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► **To cite this version:**

Corentin Bernard, Richard Kronland-Martinet, Madeline Fery, Sølvi Ystad, Etienne Thoret. Tactile perception of auditory roughness. 2022. hal-03829829v1

HAL Id: hal-03829829

<https://hal.science/hal-03829829v1>

Preprint submitted on 1 Nov 2022 (v1), last revised 3 Jan 2023 (v2)

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Tactile perception of auditory roughness

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1 Auditory roughness resulting of fast temporal beatings is often studied by summing
2 two pure tones with close frequencies. Interestingly, the tactile counterpart of
3 auditory roughness can be provided through touch with vibrotactile actuators.
4 However, whether auditory roughness could also be perceived through touch, and
5 whether they exhibit similar characteristics is unclear. Here, auditory roughness
6 perception and its tactile counterpart were evaluated using similar two pure tones
7 stimuli. Results revealed similar roughness curves in both modalities suggesting
8 similar sensory processing. This study attests of the relevance of such a paradigm for
9 investing auditory and tactile roughness in a multisensory fashion.

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11 Keywords: Roughness, Beating, Audio-tactile

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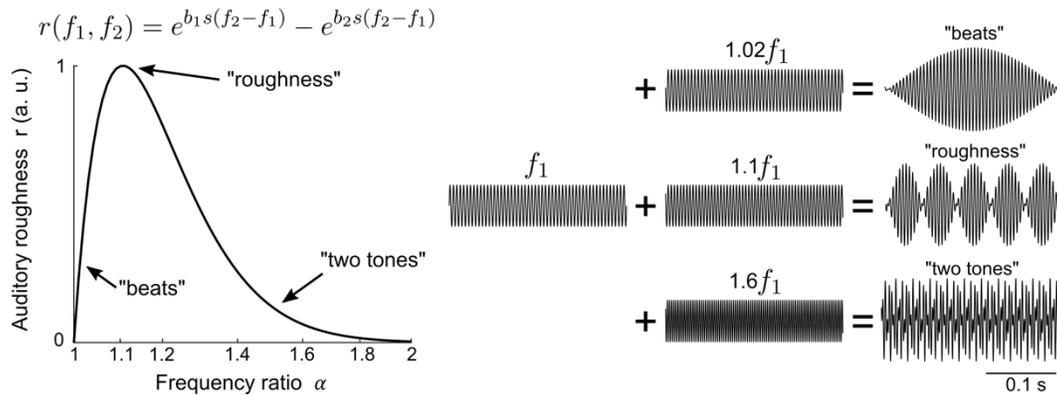
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13 1. Introduction

14 Auditory roughness is a fundamental acoustical attribute due to very fast
15 fluctuations of sounds that conveys emotions (Arnal et al., 2015), drives musical
16 consonance (Helmholtz, 1885; Plomb & Levelt, 1965), and shapes orchestral timbres
17 (Pressnitzer & McAdams, 2000). It is also at the basis of the definition of critical
18 bands (Terhardt, 1974), a fundamental property of cochlear filters characterizing the
19 ability of the cochlea to separate two pure tones. Auditory roughness has therefore
20 led to a significant body of work in psychoacoustics to identify the acoustic factors
21 that modulate this auditory sensation.

22 To unveil the mechanisms underlying auditory roughness perception, studies
23 have used combinations of monochromatic tones (Miśkiewicz et al., 2006), pure
24 tones, leading to models of perceived auditory roughness (Daniel et al., 1997;
25 Vassilakis, 2001; Leman, 2000). A combination of two monochromatic tones can
26 indeed create amplitude modulations that induce a sensation of roughness depending
27 on the frequency spacing between the two tones, also defined by the frequency ratio
28 between the two frequencies. The roughness of such sounds increases until reaching
29 a maximum and then decreases as the frequency ratio between the two frequencies
30 increases, as presented in Fig. 1. Since auditory roughness is often described as
31 characterizing very fast fluctuations in sounds, such stimuli are perfect candidates to
32 investigate such a sensation.

33



34

35 Fig. 1. Typical auditory roughness perception according to the frequency ratio of a

36 sum of two pure tones: $s(t) = \sin(2\pi f_1 t) + \sin(2\pi f_2 t) =$

37 $2\sin(2\pi \frac{f_1+f_2}{2} t)\sin(2\pi \frac{f_2-f_1}{2} t)$. When the frequency ratio $\alpha=f_2/f_1$ is small, the

38 combination of tones tends to be perceived as one tone slowly modulated by the

39 other one, a sensation that is characterized as beats. When the frequency ratio

40 increases, a sensation of roughness appears. As α becomes even larger, the perceived

41 roughness decreases and the two tones are perceived separately. This theoretical

42 auditory roughness curve is defined with the parameters $b_1 = 3.5$, $b_2 = 5.75$, $s =$

43 $\frac{0.24}{s_1 f_1 + s_2}$, $s_1=0.0207$ and $s_2 = 18.96$ (Vassilakis, 2001).

44 On the other hand, for the tactile modality, surface roughness refers to one

45 of the principal perceptual attributes used to describe textures explored with the

46 finger (Tiest & Kappers, 2006). Perceived surface roughness is defined by the

47 physical and geometrical properties of the textures, such as the height and the

48 density of the asperities (Taylor & Lederman, 1975; Stevens & Harris, 1962). Typical

49 stimuli for surface roughness evaluation are sandpapers with various grit sizes.

50 Interestingly, similar observations showing that the perceived surface roughness

51 depends on the spatial frequency and the amplitude of the haptic signal were made
52 on synthetic textures with new haptic touchscreen technologies (İşleyen et al., 2019;
53 Bodas et al., 2019).

54 In a recent review on multimodal roughness perception, Di Stefano &
55 Spence (2022) made a clear distinction between auditory roughness and surface
56 roughness: auditory roughness is a temporally based perceptual property, that is
57 experienced through hearing, while surface roughness is spatiotemporal one, related
58 to textures, that is assessed by touch (and vision). However, whether the sensation of
59 auditory roughness as historically investigated could also be experienced through
60 touch is still unclear.

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

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75 2. Methods

76 2.1 Participants

77 18 participants (8 women, M=30 years old. between 21 and 57 years old), 15
78 right-handed, voluntarily took part in the experiment. None of them reported having
79 any auditory problems or skin concerns. The participants gave their informed
80 consent before the experiment. The experiment lasted about 1 hour. The
81 experimental protocol was validated by the local ethical committee.

82 2.2 Stimuli

83 The experiment was composed of two sessions: one auditory and one tactile.
84 The same signals were used for both modalities and the stimuli were constructed by
85 combining two monochromatic tones: $s(t) = \sin(2\pi f_1 t) + \sin(2\pi f_2 t)$ of
86 frequencies f_1 and $f_2 = \alpha f_1$. Four frequency conditions were considered ($f_1 = 50, 100,$
87 $200, 300$ Hz). The experimental design did not include higher frequency conditions
88 since frequencies above 800 Hz are not perceptible by the human tactile sensory
89 system (Verrillo, 1969). The frequency ratio α ranged from 1 to 2. When $\alpha=1$, $f_1=f_2$
90 the tones are at unison, when $\alpha=2$, $f_1=2f_2$, the tones are separated by one octave.
91 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,
92 1.50, 2.00). For each frequency condition, stimuli with different α values were
93 compared pairwise leading to 66 pairs. Overall, each subject performed 2 sessions
94 with 4 blocks of 66 pairs which led to 528 trials.

95 2.3 *Apparatus*

96 Sounds were presented through Sennheiser HD-650 headphones at a
97 sampling rate of 44100 Hz powered by a Pioneer A-209R audio amplifier. Tactile
98 stimuli were presented through an Actronika HapCoil-One vibrotactile actuator
99 (dimensions: $11.5 \times 12 \times 37.7$ mm³, acceleration: 8 g-pp, Frequency bandwidth: 10
100 to 1000 Hz, resonant frequency: 65 Hz). This kind of actuator has already been used
101 in the literature to render the sensation of textures with vibrations (Rocchesso et al.,
102 2016). The actuator was powered by a Pioneer A-209R audio amplifier. The subjects
103 were asked to grab the vibrotactile actuator between the thumb and the index of
104 their right hand. During the tactile experiment, participants wore noise-canceling
105 headphones to prevent them from using potential auditory cues produced by the
106 tactile device to perform the task.

107 2.4 *Task and procedure*

108 Participants were seated in front of a computer screen in a quiet room. They
109 started randomly either with the audio or tactile session. The experiment was a
110 pairwise comparison. At each trial, two stimuli with different values of α were
111 presented successively. The stimuli lasted for 1 second and pairs were sequentially
112 presented with an inter-stimulus interval of 800 ms. For each pair of stimuli, the
113 participants were asked to determine which stimulus was the most “granular”
114 (*granuleux* in French). We avoided the terms “rough” and “pleasant” that are
115 commonly used in the literature since several participants had a musical background
116 which might have influenced their judgment. For each subject, the 4 blocks and the
117 stimuli within each block were presented in a randomized order and for each pair,

118 the presentation order was also randomized. Responses were collected with a
119 keyboard and the interface was designed with Max/MSP software to provide either
120 audio or tactile stimuli. The volume and the intensity of auditory and tactile stimuli
121 were set constant during the whole experiment.

122 *2.5 Data analysis*

123 Based on the subject's responses, each stimulus was assigned a score of
124 perceived auditory roughness. This score is the ratio of the number of times subjects
125 judged the stimulus as rougher by the number of times the stimulus was presented in
126 the pairwise comparison (=11). For one subject, if a stimulus of a given α value has
127 been judged N times as more "granular" than another, its roughness score equals
128 $N/11$. Finally for each subject, each modality and each f_1 condition, roughness
129 curves characterizing the roughness score evolution with respect to the α value were
130 computed.

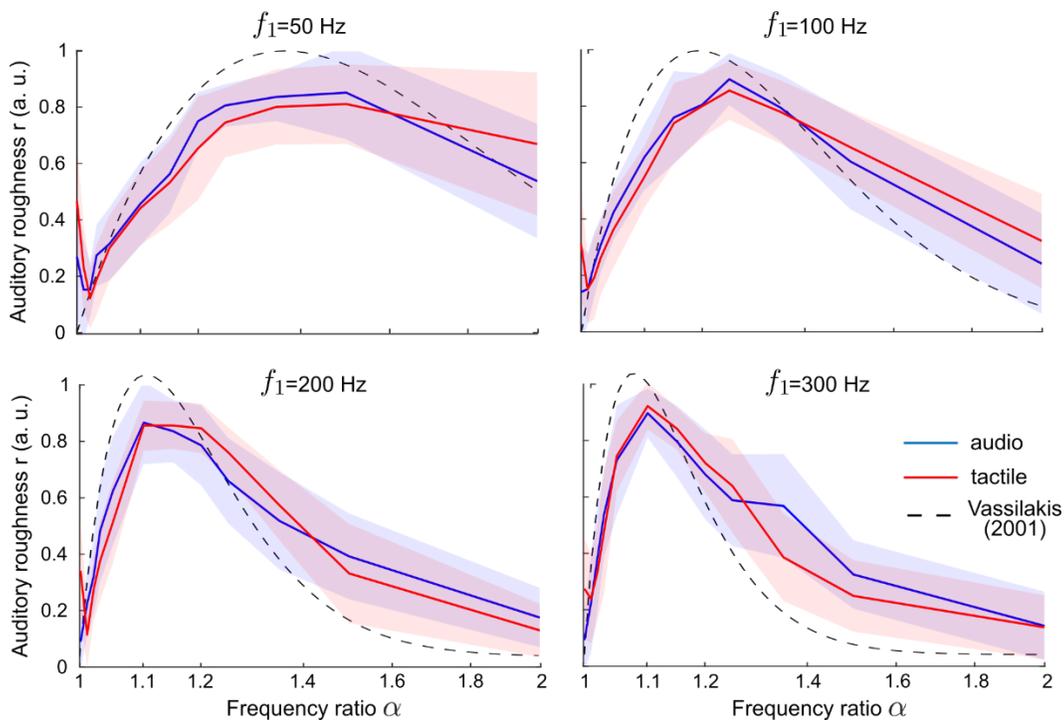
131 **3. Results**

132 Firstly, the results showed that the roughness curves obtained were coherent
133 with the theoretical roughness curve proposed by Vassilakis (2001) and Leman
134 (2000). This validates the present protocol for roughness score measurement
135 (correlations between the 8 mean curves, 2 modalities x 4 frequency ratio condition,
136 and the theoretical curves: $r(9) : M=0.89$, range=[min=0.83, max=0.97] , all
137 $p<0.001$), see Fig. 2.

138 Most importantly, the results revealed that auditory and tactile modalities
139 provide similar roughness curves in the 4 frequency conditions tested, see Fig. 2. We
140 observed a significant correlation between the tactile and auditory roughness mean

141 curves for the 4 conditions (Pearson correlations: $f_1=50$ Hz : $r(9)=0.94$, $p=4.7 \cdot 10^{-6}$,
142 $BF_{10}=5e^{-3}$; $f_1=100$ Hz: $r(9)=0.97$, $p=2e^{-7}$, $BF_{10}=9e^4$; $f_1=200$ Hz: $r(9)=0.92$, $p=1.7e^{-5}$, $BF_{10}=1.7e^3$;
143 $f_1=300$ Hz: $r(9)=0.94$, $p=3.9e^{-7}$, $BF_{10}=6.5e^3$).

144 Lastly, in order to assess potential differences between the two modalities, we
145 computed the differences between auditory and tactile roughness scores for each
146 frequency condition f_1 and α values and for each subject. This resulted in a
147 population of 864 samples, whose mean does not significantly differ from 0 (t-test:
148 $t_{863}=1e^{-15}$ $p=1$, $CI_{95\%}=[-0.0149; 0.0149]$), showing that there is no significative
149 difference between the audio and tactile roughness curves.



150
151 Fig. 2. Audio (blue) and tactile (red) roughness curves obtained from the
152 experiment for the four frequency conditions. Mean across subjects is presented in
153 solid lines, and standard deviation is presented with the shaded zones. The black

154 dashed lines depict the theoretical auditory roughness model proposed by
155 Vassilakis (2001).

156 4. Discussion

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

164 Auditory roughness curves are coherent with the model of Vassilakis (2001).
165 Interestingly, we observe the same curves in the tactile modality. In particular, the
166 position of maximal roughness perception changes according to the lower frequency
167 f_1 . It would therefore be of interest now to further investigate the multimodal process
168 of auditory roughness perception. It may indeed lead to a common process between
169 the two modalities and the critical band framework (Makous et al., 1995) could also
170 be relevant in the tactile domain. In addition, a formal comparison with the
171 modulation transfer function in the amplitude modulation domain could also be
172 done with specific experiments (Weisenberger, 1986).

173 Secondly, this study further sheds light on more fine similarities in the
174 temporal processing of vibrations through these two modalities. One major
175 difference between the two modalities is that for high α values (around 2), audition
176 discriminates the two harmonic frequencies leading to a perception of two tones,

177 whereas in touch, we perceive only one uniform complex temporal vibration
178 (Bensmaia, & Hollins, 2000).

179 It is worth noticing that the auditory roughness curves present similar shapes
180 to the surface roughness curves (Unger et al., 2010) by making analogies between
181 sound beating frequency and texture spatial frequency (i.e., the number of ridges per
182 millimeters). Firstly, for low spatial frequencies, only large undulations of the texture
183 are felt. The surface roughness then increases as the spatial frequency increases until
184 reaching a maximum. Lastly, surface roughness decreases as the ridge's density highly
185 increases until the texture becomes almost smooth. Although auditory and surface
186 roughness remain two distinct perceptual attributes, there could hereby be processed
187 with similar underlying mechanistic processes. In addition, recent evidence has
188 shown that rhythm perception is shared between audio and haptics even for textures
189 explored through active touch (Bernard et al., 2021). Our current findings suggest
190 that these results could be extended to the perception of beating and temporal
191 roughness.

192 **5. Conclusion**

193 This study provides results for the investigation of audio-tactile roughness
194 under a common framework. The framework classically dedicated to investigating
195 auditory roughness has here been formally validated for the tactile modality. One
196 particularly relevant perspective is the investigation of the multisensory integration of
197 these stimuli in congruent or incongruent situations. We may expect to observe
198 audio-tactile interactions and how one modality can enhance the perception of
199 roughness in the other. This has already been observed in several multisensory

200 situations (Jousmäki & Hari, 1998, Guest et al., 2002, Yau et al., 2009). These cases
201 are of great relevance to understanding the fine mechanistic bases of human
202 perceptual systems.

203

204 **Acknowledgments**

205 This work was supported by an ILCB/BLRI grant ANR-16-CONV-0002
206 (ILCB), ANR-11-LABX-0036 (BLRI), the Excellence Initiative of Aix-Marseille
207 University (A*MIDEX), the Sound and Music from Interdisciplinary and
208 Intersectorial Perspectives (SAMI - A*MIDEX) project and France Relance. The
209 authors would like to thank MIRA, Aflokkat and Nicolas Huloux for his thoughtful
210 comments on the paper.

211

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