Audio-Tactile Perception of Roughness

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Abstract. Auditory roughness is a perceptual attribute at the basis of phenomena such as consonance and dissonance in music. The psychophysical correlates of this attribute are often studied by combining two monochromatic tones slightly separated in frequency, leading to more or less rapid beatings. Interestingly, roughness is not limited to the auditory modality and it is possible to evoke the same kind of sensation through the tactile modality by using a vibrotactile actuator. Whether or not audio and tactile modalities share the same perceptual roughness properties is still an open question that may reveal common sensory processes between the two modalities. Here we investigate this question in 2 pairwise comparison experiments unveiling roughness curves in audio and tactile modalities. The results reveal similar roughness curves in both modalities, which suggests a common way of processing and perceiving beatings.

Keywords: Audio-tactile, Roughness, Beatings, Critical bands

1 Introduction

Auditory roughness probes the fundamental ability of audition to disentangle harmonic stimuli, a fundamental skill to perceive speech (Arnal et al., 2015), and music (Helmholtz, 1885; Plomb & Levelt, 1965) properties. This phenomenon can be described as the perception of very fast fluctuations in sounds. To understand how our ears deal with complex mixtures of harmonics (Vassilaki, 2001), a historical body of works has used basic stimuli by combining monochromatic tones. It is now well known that for stimuli composed of two monochromatic tones, the sensation of roughness is driven by the space between the frequencies of the components. The roughness first increases when the frequency ratio between components increases and reaches a maximum before it decreases with respect to the increasing frequency ratio. Figure 1 presents a typical auditory roughness curve for a sum of two monochromatic tones $s(t) = sin(2\pi f_1 t) + sin(2\pi f_2 t)$. 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. When the frequency ratio increases, a sensation of roughness appears. As α

becomes even larger, the perceived roughness falls and two the two tones are perceived separately. This theoretical roughness curve is defined by $r(f_1, f_2) = e^{-b_1 s(f_2 - f_1)} - e^{-b_2 s(f_2 - f_1)}$ with $b_1 = 3.5$, $b_2 = 5.75$, $s = \frac{0.24}{s_1 f_1 + s_2}$, s_1=0.0207 and s_2 = 18.96 (Vassilakis, 2001).
Such a phenomenon reveals the existence of auditory critical bands, a fundamental characteristic of auditory filters (Terhardt, 1974). While the auditory perception of such phenomena has been largely studied, it is not known whether other modalities such as touch, elicit similar behaviors (Makous et al., 1995). Interestingly, it is possible to produce similar stimuli as in auditory experiments with vibrotactile actuators. It would therefore be interesting to check whether roughness perception is shared between auditory and tactile modalities. This would strongly suggest that they might also share mechanistic properties during the processing of vibrations. In a larger multisensory perspective, we may wonder how this information is processed and in particular how the information is shared between the auditory and tactile inputs. Is it possible to influence auditory roughness with tactile feedback? And conversely, might a smooth surface be perceived as rough when touched in presence of a rough sound?

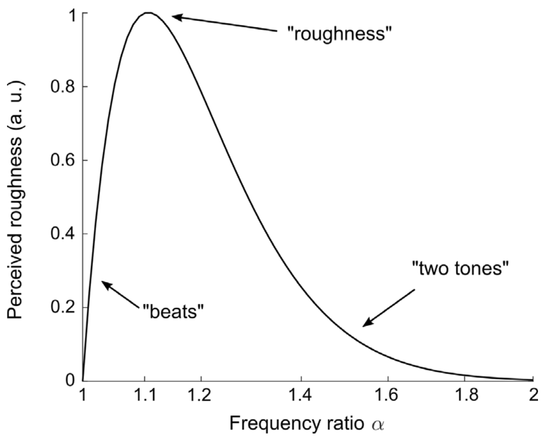

Fig. 1. Typical auditory roughness curve of a sum of two monochromatic tones and description of the three kinds of sensations provoked by pairs of pure tones for f_1=200 Hz (Vassilakis, 2001).

In this paper, we investigated the perception of roughness through an experiment that was divided in two parts, one with audio stimuli and the other one with tactile stimuli. The results are presented as audio and tactile roughness curves obtained from pairwise comparisons.

2 Method

2.1 Participants

18 subjects, 8 women and 10 men (Mean=30 years old, between 21 and 57 years old), 15 right-handed and 3 left-handed, 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 lasted about 1 hour.

2.2 Audio stimuli

Audio stimuli were pairs of sounds, each composed of the sum of two monochromatic tones of frequencies f_1 and $f_2=\alpha f_1$, of duration 1 second, and separated by 800ms. α is a coefficient between 1 and 2 that determines the frequency ratio between the two frequencies. When α=1, the frequencies are the same ($f_1=f_2$), which corresponds to unison, and when α=2 the tones are separated by an octave $f_2=2f_1$: $s(t) = sin(2\pi f_1 t) + sin(2\pi f_2 t)$.

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, 2.00) leading to 66 comparison pairs for one block. Audio stimuli were compared for 6 frequency conditions (f_1 = 50, 100, 200, 300, 600, 1200 Hz) leading to 6 blocks of 66 pairs (=396 pairs). Sounds were presented through Sennheiser HD-650 headphones at a sampling rate of 44100 Hz powered by a Pioneer A-209R audio amplifier.

2.3 Tactile stimuli

Tactile stimuli were generated with the same procedure as the audio stimuli for 4 frequency conditions only (f_1 = 50, 100, 200, 300 Hz). Frequencies above 800 Hz are indeed not perceptible by the human tactile sensory system (Verrillo, 1969). Hence, 4 blocks of 66 pairs (=264 pairs) were presented through an Actronika HapCoil-One vibrotactile actuator (dimensions: 11.5 × 12 × 37.7 mm^3, acceleration: 8 g-pp, frequency bandwidth: 10 to 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 subjects were asked to grab the vibrotactile actuator between the thumb and the index of their right hand. During the tactile experiment, participants wore noise canceling headphones to prevent them from using auditory cues.

2.4 Tasks and procedure

In each experiment, participants were seated in front of a computer screen in a quiet room. For each subject, the pairs of stimuli were presented in randomized order. For each pair, the presentation order was also randomized. In each experiment and for each pair of sounds, subjects were asked to judge which tone combination (or tactile stimulation) was the most "granular" (*granuleux* in French). As several participants had a musical background, we avoided the terms *rough* and *pleasant* that might also have been used. Answers were collected with a keyboard and the interface was designed with Max/MSP software to display either audio or tactile stimuli. The volume and the intensity of audio and tactile stimuli were set constant during the whole experiment.

2.5 Data analysis

In each experiment, the data were analyzed with the Bradley-Terry model (Hunter, 2004). This probabilistic model allows us to predict the outcome of a pairwise comparison from a win matrix. Practically, for each subject, a win matrix was obtained from the 66 pairwise comparisons which were sorted as follows: the cell (i,j) corresponds to the number of times the sound i has been judged rougher than the sound j. The win matrices were then aggregated between subjects and an iterative algorithm was used to fit the Bradley-Terry probabilistic model. Hence, for each frequency ratio, we obtained the probability that the corresponding combination tone was judged as rough compared to another combination. In the end, for the sake of comparison between experiments and with the literature, this probability was normalized into a perceived roughness score.

3 Results

The results, presented in Figure 2, exhibit that auditory and tactile roughness curves are very close in the 4 frequency conditions tested. Interestingly, the roughness curves obtained are also coherent with the theoretical roughness curve proposed by Vassilakis (2001). These results might suggest that auditory and tactile modalities share common principles in the perception of roughness and beatings. It would be of great relevance as it may for the first time lead to a common way between the two modalities of modeling roughness within the critical band framework. Secondly, it might further shed light on more fine similarities in the temporal processing of vibrations through these two modalities. Recent evidences have for instance shown that rhythm perception is shared between audio and haptics (Bernard et al., 2021). Our current findings suggest that these results could be extended to the perception of beating and roughness.

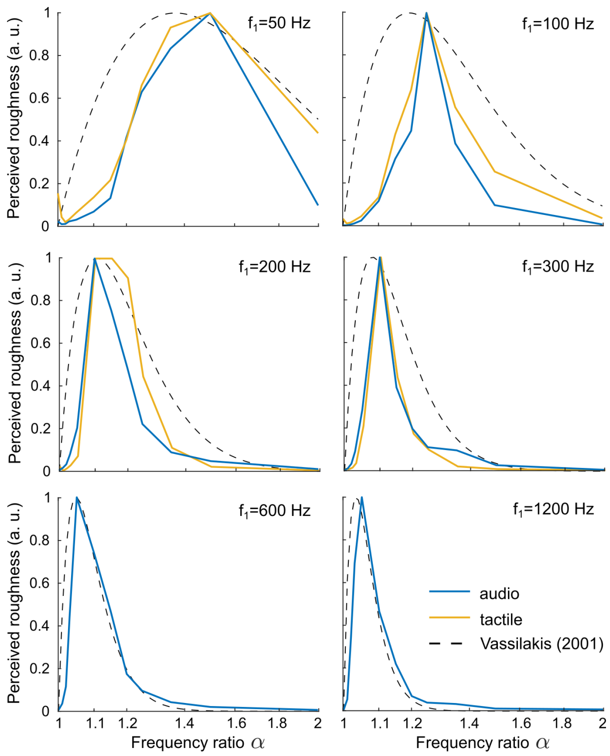

Fig. 2. Audio (blue line) and tactile (yellow line) roughness curves obtained from the experiment. The two modalities elicit similar roughness maxima and are coherent with the theoretical auditory roughness model proposed by Vassilakis (2001) (dashed line). The stimuli with f_1 = 600 and 1200 Hz were presented only for the audio condition, because they are beyond the frequency bandwidth of tactile perception.

4 Discussion

As it has already been observed in audition (Vassilakis, 2001), the position of maximal roughness perception changes according to the lower frequency f_1 also in the tactile modality. It is noteworthy that, in audition, the position of the maximum varies much more at lower frequencies, when the frequencies are inside the tactile perception range. In addition to these unimodal studies, it would be interesting to run a larger study in which subjects are asked to judge the roughness of audio-tactile stimuli. The ultimate goal is indeed to decipher and to model the way our perceptual systems combine audio and tactile senses into a coherent percept. We in particular hope to observe interactions between the two modalities and to observe how one modality may enhance the perception of roughness in the other. This has already been observed in several multisensory situations (Jousmäki & Hari, 1998, Guest et al., 2002), and such cases are of great relevance to understand the fine mechanistic bases of human perceptual systems.

5 Acknowledgments

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