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Annoyance penalty of low-level tonal sounds

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Summary

Environmental and building service appliance sounds involving tonal components can be more annoying than broad-band noise. Mandatory penalty values exist in many countries for tonal sound. The purpose of our study was to determine how tonal sounds are perceived compared to non-tonal sounds at overall level 25 dB L_{Aeq}, which is close to typical regulated levels inside residential dwellings. Forty participants rated the loudness and annoyance of 20 tonal sounds and 14 non-tonal reference sounds (19–45 dB L_{Aeq}) in laboratory conditions. The tonal frequencies were 50, 110, 290, 850, and 2100 Hz. Four levels of tonal audibility were used: 5, 10, 17, and 25 dB. The overall level of each tonal sound was 25 dB L_{Aeq}. Penalty was determined by determining the level difference with an equally annoying reference sound. The penalty depended on the tonal frequency and the tonal audibility. Annoyance penalty was zero or even negative at two lowest tonal frequencies 50 and 110 Hz. At other tonal frequencies, the penalty increased with increasing tonal audibility and tonal frequency. The largest penalty value, 12 dB, was obtained at tonal frequency 2100 Hz with the largest level of tonal audibility. Our results disagree with penalty values applied in many national regulations, when the overall level is low, 25 dB L_{Aeq}. A mathematical prediction model was developed which predicts the penalty as a function of tonal frequency and tonal audibility.

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1. Introduction

Environmental sounds or building service sounds transmitted inside of a residential dwelling can lead to noise annoyance. Prolonged experience of high noise annoyance and noise induced sleep disturbance can lead to more serious health effects. Therefore, it would be important to predict the probability of high annoyance from objective measurement of sound. Annoyance cannot be predicted by measuring only the A-weighted equivalent sound pressure level, L_{Aeq} [dB]. It can also be affected by other properties of sound (tonality, impulsivity, intermittency, spectrum), duration of noise, activity during the exposure at home (e.g. sleep, relaxing, celebrating), attitudes towards the source (e.g. fear, necessity, ownership), and individual factors (e.g. noise sensitivity).

The annoyance can be controlled by noise regulations given for the design of land use [1], health protection of citizen [2], and design of buildings [3] (**Table I**). They state various alternative values for penalty k to be added to the measured or predicted value of L_{Aeq}. The resulting value, $L_{Aeq}+k$, is compared to the regulated value of L_{Aeq}. Penalty k is applied only to those periods when tonality exists.

Our study focuses on tonal sounds (*narrow-band sound*). The application of penalty is difficult since the regulations [1-3] do not unambiguously refer to any objective method to assess either the existence or the strength of tonality. In addition, the penalty value depends on the selected regulation, which can lead to contradictory interpretations and conclusions of a measurement result. Some standards [4-9] present objective methods to determine the degree of tonality (*audibility*, *tone prominence*). Some of them also give methods to determine the penalty [5,7]. However, the relationship between penalty and degree of tonality has been proven by a limited number of psychoacoustic experiments. In addition, all experiments have been conducted with levels at or far above 40 dB. Such a high levels seldom exist inside residential dwellings (see regulated levels of **Table I**). The scientific literature does not present evidence about the penalty that could be given for tonal sounds, when the level is low, under 30 dB L_{Aeq}.

The purpose of our study was to determine how tonal sounds are perceived compared to non-tonal sounds at overall level 25 dB L_{Aeq}, which is close to typical regulated levels inside residential dwellings.

The full version of the experimental study is published in Ref. [10]. A follow-up study expressing the mathematical form of the penalty is presented in a submitted manuscript [11].

Table I. Regulated levels of indoor noise level caused by environmental noise or building service appliances according to three Finnish mandatory regulations. Footnotes involve the penalty values for tonal sounds.

	Day 07 - 22 T=15 h	Night 22 - 07 T=9 h	Night 22-07 T=1h
a) Decision 993/1992 [1].[a]			
Environmental noise.			
Living rooms	35	30	-
b) Decree 545-2015 [2].[b]			
Environmental noise.			
Living rooms	35	30	-
Other rooms and kitchen	40	40	-
Sleeping rooms, noise causing sleep disturbance	-	-	25
c) Decree 796-2017 [3].[c]			
Building service noise.			
Living room	28	28	28
Kitchen	33	33	33

[a] If noise is impulsive or tonal, a penalty of 5 dB is added to the measured or predicted value before comparison to these values.

[b] A penalty of 5 or 10 dB is added to the measured value depending on the level of impulsivity. A penalty of 3 or 6 dB is added to the measured value depending on the level of tonality.

[c] If noise is impulsive or tonal, a penalty of 3 dB is added to the measured or predicted value before comparison to these values.

2. Materials and methods

Forty participants were recruited to the psychoacoustic experiment. The independent variable was *sound*. The dependent variable was subjective *annoyance* of each sound. The subjects rated the *annoyance* of each sound on a scale from 0 (Not at all) to 10 (Extremely annoying).

The *sounds* consisted of both reference *sounds* and tonal *sounds*. The properties of the 34 *sounds* are depicted in **Table II** and **Figure 1**. The twenty tonal *sounds* were combinations of five tonal frequencies, A_{T} [dB] (50, 110, 290, 850 and 2100 Hz), and four tonal audibility levels, A_{T} [dB] (A1 – A4). All tonal *sounds* had the same overall level, 25 dB L_{Aeq}. The tonal *sounds* were created from sinusoidal and broadband component. Reference *sounds* had a constant broadband spectrum shape without any tone. The shape was the inverse of the A-weighting network. Their overall level varied from 19 to 45 dB L_{Aeq}. Reference *sounds* were needed to determine the penalty according to **Figure 2**.

Table II. The properties of the reference *sounds* (R1 – R14) and the tonal *sounds* (T1 – T20). Tonal frequency, f_{T}, the tonal audibility, A_{T}, and the overall level, L_{Aeq} are reported. In addition, the *annoyance* ratings are given. M is the mean value and SE is the standard error of the mean.

Sound	f_{T}	A_{T}		L_{Aeq}	*Annoyance*	
	[Hz]	Level	[dB]	[dB]	M	SE
R1	-	-	0	19	0.68	0.20
R2	-	-	0	21	1.08	0.17
R3	-	-	0	23	1.88	0.26
R4	-	-	0	25	2.55	0.28
R5	-	-	0	27	3.03	0.30
R6	-	-	0	29	4.00	0.34
R7	-	-	0	31	4.93	0.30
R8	-	-	0	33	5.85	0.30
R9	-	-	0	35	6.33	0.31
R10	-	-	0	37	7.03	0.26
R11	-	-	0	39	7.50	0.24
R12	-	-	0	41	8.23	0.22
R13	-	-	0	43	8.68	0.17
R14	-	-	0	45	8.88	0.17
T1	50	A1	5	25	2.35	0.29
T2	50	A2	10	25	2.35	0.29
T3	50	A3	18	25	1.78	0.32
T4	50	A4	25	25	1.93	0.38
T5	110	A1	5	25	2.78	0.29
T6	110	A2	10	25	2.48	0.29
T7	110	A3	17	25	2.38	0.30
T8	110	A4	24	25	2.83	0.37
T9	290	A1	5	25	2.75	0.30
T10	290	A2	10	25	3.63	0.37
T11	290	A3	17	25	3.75	0.39
T12	290	A4	25	25	5.38	0.35
T13	850	A1	5	25	2.95	0.32
T14	850	A2	10	25	4.15	0.34
T15	850	A3	18	25	4.70	0.36
T16	850	A4	25	25	6.05	0.39
T17	2100	A1	5	25	3.08	0.31
T18	2100	A2	10	25	4.13	0.38
T19	2100	A3	18	25	5.68	0.39
T20	2100	A4	25	25	6.85	0.30

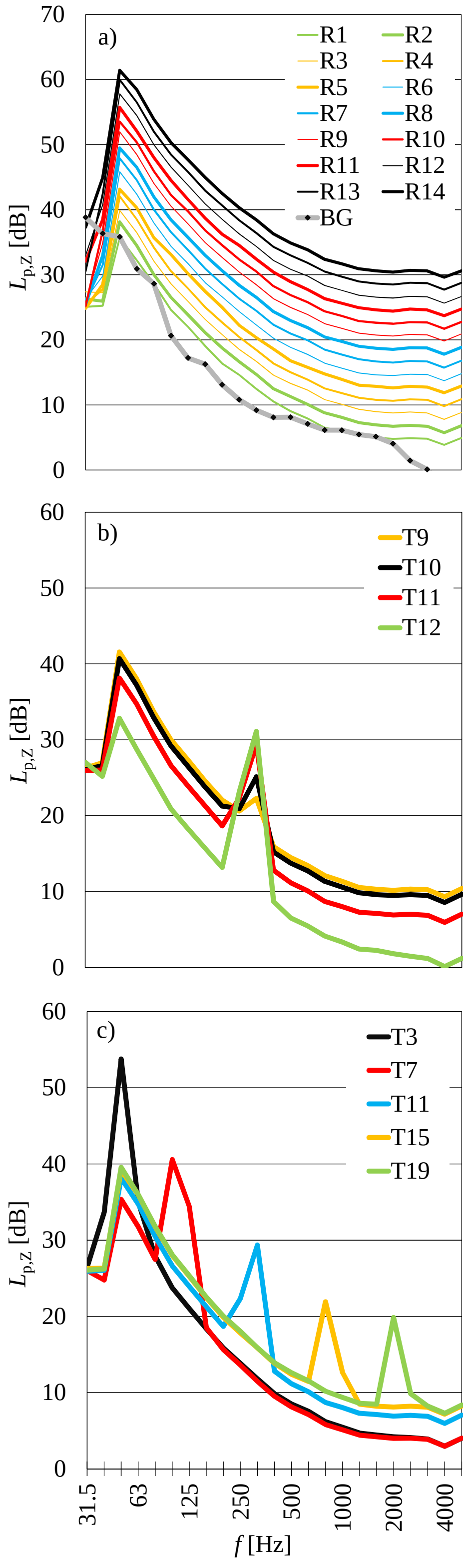

Figure 1. Linear sound pressure level, $L_{p,Z}$, as a function of frequency, f, in third-octave bands. a) Reference *sounds* R1 – R14 and the background noise of the room, BG. b) Four tonal *sounds* of Table 1 demonstrating the four levels of tonal audibility, A_T, when $f_T = 290$ Hz. c) Five tonal *sounds* demonstrating the five studied tonal frequencies at the same tonal audibility level (A3).

The experiment consisted of three phases. Familiarization phase involved the listening of 13 examples. Rehearsal phase involved the rating of the same examples. Experiment consisted of the rating of all 34 *sounds* preceded by three dummy sounds which were not analyzed. One participant performed the experiment at a time. The *sounds* were played with headphones. The experiment was conducted in a soundproof room with background noise 19 dB L_{Aeq}. The order of the *sounds* was counterbalanced between participants. Each *sound* was played first for 9 seconds after which the rating scale was enabled.

Each participant conducted actually two experiments. The first part of the experiment was described above. The second part was similar to the first part but the tonal sounds were 10 dB louder (35 dB L_{Aeq}). Due to the limited space, we do not present the results here. However, the results of the second part were basically similar to first part which is reported in this paper. It was allowed to present the results of the first part only since the order of the parts was the same for all participants.

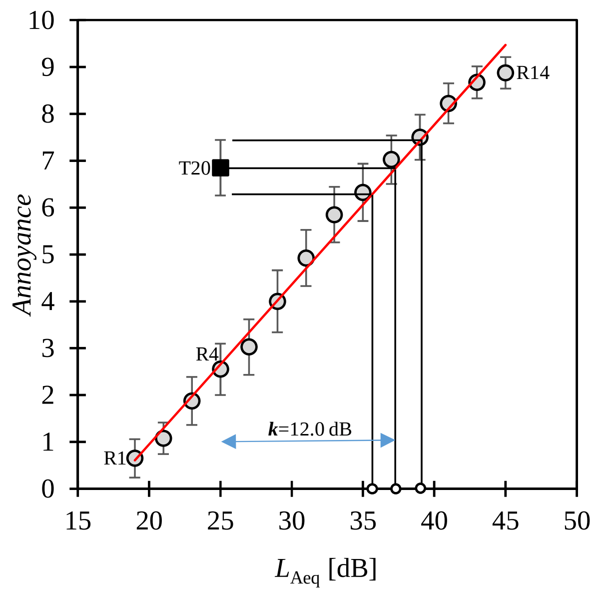

Figure 2. Mean *annoyance* values and 95% confidence intervals of reference sounds R1 – R14 (circles) and the tonal sound T20 (black square). The penalty k was determined by finding the equally annoying reference sound from the linear fitting curve drawn over the reference sounds (red line). In this case, the penalty value was $k = 12.0$ dB. The confidence interval was 10.3 – 13.6 dB. That is, the annoyance of tonal sound T20 is statistically significantly different from the *annoyance* of the reference sound R4 having the same overall level, $L_{Aeq} = 25$ dB.

3. Results

The results of *annoyance* for each *sound* are shown in **Table II**. The *annoyance* of reference *sounds* depended strongly on their overall level (**Figure 2**). The Pearson's correlation coefficient between mean annoyance and L_{Aeq} was 0.995. Therefore, the curve fitted over the reference *sounds* formed a solid ground to the determination of the penalty of tonal *sounds*.

The *annoyance* of tonal *sounds* varied strongly, from 1.78 to 6.85, although their overall level was constant (25 dB L_{Aeq}). This elucidates that tonal sounds can be very annoying with certain combinations of tonal frequency and tonal audibility. For comparison, the *annoyance* of the reference *sound* R4, which had the same overall level as all tonal *sounds*, was 2.55.

The penalty determined for each tonal *sound* is shown in **Figure 3**. Penalty increases with increasing tonal frequency and tonal audibility. Surprisingly, penalty was negligible for tonal frequencies 50 and 110 Hz independent on tonal audibility.

The mathematical form of the penalty *k* [dB] of **Figure 3** was determined in Ref. [11]:

$$k = -0.036 A_{\mathrm{T}} + 0.326\, A_{\mathrm{T}} \tan^{-1}\left(6\left(\frac{f_{\mathrm{T}}}{1000\ \mathrm{Hz}} - 0.0858\right)\right) \quad (1)$$

4. Discussion

Our study is perhaps the only experiment so far studying the annoyance of low-level tonal sounds. This field is extremely relevant regarding public health since people stay indoors most of their time at home and the indoor levels of environmental noise are usually less than 30 dB L_{Aeq}. Our parametric study revealed very clear and logical dependence of the tonal penalty on tonal frequency and tonal audibility. Because the study involved 40 participants, the reliability of the results is relatively good.

A mathematical form was derived for the penalty (Equation 1). It was based on data in the frequency range 50 – 2100 Hz, but we expect that the model could be applied for a wider range of tonal frequencies, e.g. 25 – 4000 Hz.

We found that penalty is negligible, or even negative, at low tonal frequencies (50, 110 Hz). On the other hand, the penalty was even 12 dB at the highest studied frequency, 2100 Hz, when the tonal audibility was large (level A4, A_{T} = 25 dB). Our results disagree with the constant penalty values (3, 5, or 6 dB) applied in the Finnish regulations (**Table I**). Our results also disagree with the predicted penalty values of existing standards [5,7] although we did not present the comparison in this paper.

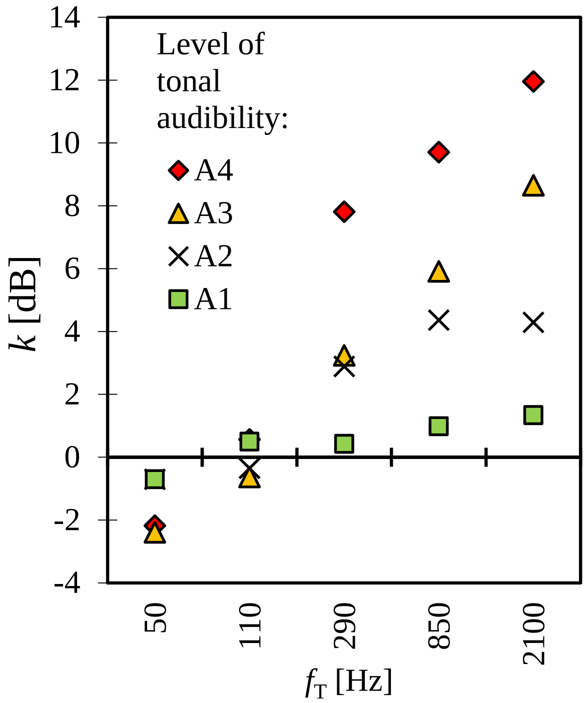

Figure 3. Penalty of tonal sounds as a function of tonal frequency, f_{T}, and tonal audibility level, which are depicted in Table II. The overall level of tonal sounds was 25 dB L_{Aeq}.

The weakness of our study was that the studied sounds were synthetic and only single tones over a smooth spectrum were involved. Therefore, future research with real sounds are needed to confirm our findings, especially the validity of Equation (1). An independent psychoacoustic experiment (Manuscript under preparation, 2018) has already been conducted. It involved recorded real-life tonal sounds with varying overall spectra and tonal features. The preliminary results suggest that Equation (1) predicted the penalty of tonal sounds at 30 and 50 dB L_{Aeq} much better than standardized penalty models [5,7]. Constant penalty values were not supported. However, in this newer study, Equation (1) could not alone predict the annoyance penalty with sufficient accuracy but the overall spectrum of the sound played also an important role. This could be expected by our prior study which showed that large annoyance are found for different spectra of background sounds [12,13].

Our results can be taken into account when the future penalty policies are planned. Future research on the annoyance of sounds of any kind (tonal, impulsive, spectrally different, amplitude modulated, intermittent) prevailing in residential dwellings (<35 dB L_{Aeq}) is highly justified since most psychoacoustic studies have been conducted at higher levels which are not relevant inside residential dwellings.

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