, indicating that rougher sounds or vibrations are generally judged as less pleasant.

This experiment confirms that, as in audition, tactile roughness can influence affective judgments. Stimuli that were perceived as rougher were also rated as less pleasant, and this relationship was robust at both the group and individual level.

III. Discussion

We explored how core musical features, pitch, roughness, and pleasantness, can be conveyed through tactile vibration. Our findings highlight a central difference between auditory and tactile processing: the capacity for spectral decomposition. In audition, the basilar membrane mechanically separates incoming sound into narrow frequency bands, enabling precise encoding of both spectral and temporal features. In contrast, vibrotactile signals are processed largely through two specialized frequency channels, the Meissner, 5 to 50 Hz, and Pacinian corpuscles, 40 to 1000 Hz, which offer limited spectral resolution [13]. As a result, tactile perception relies more heavily on the fast temporal envelope than on detailed spectral content. Nevertheless, our data indicate that vibrotactile stimuli can convey some musical information and these limitations are crucial to consider when designing an effective haptic device for conveying music.

A. The perception of pitch through vibrotactile stimulation

We observed a monotonic relationship between the physical frequency of vibrotactile stimuli and their perceived pitch, Fig. 1. This suggests that changes in melody contour can indeed be encoded through variations in the frequency of tactile stimuli. However, the slope describing the relationship between the stimulus frequency and its perceived pitch was smaller than in the auditory domain. Practically, this means that larger frequency differences are required in the tactile domain to achieve perceptual changes equivalent to those in the auditory domain. For example, while a 6% frequency difference in auditory stimuli is sufficient to produce a perception of one semitone, the distance between two adjacent notes on a piano, an 8% difference is necessary for tactile stimuli. Consequently, direct translation of audio signals to tactile stimuli would result in a compressed perception of melody contour. This finding aligns with previous studies that have demonstrated significantly larger just noticeable differences for tactile frequencies compared to auditory frequencies [20].

B. The effect of waveform on the perception of vibrotactile pitch

We hypothesized that a sinusoidal vibration might not be the optimal stimulus to convey pitch. Therefore, our study explored how waveform differences affect vibrotactile pitch perception. Specifically, we found that stimuli with abrupt discontinuity, such as sawtooth waves, were more sensitive to frequency changes than simpler and smoother waveforms like sinusoids. Although our Experiment on complex perceived frequency was limited to a relatively narrow frequency range, the data suggest that the slope relating physical frequency to perceived frequency might be steeper for the sawtooth waveforms than for the sinusoidal. We propose that this enhanced sensitivity observed results from the efficient detection by Pacinian corpuscles of more salient changes in the stimulus.

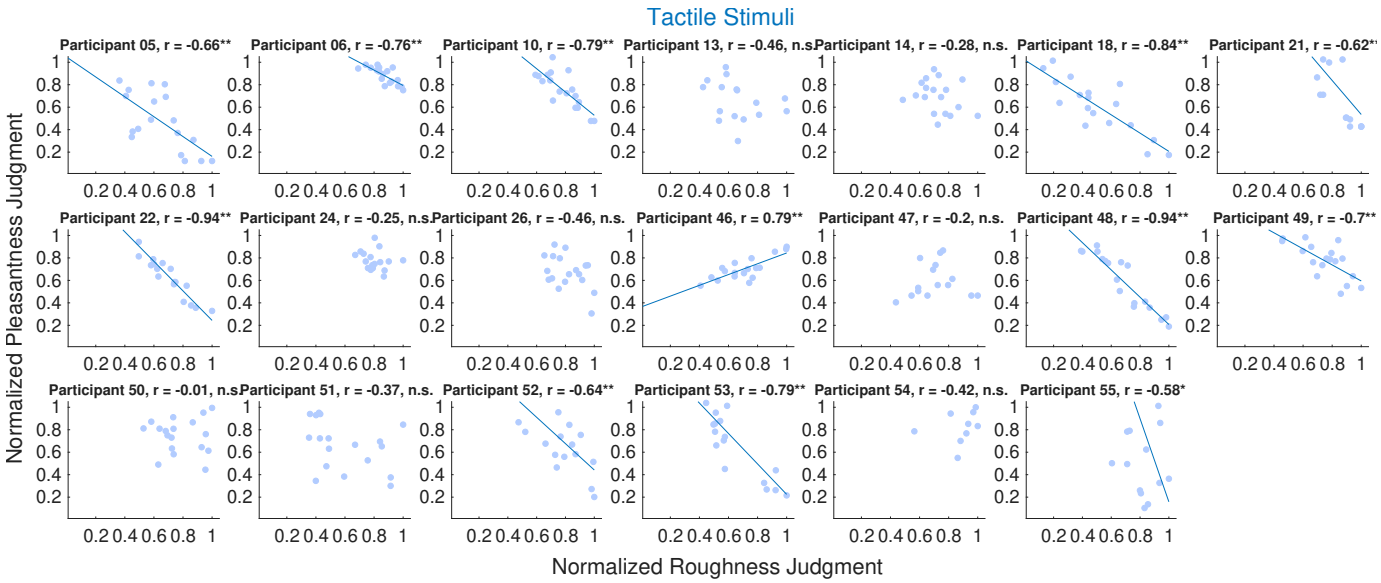

Fig. 5. Correlation between roughness and pleasantness ratings for tactile stimuli. Each panel shows the data of an individual participant. Dots represent single stimulus ratings, and straight lines indicate significant regression fits.

To illustrate this hypothesis, we modeled the responses of tactile neurons using TouchSim, a somatosensory neuron activation simulation [23]. The simulations demonstrated that sinusoidal waveforms induced neuronal firing at various phases, accompanied by minor temporal jitter, Figure 6a. In contrast, the sawtooth waveform elicited strong neural activation at two specific moments corresponding precisely to the waveform's abrupt changes, Figure 6b. It is important to note a fundamental difference in how auditory and tactile systems respond to oscillatory stimuli. In the auditory system, inner hair cells are activated only during positive pressure displacement of the basilar membrane, while negative displacement does not trigger activation. Since sound waves are oscillatory, every positive pressure phase is followed by a negative one; thus, auditory hair cells typically activate once per cycle, at frequencies below the phase locking limit [24]. In contrast, Pacinian corpuscles respond to both positive and negative pressure displacements, resulting in two activations per cycle [25]. This difference in activation mechanisms is clearly observed in our model (Figure 6).

It is also important to note that since all stimuli were matched in perceived intensity, they differed significantly in maximal displacement. For instance, at 52 Hz, the sinusoidal waveform required a displacement amplitude 5.6 times greater than the sawtooth waveform to achieve the same perceptual intensity. Therefore, to convey pitch effectively using a simple waveform, the sawtooth not only produces a more salient percept but also requires substantially smaller actuator displacement. However, generating sawtooth mechanical movements is technically more challenging compared to sinusoidal waveforms and cannot be achieved with simple actuators like an eccentric rotating mass, ERM.

C. The effect of the missing fundamental is perceivable in the tactile domain

Our data provide support for the missing fundamental phenomenon in the tactile domain. Specifically, waveforms lacking energy at the fundamental frequency, Missing F_0 and Missing F_0/F_1, were perceived with comparable or nearly comparable frequencies to sinusoidal vibrations. Despite their distinct spectral envelopes, all tested stimuli shared identical periodicity, as confirmed by autocorrelation analysis, see Figure 2. Similarly, the modeled neuronal responses, Figure 6c, demonstrated repetition periods analogous to sinusoidal stimuli. Analogous to findings in the auditory domain, these results suggest that tactile pitch perception primarily depends on stimulus periodicity rather than the physical presence of the fundamental frequency itself [15], [16]. To our knowledge, this represents the first demonstration of this phenomenon within the tactile modality.

This finding contributes to the growing evidence of perceptual parallels between auditory and vibrotactile systems. Furthermore, leveraging the missing fundamental effect offers a promising strategy to create lower-frequency vibrotactile pitches without the need to generate large-displacement, low-frequency vibrations, which can be difficult and energy-intensive to produce based on the vibrotactile equal-loudness contour. By employing this technique, achievable also through amplitude-modulated waveforms [26] lower tactile pitches could be produced efficiently with significantly reduced amplitude requirements.

D. The physiological mechanism of vibrotactile pitch

One proposed mechanism for vibrotactile pitch perception is the ratio hypothesis [27], which suggests that pitch is determined by the relative activation of Meissner and Pacinian corpuscles. These mechanoreceptors have distinct frequency tuning: in humans, Meissner corpuscles are most sensitive to

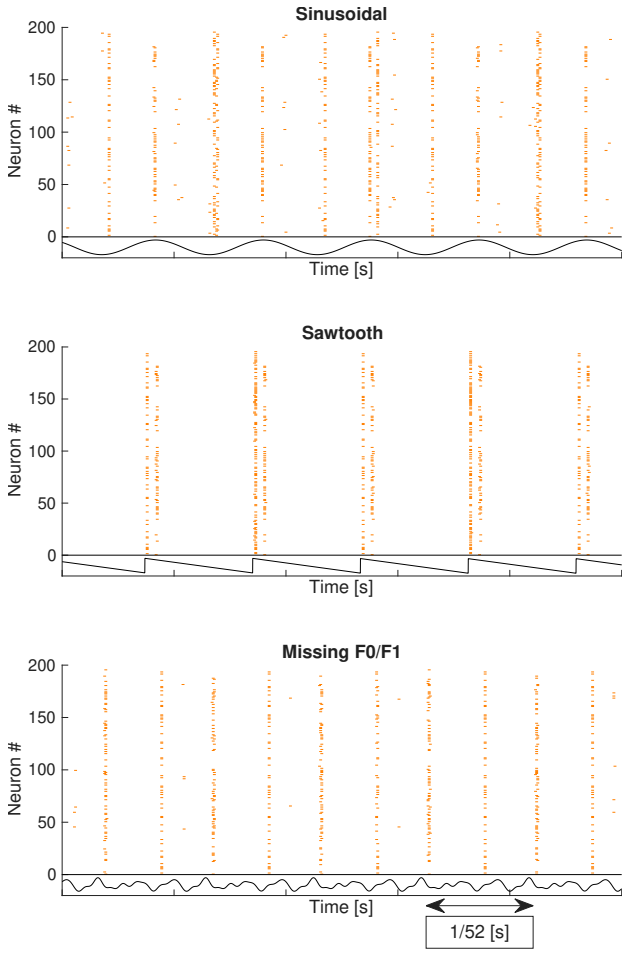

Fig. 6. Modeled neuronal responses to a) sinusoidal, b) Sawtooth, c) Missing F0/F1 waveforms with a (fundamental) frequency of 52 Hz, using TouchSim.23 The figure shows the activation pattern of 200 PCs along the different waveforms. Notably, the Sawtooth waveform elicited pronounced neural activations corresponding to abrupt slope transitions, while waveforms lacking fundamental frequency energy still produced activation patterns reflecting their periodicity.

vibrations between 5 and 50 Hz, while Pacinian corpuscles are tuned to the higher range from 40 to 800 Hz, with peak sensitivity at 250 Hz [13]. According to the ratio hypothesis, lower frequency stimuli would primarily activate Meissner corpuscles and higher frequency stimuli would increasingly recruit Pacinian corpuscles. Vibrotactile pitch, under this framework, would be encoded by the relative contribution of each receptor population.

If this hypothesis held, we would expect a systematic increase in perceived pitch across stimuli that shift energy toward higher frequencies, for example, from sinusoidal to Missing F_0, then Missing F_0/F_1, and finally to AM stimuli, which contain only high frequency components within the Pacinian range. Furthermore, as soon as the frequency content of the stimuli lies entirely above the Meissner range, such that only Pacinian corpuscles are stimulated, any further change in spectral content should not affect perceived pitch. That is, pitch perception should plateau once Meissner activity is minimal or absent.

However, our results do not align with this prediction. We observed similar pitch percepts for sinusoidal and Missing F_0/F_1 stimuli, despite large differences in their spectral content and presumed receptor activation patterns. More critically, AM stimuli, composed entirely of high frequency carriers within the Pacinian range, showed clear changes in perceived pitch as a function of modulation frequency. This contradicts the expectation that pitch should remain constant once only the Pacinian channel is engaged. A similar pattern was observed in Experiment 1, where changes in frequency continued to affect perceived pitch even in a range that would exclusively stimulate Pacinian corpuscles.

While these findings argue against a strict implementation of the ratio hypothesis, we cannot fully rule it out. The hypothesis was originally formulated based on responses to sinusoidal stimuli, and it is possible that, with more complex signals, the skin and somatosensory system act as a low pass filter, effectively extracting the temporal envelope. This would shift the relevant energy toward the fundamental frequency or modulation rate, potentially explaining the observed alignment in pitch percepts across stimuli with very different spectra. Nonetheless, the failure of perceived pitch to plateau once Meissner input is presumably absent challenges the idea that vibrotactile pitch is determined solely by the relative activation of these two afferent populations.

E. Perception of tactile roughness and pleasantness

Roughness, an important attribute linked to musical dissonance, exhibited significant effects of waveform but was highly idiosyncratic across participants. Unlike auditory roughness, which relies on temporal fluctuations, tactile roughness is often influenced by spatial texture cues, such as fine surface details experienced during hand movement [21]. In our experiment, however, roughness was conveyed purely through temporal cues, as participants interacted with a smooth snooker ball as the contact surface. This setup created a novel and unfamiliar task, likely contributing to the response variability.

Nevertheless, the inter participant variability could be attributed to consistent personal preferences, as roughness judgments showed a negative correlation with pleasantness, mirroring findings in auditory perception where rougher stimuli are generally rated as less pleasant [21], [22]. Waveforms influenced both roughness and pleasantness rating similarly. Waveforms with sharper edges, like the sawtooth and irregularity like the AM stimuli, were perceived as both rougher and less pleasant compared to smoother waveforms like the sinusoidal or harmonic complex, Figure 3. High frequency components, often linked to harshness in auditory perception, appeared to play a similar role in tactile perception [21].

F. The perception of the fast envelope instead of the fine structure

In auditory science, signals can be conceptually decomposed into two complementary components: the temporal envelope and the temporal fine structure. The temporal envelope refers to the slowly varying amplitude modulation of the waveform, capturing broad fluctuations that guide perceptual attributes such as rhythm, speech intelligibility, and overall loudness.

Conversely, the temporal fine structure encompasses the rapid, cycle by cycle fluctuations within the waveform, crucial for precise pitch perception, source localization, and discerning complex auditory scenes. Cochlear implant users, who rely predominantly on envelope information due to technological limitations in encoding fine structure, often exhibit significant deficits in perceiving pitch nuances and understanding speech in noisy environments [15].

Similarly, our tactile stimuli can be analyzed using this decomposition. However, the distinction between envelope and fine structure in tactile signals depends on the chosen temporal resolution. In this study, we adopted a high temporal resolution, defining a fast temporal envelope that accurately follows rapid amplitude transitions, such as those in a sawtooth waveform. Our results consistently demonstrate the critical role of this fast temporal envelope in tactile perception. Specifically, the prominence of pitch and roughness perception observed with sharp edged waveforms like the sawtooth highlights the envelope's significance. Moreover, the tactile equivalent of the auditory missing fundamental phenomenon observed in our experiments further supports the conclusion that vibrotactile pitch perception primarily relies on the periodicity conveyed by the fast envelope rather than on detailed fine structure elements.

G. Limitations of the study

This study provides valuable insights into the potential of tactile stimuli to convey musical information, but several limitations must be acknowledged.

First, the equal intensity setting for the stimuli was critical to control for the interaction between frequency and intensity in the tactile domain [28], [40]. Individual calibration was performed to ensure that all stimuli were perceived at consistent intensity levels across participants. However, this approach introduces challenges for real world applications, where music dynamically varies in both intensity and frequency. It remains unclear how well such calibrations would translate to dynamic musical contexts or whether additional adjustments would be necessary to maintain perceptual consistency.

Second, the stimuli were presented in isolation, which does not reflect the complex nature of music. In audition, multiple tones can be perceived concurrently, with mechanisms such as auditory stream segregation enabling the distinction of overlapping musical lines. This process relies on the cochlea's ability to decompose signals into separate frequency bands. Tactile perception, however, lacks an equivalent mechanism, and it is uncertain whether a single actuator could effectively convey multiple tactile pitches simultaneously. This limitation suggests that simultaneous tactile pitches may not be feasible with single point vibration sources, highlighting the need for multi actuator setups or other innovations to approximate the polyphonic richness of music.

Lastly, judging the perceived frequency of a vibration is an unusual task. Unlike auditory frequency, which plays a crucial role in music perception and speech processing, tactile frequency perception lacks similar everyday relevance, likely contributing to the observed large variability among participants.

H. Impact for developing a tactile device

For the tactile stimuli, we found that many participants showed similar response slopes to those in the auditory condition, suggesting that the perception of musical pitch can extend to touch. This supports the idea that tactile melodies are feasible and that vibration based devices could be used for music perception. Although the tested frequency range, 40 to 750 Hz, is narrower than the full auditory range of 27.5 Hz to 4186 Hz in Western music, a meta analysis of $10{,}000$ piano solo pieces revealed that most notes played fall within 262 to 523.5 Hz, $C4$ to $C5$, which is within the tactile sensory spectrum [32].

To perceive the higher notes, outside the tactile range, music could be pitch shifted down by one or two octaves [33], [34]. However, this approach assumes that participants will perceive the differences between notes with the same magnitude as in the auditory modality. When considering the average slope across all participants, it was significantly reduced. Additionally, just noticeable differences for frequency are larger than the auditory just noticeable difference, even among experienced musicians [35]. This implies that a tactile melody may not be perceived in the same way as an auditory melody, but rather as a compressed version. To mitigate this effect, one potential solution is to stretch the melody temporally, as tested by Aker et al. [36]. The degree of stretching would need to be carefully calibrated so that stimuli presented an octave apart are perceived as the same musical note.

Our findings provide valuable insights for designing tactile devices aimed at conveying musical information. First, the use of complex waveforms, such as harmonic complexes or sawtooth waveforms, can enhance the clarity of perceived frequency by leveraging the tactile system's ability to interpret periodicity and harmonic structure. Additionally, since roughness and pleasantness were influenced by waveform and frequency, devices could dynamically adjust these parameters to evoke specific emotional or musical effects, such as creating tension through rougher waveforms, such as AM stimuli, or resolving it with smoother, more pleasant stimuli, such as harmonic complex.

The observed negative correlation between roughness and pleasantness highlights the importance of balancing these factors when designing tactile feedback. For example, using sinusoidal or harmonic complex waveforms could prioritize pleasantness for general music playback, while sharper waveforms, such as the sawtooth, might be reserved for encoding dissonance or tension. Furthermore, frequency range adjustments, such as pitch shifting music down by one or two octaves, could align the signal with the most salient frequencies in the tactile modality, while preserving the overall structure of musical content.

Finally, future tactile devices should account for individual differences in tactile perception by incorporating customizable calibration routines. Such routines could optimize stimulus intensity, waveform selection, and frequency presentation based on user specific thresholds and preferences. Incorporating multi actuator systems could also help overcome the limita-

tions of single point stimulation by enabling more complex spatial patterns, approximating the richness of auditory stream segregation in music.

IV. Conclusions

We explored the potential of tactile stimuli to convey key aspects of musical information, including pitch, roughness, and pleasantness. By investigating the tactile perception of sinusoidal and complex waveforms, we assessed whether tactile devices can replicate critical elements of music perception for individuals who cannot rely on hearing.

Our findings suggest that tactile stimuli can effectively convey certain musical dimensions. Approximately two thirds of participants perceived frequency in a manner similar to auditory pitch, with a linear relationship between perceived frequency and the logarithm of the presented frequency. Additionally, waveforms with harmonic content were found to enhance the clarity of frequency perception, highlighting the importance of waveform design in tactile pitch representation.

For roughness and pleasantness, individual variability was more pronounced, particularly in the tactile modality. While roughness judgments were influenced by frequency and waveform, these effects were idiosyncratic. However, the observed negative correlation between roughness and pleasantness aligns with auditory findings, suggesting that tactile roughness could serve as a proxy for dissonance in musical applications.

Despite these promising results, several challenges remain. The narrower frequency range of tactile perception, the reduced sensitivity to frequency changes, and the limited ability to present overlapping signals with single point actuators highlight the need for further advancements in tactile technology. Finally, our findings reinforce the importance of distinguishing between the fast temporal envelope and the temporal fine structure in vibrotactile perception. Therefore, future tactile musical interfaces should focus on optimizing the fast envelope to effectively convey musical dimensions, thereby enhancing the tactile experience of music for hearing impaired users.

V. Methods

A. Participants

A total of 32 participants took part in the study (12 in the auditory group and 20 in the tactile group, 18 female, mean age = 28.3 years, range = 20–42). All participants reported normal hearing and normal tactile sensitivity, and none reported neurological disorders. All provided informed written consent before participation. The study was approved by the Ethics Committee of the University of Geneva and conducted in accordance with the Declaration of Helsinki.

B. Stimuli

All stimuli were generated in MATLAB (MathWorks, Natick, USA) at a sampling rate of 44.1 kHz and presented either auditorily through headphones (Sennheiser HD 650) or as vibrations via a voice-coil tactile actuator (C2 Tactor, Engineering Acoustics, USA). For auditory stimuli, intensities were set at 60 dB SPL and equalized across frequencies. For tactile stimuli, amplitudes were calibrated for each participant to achieve equal perceived intensity across all conditions (see below).

1) Sinusoidal stimuli: For Experiment 1, stimuli consisted of pure sinusoidal tones at frequencies ranging from 40 to 750 Hz in logarithmic steps.

2) Complex stimuli: For Experiment 2 and onward, six different waveform types were created at three fundamental frequencies ($F_0 = 52, 73$, and 98 Hz):

1) Sinusoidal
2) Sawtooth
3) Harmonic complex (harmonics attenuated by 3 dB/octave, randomized phase)
4) Missing F_0 (first harmonic removed)
5) Missing F_0/F_1 (first two harmonics removed)
6) Amplitude Modulated (AM) signal with a 500 Hz carrier and modulation rate equal to F_0

Each stimulus was 500 ms in duration with 10 ms onset/offset ramps to avoid transients. Example waveforms and spectrograms are shown in Figure 2.

C. Apparatus and Procedure

Tactile stimuli were delivered to the glabrous skin of the left hand (index fingertip) using a rigid coupling to the tactor. Participants rested their hand on a smooth snooker ball to minimize spatial texture cues. The auditory group was tested in a sound-attenuated booth.

Each trial consisted of a single stimulus presentation, after which participants rated the stimulus on a continuous visual analog scale displayed on a computer monitor. Three tasks were tested across different blocks:

1) Perceived frequency (Experiment 1–2)
2) Roughness (Experiment 3)
3) Pleasantness (Experiment 4)

For perceived frequency, participants were instructed to judge the perceived repetition rate or "how fast the vibration oscillates." For roughness, they were asked to rate the irregularity or harshness of the stimulus. For pleasantness, they rated overall liking.

D. Equal Intensity Calibration

Because tactile detection thresholds vary strongly with frequency [40], we equalized perceived intensity across frequencies and waveforms. Before each session, participants performed a magnitude estimation task relative to a reference sinusoidal vibration at 280 Hz. Stimulus amplitudes were adjusted by an adaptive procedure until all stimuli were matched in perceived intensity to this reference. The resulting equal-intensity settings were then used in the main experiments.

E. Data Analysis

All ratings were normalized within participants to account for individual scale usage. Linear regressions were fitted to perceived frequency judgments, and model comparisons (linear vs quadratic vs null) were conducted using ANOVAs

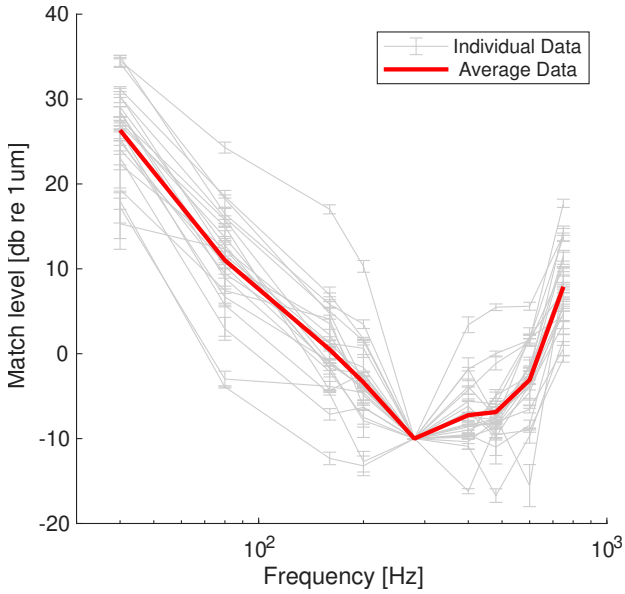

Fig. 7. Figure 7 Equal intensity matches for tactile stimuli. Grey lines represent individual participants, while the thick red line represents the median response.

with Bonferroni corrections. Group-level effects were analyzed with repeated-measures ANOVAs (within-subject factors: Waveform and Frequency). When appropriate, post-hoc pairwise comparisons were Bonferroni corrected. Effect sizes are reported as R^2. Correlations between roughness and pleasantness were computed for each participant across the 27 stimuli, yielding $df = 26$. Only correlations significant at $p < 0.05$ are reported in Figures 4 and 5.

F. Equal-Perceived-Intensity Matching

To investigate the influence of frequency on vibrotactile pitch, it was critical to individually calibrate the intensity of diverse stimuli, each played at a different frequency, to achieve a uniform perceived intensity. While the threshold profile serves as an initial approximation, pilot studies indicated that this method was insufficient. Thus, we introduced a new condition in which participants were required to adjust the intensity of various sinusoidal signals to match the perceived intensity of a reference signal. This reference signal was a 280 Hz tone played at -10 dB [re 1 µm]. Our perceived intensity balancing method mirrored the procedure established in McKay and McDermott. The stimulus to be balanced and the reference stimulus were presented, separated by a 500-ms silent interval, in a randomized order, in a two-interval forced-choice task following a 1-up 1-down adaptive rule. Participants were instructed to determine which stimulus appeared stronger, disregarding perceived frequency differences. If the reference was selected as stronger, the intensity of the stimulus to be balanced was increased, and vice versa. We initially set the step size at 5 dB, which was later reduced to 2 dB after two reversals. The test concluded after six reversals in total. The balanced stimulus level was calculated by averaging the final two reversal points.

We repeated this balancing run with different starting levels: one 5 dB above and one 5 dB below the predicted level. To mitigate potential bias, the roles of the reference and balanced stimuli were reversed in two additional runs. The final balanced level was established by averaging across all four runs. The tested frequencies were: 40, 80, 160, 200, 400, 480, 600, and 750 Hz.

G. Tactile Threshold Screening

A tactile threshold screening was conducted prior to the experiment to ensure that all participants had sensitivity within the normal range. Thresholds were measured using sinusoidal vibrations at frequencies between 40 and 750 Hz, delivered via the piezoelectric actuator. A two-interval forced-choice procedure with a 1-up 2-down adaptive rule was used to estimate the detection threshold for each frequency. Participants with thresholds exceeding 20 dB above the median were excluded from the study.

H. Setting the Intensity for the Complex Stimuli

For the complex tactile stimuli, the intensity of each waveform was set by a panel of six expert participants familiar with vibrotactile psychophysics. Each expert rated the perceived intensity of the stimuli, and adjustments were iteratively made until a consensus was reached that the stimuli were matched in overall intensity across waveform types. This procedure ensured that differences in participant ratings could not be attributed to residual differences in perceived intensity between stimuli.

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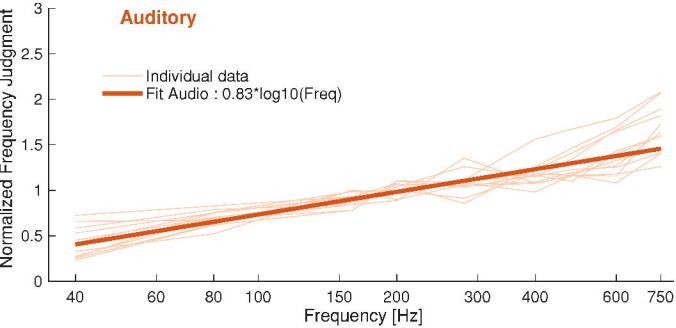
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Frequency [Hz]
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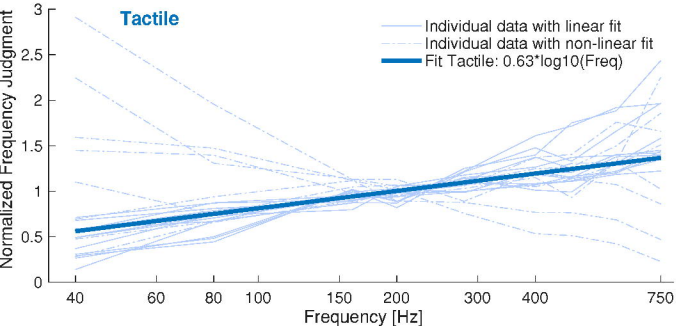
Tactile
Individual data with linear fit
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Normalized Frequency Judgment
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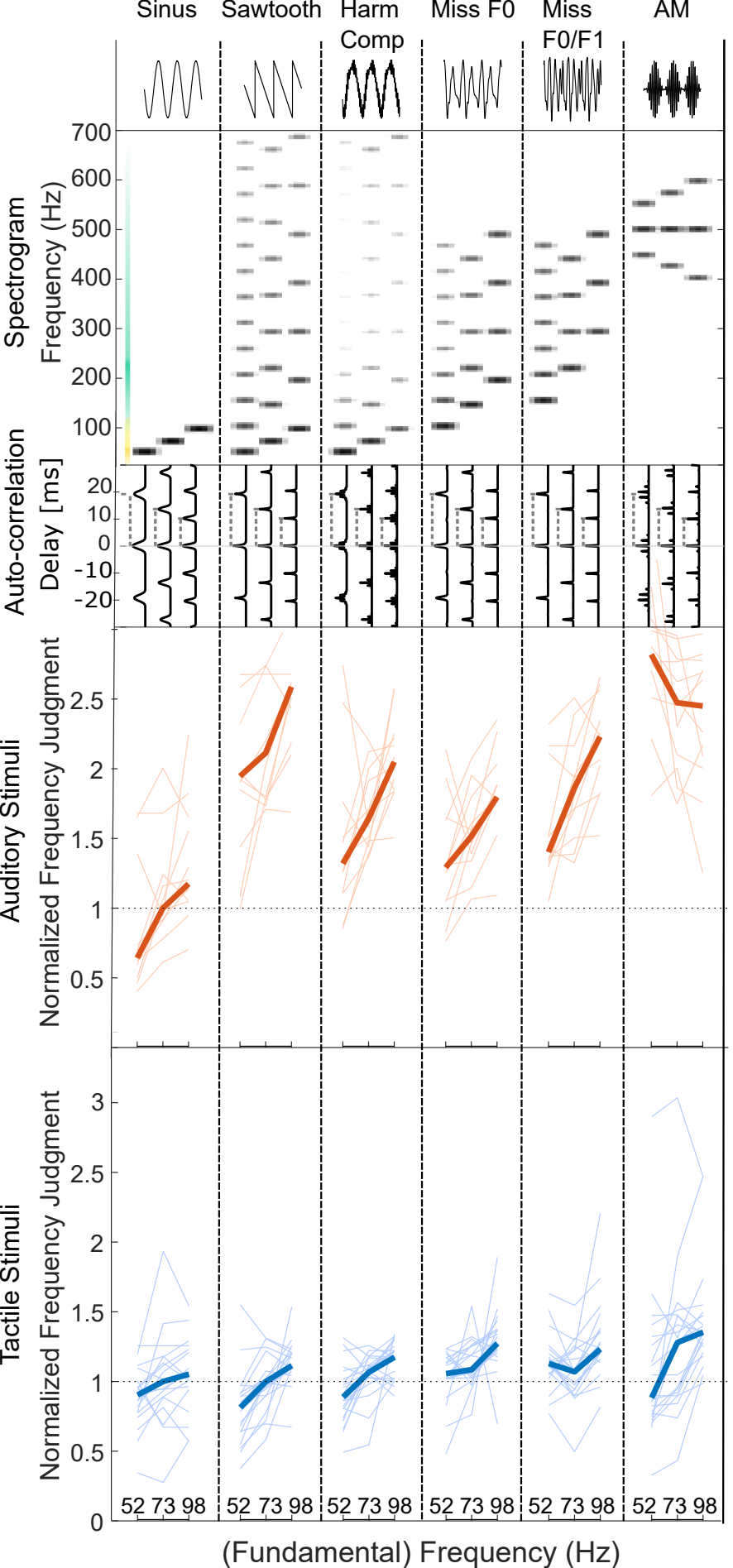
Sinus
Sawtooth
Harm Comp
Miss F0
Miss F0/F1
AM
Spectrogram
Frequency (Hz)
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600
500
400
300
200
100
Auto-correlation
Delay [ms]
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10
0
-10
-20
Auditory Stimuli
Normalized Frequency Judgment
2.5
2
1.5
1
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1
0.5
0
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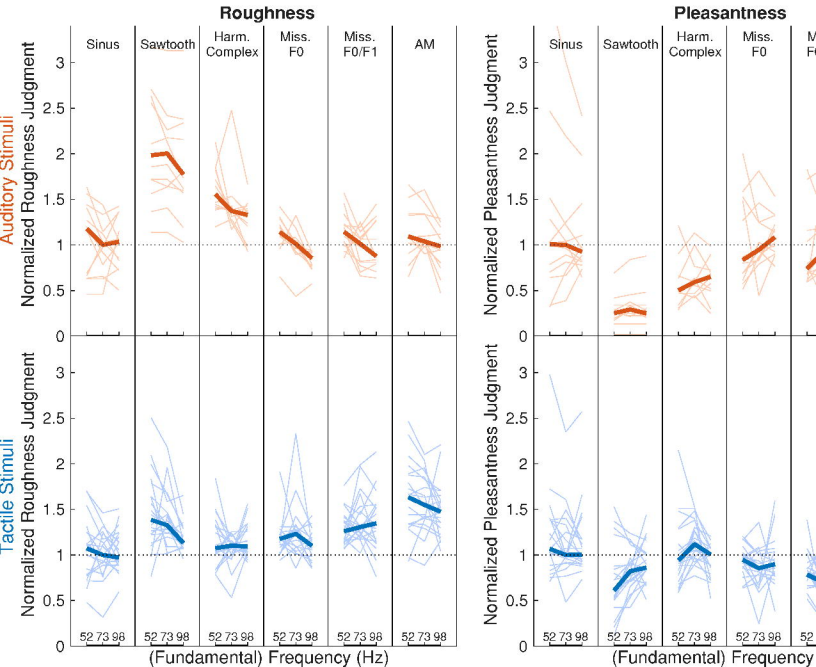
(Fundamental) Frequency (Hz)


Roughness
Pleasantness
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Miss. F0
Miss. F0/F1
AM
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Normalized Pleasantness Judgment
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0.5
1
1.5
2
2.5
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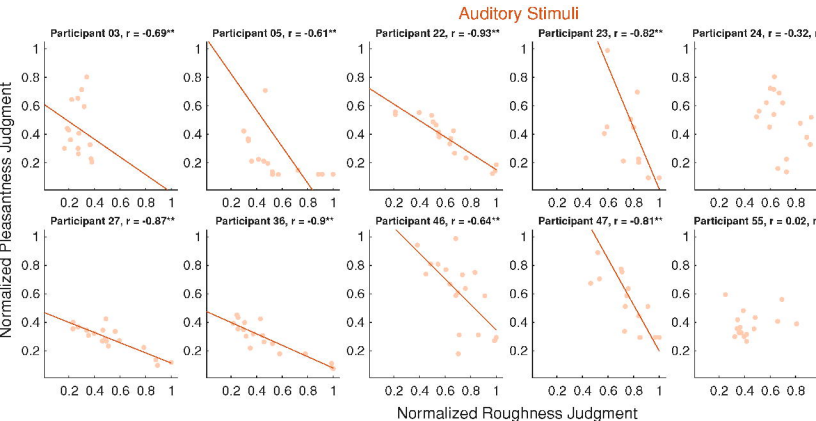
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Participant 24, r = -0.32,
Participant 27, r = -0.87**
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Participant 46, r = -0.64**
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Normalized Roughness Judgment
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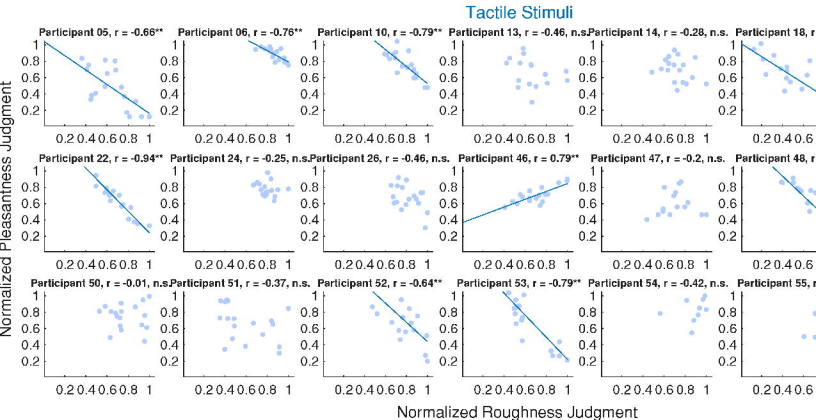
Tactile Stimuli
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Participant 10, r = -0.79**
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Participant 18, r
Participant 22, r = -0.94**
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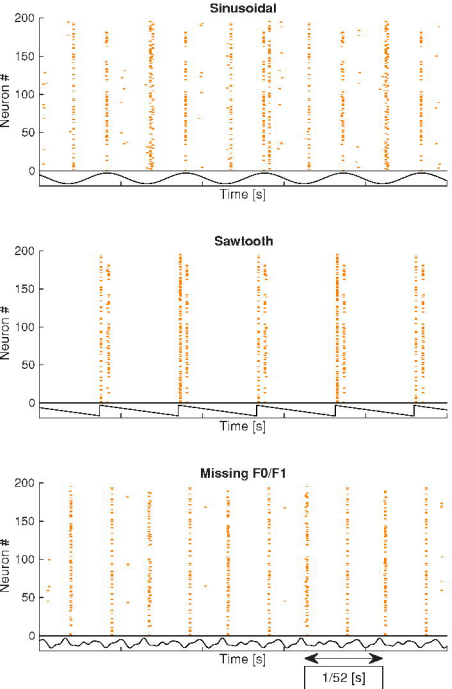
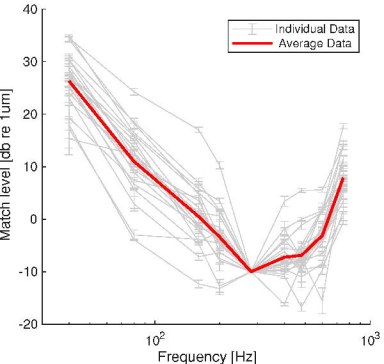
Participant 26, r = -0.46, n.s.
Participant 46, r = 0.79**
Participant 47, r = -0.2, n.s.
Participant 48, r
Participant 50, r = -0.01, n.s
Participant 51, r = -0.37, n.s.
Participant 52, r = -0.64**
Participant 53, r = -0.79**
Participant 54, r = -0.42, n.s.
Participant 55, r
Normalized Pleasantness Judgment
Normalized Roughness Judgment


Sinusoidal
Neuron #
200
150
100
50
0
Time [s]
Sawtooth
Neuron #
200
150
100
50
0
Time [s]
Missing F0/F1
Neuron #
200
150
100
50
0
Time [s]
1/52 [s]


Individual Data
Average Data
Match level [db re 1um]
Frequency [Hz]
40
30
20
10
0
-10
-20
10^2
10^3