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Tactile perception of auditory roughness

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Abstract: Auditory roughness resulting from fast temporal beatings is often studied by summing two pure tones with close frequencies. Interestingly, the tactile counterpart of auditory roughness can be provided through touch with vibrotactile actuators. However, whether auditory roughness could also be perceived through touch and whether it exhibits similar characteristics are unclear. Here, auditory roughness perception and its tactile counterpart were evaluated using pairs of pure tone stimuli. Results revealed similar roughness curves in both modalities, suggesting similar sensory processing. This study attests to the relevance of such a paradigm for investigating auditory and tactile roughness in a multisensory fashion. © 2022 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).

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1. Introduction

Auditory roughness is a fundamental acoustical attribute due to fast fluctuations of sounds perceived when a carrier pure tone is modulated in amplitude at a frequency above around 15 Hz (Zwicker and Fastl, 2013). In complex sounds, roughness conveys emotions (Arnal *et al.*, 2015), drives musical consonance (Helmholtz, 1885; Plomp and Levelt, 1965), and shapes orchestral timbres (Pressnitzer *et al.*, 2000). It is also at the basis of the definition of critical bands (Terhardt, 1974), a fundamental property of cochlear filters characterizing the ability of the cochlea to separate two pure tones. Auditory roughness has, therefore, led to a significant body of work in psychoacoustics to identify the acoustic factors that modulate this auditory sensation.

To unveil the mechanisms underlying auditory roughness perception, studies have used combinations of monochromatic tones (Miśkiewicz *et al.*, 2006), also called pure tones, made of single sinusoidal signals. A combination of two monochromatic tones can indeed create amplitude modulations that induce a sensation of roughness depending on the frequency spacing between the two tones, also described as the frequency ratio between the two frequencies. The roughness of such sounds increases until reaching a maximum and then decreases as the frequency ratio between the two frequencies increases, as presented in Fig. 1. Since auditory roughness is often described as an attribute that characterizes very fast fluctuations in sounds, pure tones are perfect candidates to investigate such a sensation. Previous studies based on frequency ratios between such sounds have led to models of perceived auditory roughness (Daniel and Weber, 1997; Vassilakis, 2001; Leman, 2000).

On the other hand, for the tactile modality, surface roughness refers to one of the principal perceptual attributes used to describe textures explored with the finger (Tiest and Kappers, 2006). Perceived surface roughness is defined by the physical and geometrical properties of the textures, such as the height and the density of the asperities (Taylor and Lederman, 1975; Stevens and Harris, 1962). Typical stimuli for surface roughness evaluation are sandpapers with various grit sizes. Interestingly, observations showing that the perceived surface roughness depends on the spatial frequency and the amplitude of the haptic signal have been made on synthetic textures with new haptic touchscreen technologies (İşleyen *et al.*, 2020; Bodas *et al.*, 2019).

The investigation of audio and tactile roughness perception also refers to a series of works where detection thresholds of modulated monochromatic sounds or vibrations have been studied (Formby *et al.*, 1992). Such studies allow the derivation of so-called temporal modulation transfer functions (TMTFs), which revealed a maximum of sensitivity around 40 Hz of modulation (Weisenberger, 1986). In addition, auditory and vibrotactile performances were similar around this frequency, whereas auditory performances were better for frequencies above and below (Formby *et al.*, 1992).

In a recent review on multimodal roughness perception, Di Stefano and Spence (2022) made a clear distinction between auditory roughness and surface roughness: auditory roughness is a temporally based perceptual property that is

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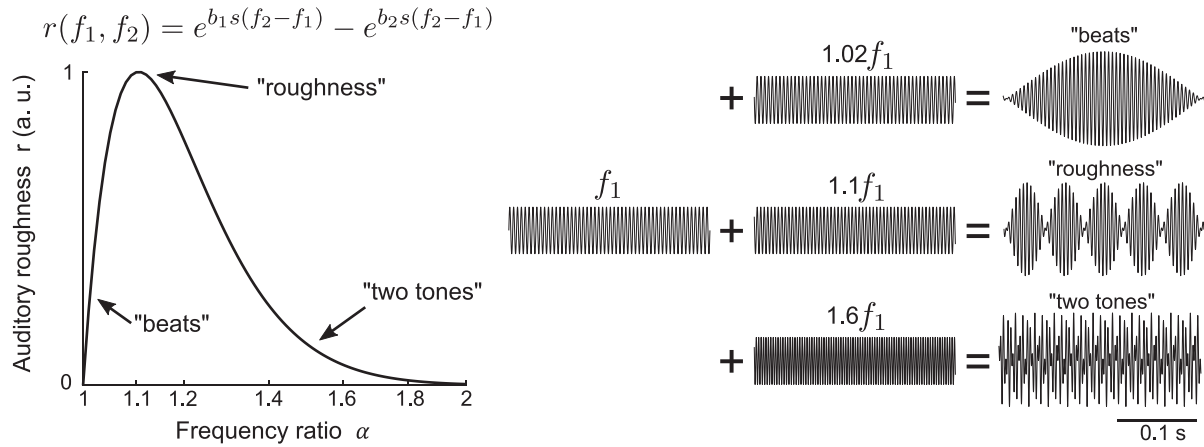


Fig. 1. Typical auditory roughness perception according to the frequency ratio of a sum of two pure tones: $s(t) = \sin(2\pi f_1 t) + \sin(2\pi f_2 t) = 2\sin(2\pi((f_1 + f_2)/2)t)\sin(2\pi((f_2 - f_1)/2)t)$. When the frequency ratio $\alpha = f_2/f_1$ is small, the combination of tones tends to be perceived as one tone slowly modulated by the other one, a sensation that is characterized as beats. When the frequency ratio increases, a sensation of roughness appears. As α becomes even larger, the perceived roughness decreases until the two tones are perceived separately. The theoretical auditory roughness curve in the left part of the figure is defined with the parameters $b_1 = 3.5$, $b_2 = 5.75$, $s = 0.24/(s_1 f_1 + s_2)$, $s_1 = 0.0207$, and $s_2 = 18.96$ (Vassilakis, 2001).

experienced through hearing, while surface roughness is spatiotemporal, related to textures, and assessed by touch (and vision). However, whether the sensation of auditory roughness as investigated through the auditory system could also be experienced through touch is still unclear.

In this paper, we investigate the tactile counterpart of auditory roughness using the same couple of pure tone signals in both modalities. In the auditory domain, stimuli were presented through headphones while a vibrotactile actuator was used in the tactile domain. The experiment was carried out in two sessions, one with auditory stimuli and the other with tactile stimuli. The goal was to determine the relationship between the roughness sensation and the frequency ratio of two different pure tones to compare the roughness curves in both modalities. Showing such a coherence would suggest that hearing and tactile sensory systems share similar processes. This would also validate these stimuli for further investigations in a multisensory context.

2. Methods

2.1 Participants

Eighteen participants [eight women, median (Mdn) = 25.5 years old, interquartile range (IQR) = 7, between 21 and 57 years old], 15 right-handed, 14 musicians, voluntarily took part in the experiment. None of them reported having any auditory problems or skin concerns. The participants gave their informed consent before the experiment. The experiment was divided into two sessions of about 30 min each separated by a short break. The experimental protocol was approved by the local ethical committee.

2.2 Stimuli

The experiment was composed of two sessions: one auditory and one tactile. The same signals were used for both modalities, and the stimuli were constructed by combining two monochromatic tones: $s(t) = \sin(2\pi f_1 t) + \sin(2\pi f_2 t)$ of frequencies f_1 and $f_2 = \alpha f_1$. Four frequency conditions were arbitrarily considered ($f_1 = 50, 100, 200,$ and 300 Hz). The experimental design did not include higher frequency conditions since frequencies above 800 Hz are not perceptible by the human tactile sensory system (Verrillo, 1969). The frequency ratio α ranged from 1 to 2. When $\alpha = 1$, $f_1 = f_2$, the tones are in unison; when $\alpha = 2$, $f_1 = 2f_2$, the tones are separated by one octave. Twelve values of α were chosen (1, 1.01, 1.02, 1.03, 1.05, 1.10, 1.15, 1.20, 1.25, 1.35, 1.50, and 2.00). The range was non-linearly sampled to provide a finer sampling in the portions where the roughness is more likely to vary a lot according to the literature, i.e., for values below 1.5. For each frequency condition, stimuli with different α values were compared pairwise, leading to 66 pairs. Overall, each participant performed two sessions with four blocks of 66 pairs, which led to 528 trials.

2.3 Apparatus

Sounds were presented through Sennheiser HD-650 headphones at a sampling rate of 44 100 Hz powered by a Pioneer (Tokyo, Japan) A-209R audio amplifier. Tactile stimuli were presented through an Actronika (Paris, France) HapCoil-One vibrotactile actuator (dimensions, $11.5 \times 12 \times 37.7$ mm³; maximal acceleration, 8 g peak-to-peak; frequency bandwidth,

10–1000 Hz; resonant frequency, 65 Hz). This kind of actuator has already been used in the literature to render the sensation of textures with vibrations (Rocchesso *et al.*, 2016). The actuator was powered by a Pioneer A-209R audio amplifier. The participants were asked to grab the vibrotactile actuator between the thumb and the index finger of their right hand. During the tactile experiment, participants wore noise-canceling headphones to prevent them from using potential auditory cues produced by the tactile device to perform the task.

2.4 Control measurements

To ensure replicability, control measurements were performed with a calibrated bench composed of an artificial ear (artificial ear 4153 with DB0843 and YT0304 adaptors, Brüel & Kjær, Nærum, Denmark), a free-field microphone (type 4190 No. 2009277, Brüel & Kjær), a pre-amplifier (type 4138, Brüel & Kjær), a signal conditioner (type 1708, Brüel & Kjær), and an acquisition card with a 20 dB gain (Fireface UCX, RME, Haimhausen, Germany). The Sennheiser (Wedemark, Germany) headphones were placed on the artificial ear to measure the intensity of each audio stimulus. The measures were performed on both headphones' ears and then averaged. The sound levels were on average 78.0 dB sound pressure level (SPL) [standard deviation (SD) = 2.25], which is largely above the hearing threshold. The detailed measurements are presented in supplementary Table 1.¹

The input voltage for the vibrotactile actuator was measured for each tactile stimulus with an acquisition card (USB-6003, National Instruments, Austin, TX). The detailed measurements for replicability are presented in supplementary Table 2.¹

Finally, noise-canceling headphones were placed on the artificial ear while tactile stimuli were played by the vibrotactile actuator held by the experimenter's fingers at a 60 cm distance from the artificial ear. The measures were repeated five times and averaged. The sound levels of the actuator behind the noise-canceling headphones were, on average, 42.4 dB SPL (minimum = 40.7, maximum = 44.3, SD = 0.97 among stimuli), which does not emerge from the background noise at 42.6 dB SPL. The tactile stimuli were, therefore, not hearable.

2.5 Task and procedure

Participants were seated in front of a computer screen in a quiet room. They started randomly with either the audio or tactile session. The experiment was a pairwise comparison. At each trial, two stimuli with different values of α were presented successively. The stimuli lasted for 1 s, and pairs were sequentially presented with an inter-stimulus interval of 800 ms. For each pair of stimuli, the participants were asked to determine which stimulus was the most "granular" ("granuleux" in French). We avoided the terms "rough" and "pleasant" that are commonly used in the literature since several participants had a musical background that could have influenced their judgment. For each participant, the four blocks and the stimuli within each block were presented in a randomized order, and for each pair, the presentation order was also randomized. Responses were collected with a keyboard, and the interface was designed with Max/MSP software to provide either audio or tactile stimuli. The volume and the intensity of auditory and tactile stimuli were set constant during the whole experiment.

2.6 Data analysis

Based on the participant's responses, each stimulus was assigned a score of perceived auditory roughness. This score is the ratio of the number of times participants judged the stimulus as rougher to the number of times the stimulus was presented in the pairwise comparison (=11). For one participant, if a stimulus of a given α value has been judged N times as more "granular" than another, its roughness score (r) equals $N/11$. Finally, for each participant, each modality, and each f_1 condition, roughness curves characterizing the roughness score evolution with respect to the α value were computed.

3. Results

First, the results showed that the roughness curves obtained were coherent with the theoretical roughness curve proposed by Vassilakis (2001) and Leman (2000). This validates the present protocol for roughness score measurement {correlations between the 8 mean curves (2 modalities \times 4 frequency ratio conditions) and the theoretical curves: $r(9)$: $M = 0.89$, range = [minimum = 0.83, maximum = 0.97], all $p < 0.001$ } (see Fig. 2).

Most importantly, the results revealed that auditory and tactile modalities provide similar roughness curves in the four frequency conditions tested (see Fig. 2). We observed a significant correlation between the tactile and auditory roughness mean curves for the four conditions [Pearson correlations: $f_1 = 50$ Hz: $r(9) = 0.94$, $p = 4.7 \cdot 10^{-6}$, $BF_{10} = 5e^{-3}$; $f_1 = 100$ Hz: $r(9) = 0.97$, $p = 2e^{-7}$, $BF_{10} = 9e^4$; $f_1 = 200$ Hz: $r(9) = 0.92$, $p = 1.7e^{-5}$, $BF_{10} = 1.7e^3$; $f_1 = 300$ Hz: $r(9) = 0.94$, $p = 3.9e^{-7}$, $BF_{10} = 6.5e^3$].

Last, to assess potential differences between the two modalities, we computed the differences between auditory and tactile roughness scores for each frequency condition f_1 and α values and for each participant. This resulted in a population of 864 samples, whose mean does not significantly differ from 0 { t -test: $t(863) = 1e^{-15}$, $p = 1$, confidence interval (CI) 95% = [-0.0149; 0.0149]}, showing that there is no significant difference between the audio and tactile roughness curves.

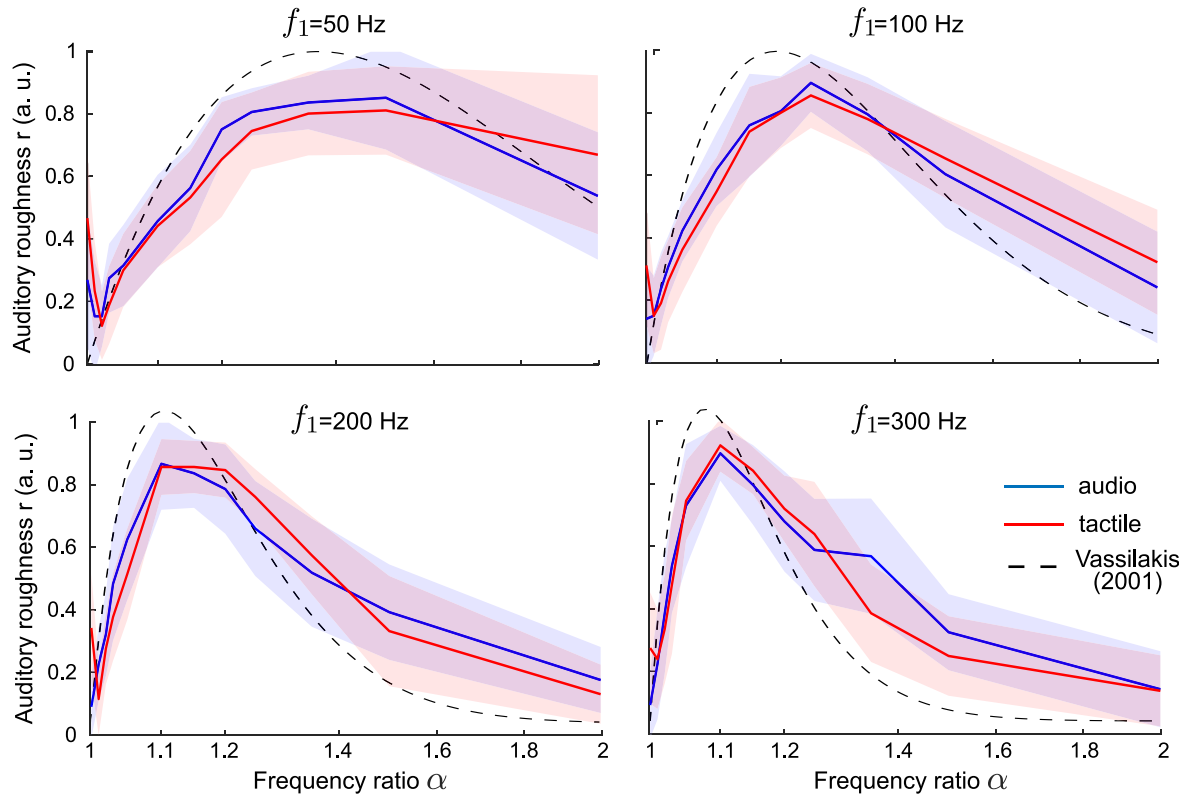


Fig. 2. Audio (blue) and tactile (red) roughness curves obtained from the experiment for the four frequency conditions. Mean across participants is presented in solid lines, and SD is presented with the shaded zones. The black dashed lines depict the theoretical auditory roughness model proposed by Vassilakis (2001).

4. Discussion

In this paper, auditory roughness perception induced by temporal beatings was compared between the auditory and the tactile sensory systems. In one experiment with two sessions, participants had to compare the roughness of pairs of sounds or tactile vibrations parametrized by the ratio between the frequencies of two monochromatic components. Roughness curves were then computed for both modalities and were found to be similar in the two modalities and with the theoretical auditory roughness model.

Auditory roughness curves are coherent with the model of Vassilakis (2001). Interestingly, we observe the same curves in the tactile modality. In particular, the position of maximal roughness perception changes according to the lower frequency f_1 . It would, therefore, be of interest now to further investigate the multimodal process of auditory roughness perception. It may indeed lead to a common process between the two modalities, and the critical band framework (Makous *et al.*, 1995) could also be relevant in the tactile domain. It could also be interesting to investigate whether perceived roughness relates to the consonance of vibrotactile stimuli (Yoo *et al.*, 2014) in touch as with audition, supporting the idea of crossmodal harmony (Spence and Di Stefano, 2022).

It is noticeable that our results suggest a coherence with the maximum of sensitivity of the TMTF measured by Weisenberger (1986) around 40 Hz. Such results can also be interpreted in light of recent neuroscientific results showing that 40 Hz modulated signal provides the best neural excitability within the auditory system (Schneefeld *et al.*, 2022).

Second, this study further sheds light on more fine similarities in the temporal processing of vibrations through these two modalities. One major difference between the two modalities, however, is that for high α values (around 2), audition discriminates the two harmonic frequencies, leading to a perception of two tones, whereas in touch, we perceive only one uniform complex temporal vibration (Bensmaia and Hollins, 2000).

It is worth noticing that auditory roughness curves present similar shapes as surface roughness curves (Unger *et al.*, 2011). This comparison was done by making analogies between the sound beating frequency and the texture spatial frequency (i.e., number of ridges per millimeter). First, for low spatial frequencies, only large undulations of the texture are felt. The surface roughness then increases as the spatial frequency increases until reaching a maximum. Last, surface roughness decreases as the ridge's density highly increases until the texture becomes almost smooth. Although auditory and surface roughness remain two distinct perceptual attributes, this could imply that they are processed with similar underlying mechanisms.

In addition, recent evidence has shown that rhythm perception is shared between audio and haptics even for textures explored through active touch (Bernard *et al.*, 2022). Our current findings suggest that these results could be extended to the perception of beating and temporal roughness.

5. Conclusion

This study provides results for the investigation of audio-tactile roughness under a common framework. The framework classically dedicated to investigating auditory roughness has here been formally validated for the tactile modality. One particularly relevant perspective is the investigation of the multisensory integration of these stimuli in congruent or incongruent situations. We may expect to observe audio-tactile interactions and how one modality can enhance the perception of roughness in the other (Tan *et al.*, 1999). This has already been observed in several multisensory situations (Jousmäki and Hari, 1998; Guest *et al.*, 2002; Yau *et al.*, 2009; Wilson *et al.*, 2009). These cases are of great relevance to understanding the fine mechanistic bases of human perceptual systems.

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¹See supplementary material at <https://www.scitation.org/doi/suppl/10.1121/10.0016603> for supplementary Tables 1 and 2.

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