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Annoyance penalties due to tonal, impulsive, and amplitude-modulated characters in sound

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ABSTRACT

Many countries apply annoyance penalties, AP (a.k.a. adjustment, surplus, sanction), for noise carrying a specific, measurable property such as tonality or impulsiveness that is expected to raise noise annoyance. Amplitude-modulated sound has been suggested to be a third specific property deserving an AP. Many legislations apply constant penalty values, *k* [dB], that are added to the equivalent A-weighted sound pressure level, L_{Aeq}, if the feature genuinely is present in the sound. However, the justification of a constant *k* can be questioned because quantitative descriptors of the specific properties significantly vary between environmental sounds. There is little experimental knowledge how the objectively measurable descriptors of these properties affect AP. The purpose of this study is to introduce the findings of three psychoacoustic experiments touching this issue. Experiment A concerned tonality, where the quantitative descriptors were tonal frequency and tonal audibility. Experiment B concerned impulsivity, where the quantitative descriptors were onset rate and level difference. Experiment C concerned amplitude modulation, where the quantitative descriptors were modulation frequency and modulation depth. Based on the experimental data, the penalty in decibels ranged from 0 to 12, 8, and 12 dB in experiments A, B, and C, respectively. Each experiment showed a logical dependence of AP on the objective descriptors. Constant penalty models were not supported by the findings. The results can be applied in the assessment of annoyance penalty when scientifically justified methods are favored. The results can also be used in the development of future penalty models.

Keywords: annoyance, penalty, tonal sound, impulsive sound, amplitude-modulated sound, psychoacoustics

INTRODUCTION

Many countries apply a constant *annoyance penalty*, AP (a.k.a. adjustment, surplus, sanction), for environmental noise and/or building service noise carrying a specific, measurable property such as tonality or impulsiveness that is expected to raise noise annoyance. Amplitude-modulated sound has been suggested to be a third specific property deserving an AP, but national legislations are still lacking. Many legislations apply constant penalty values, *k* [dB], that are added to the equivalent A-weighted sound pressure level, L_{Aeq}, if tonal or impulsive character genuinely is present in the sound. However, the justification of a constant *k* can be questioned due to the fact, that the quantitative descriptors of the specific properties significantly vary between different sounds. There is little experimental knowledge how the objectively measurable descriptors of these properties affect AP.

The purpose of this study is to introduce the findings of three psychoacoustic Experiments A–C [1–3] touching this issue. The Experiments A–C were conducted using similar motivation, design, and analysis.

METHODOLOGICAL OVERVIEW OF EXPERIMENTS A–C

Experiment A – tonal sound. The assessment of the presence of tonal components in sound can be made using at least three methods: subjective assessment, one-third octave analysis, or narrow-band analysis. In this study, the third option was applied since it is the most precise. Standard ISO 1996-2 depicts a method where the tonality is assessed using two properties of the tone: *tonal frequency,* f_T [Hz], and *tonal audibility*, A_T [dB] (**Fig. 1a**). The standard also contains a penalty assessment method, which defines a stepwise penalty according to the tonal audibility. However, the scientific foundations of this method are lacking. Most of the research on tonal sound has been done using moderate or high sound levels, although the legally critical levels in residential environments are low (40–50 dB L_{Aeq} outdoors) or extremely low (20–30 dB indoors). The purpose of the experiment was to determine, how penalty is affected by different choices of f_T and A_T of a single tone, when total L_{Aeq} is 25 dB. Twenty tonal sounds were investigated. Since the modification of both f_T and A_T affect the L_{Aeq} value, each experimental sound was created as a combination of a tone (with specified f_T and A_T) and wideband noise. Tones were created as the systematic combinations of five single-tone frequencies (50, 110, 290, 850, and 2100 Hz) and four tonal audibilities (5, 10, 18, and 25 dB). The spectrum of wideband noise conformed with inverse A-weighting so that each one-third frequency band contributed to L_{Aeq} equally much. The level of wideband noise was adjusted to reach the desired 25 dB L_{Aeq} for each experimental sound. In addition, fourteen reference sounds were included to the experiment. They were used to determine the AP of tonal sounds (see **Fig. 2**). The reference sound was wideband noise with a spectrum of inverse A-weighting. In overall, the experiment consisted of thirty-four experimental sounds. Forty people participated in the experiment.

Experiment B – impulsive sound. The assessment of the presence of impulsive components in sound can be made using at least three ways: subjective method, EEC (1978), and Nordtest (2002). In this study, the third option was applied since it describes the microstructure of the impulse quite precisely. Nordtest (2022) describes a single impulse using two properties: *onset rate,* R_{on} [dB/s], and *level difference*, D_L [dB] (**Fig. 1b**). Nordtest method also contains a method of determining the AP. However, the scientific foundations are weak. The purpose of the experiment was to determine how penalty is affected by different choices of R_{on} and D_L of an impulse, when L_{Aeq} of noise containing periodic impulses is 55 dB. Thirty-three impulses were created at different values of R_{on} (from 5 to 800 dB/s) and D_L (5 to 40 dB). The experimental sounds were combinations of wideband noise (conformed with the spectrum of road traffic noise, RTN) and periodically presented impulses. Impulses had RTN spectrum as well. The level of steady-state noise depended on the properties of the impulses so that the overall sound level of broad-band noise and impulses was 55 dB L_{Aeq}. The impulses were presented to participants using constant period of 2.5 seconds between impulses. In addition, eight steady-state reference sounds conforming with RTN spectrum were included to the experiment. They were presented from 49 to 70 dB L_{Aeq} in 3 dB steps. They were used to determine the penalty of impulsive sounds. In overall, the experiment consisted of forty-one experimental sounds. Thirty-two people participated in the experiment.

Experiment C – amplitude-modulated sound. The assessment of the presence of periodic amplitude modulation in sound is often made by determining the *modulation frequency*, f_m [Hz], and *modulation depth*, D_m [dB] (**Fig. 1c**). There is very little scientific evidence, how they affect the AP. The purpose of the experiment was to determine how penalty is affected by different choices of f_m [Hz] and D_m of broadband noise, when L_{Aeq} is 35 dB. Such level is usual both in residential yards and inside dwellings. The modulated noise was broadband noise having wind turbine noise spectrum. The thirty-five modulated sounds were combinations of seven modulation frequencies (0.25, 0.5, 1, 2, 4, 8, and 16 Hz) and five modulation depths (1, 2, 4, 8, and 14 dB). The overall level of modulated sounds was 35 dB L_{Aeq}. In addition, eleven steady-state reference sounds (having wind turbine noise spectrum) were included to the experiment. They were presented from 29 to 49 dB L_{Aeq} in 2 dB steps. They were used to determine the penalty of amplitude-modulated sounds. In overall, the experiment consisted of forty-six experimental sounds. Forty people participated in the experiment.

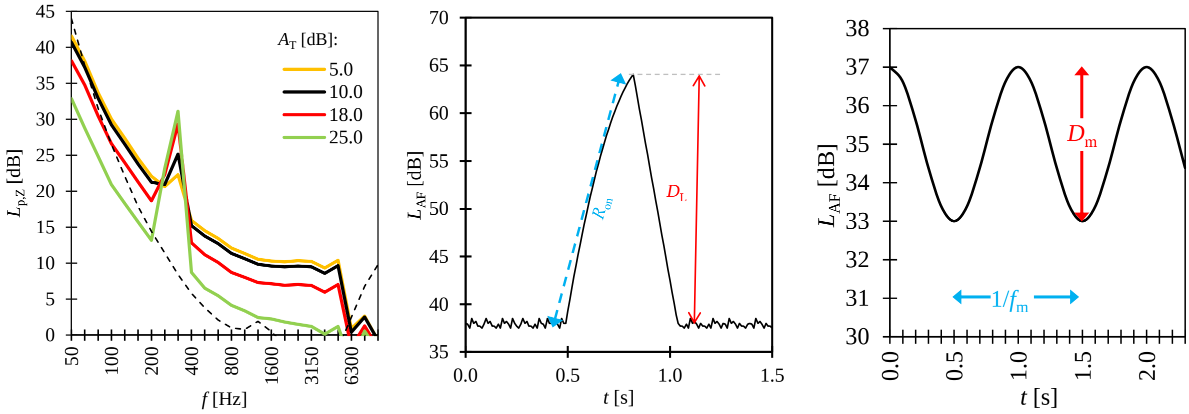

Fig. 1. Objective description of the three specific features in sound. (a) Unweighted SPL, $L_{p,Z}$, is shown as a function of frequency, f, for four experimental sounds of Experiment A. The tonal audibility, A_T, was investigated at four levels: 5, 10, 18, and 25 dB. This example concerns the tonal frequency, f_T=290 Hz and one-third octave band analysis. (b) A-weighted SPL using Fast time weighting, L_{AF}, as a function of time, t. In Experiment B, impulses were characterized by onset rate, R_{on}, and level difference, D_L. For this impulse, R_{on}=120 dB/s and D_L=25 dB. (c) A-weighted SPL using Fast time weighting, L_{AF}, as a function of time, t. In Experiment C, amplitude modulation was characterized by modulation frequency, f_m, and modulation depth, D_m. For this example, f_m=1 Hz and D_m=4 dB.

Participants. Participants were mostly students recruited from the local universities. The inclusion criteria were age 20–40 y, Finnish native language, normal health status, and normal hearing. Participants received a gift token as a compensation for their participation.

Annoyance measurement. Noise annoyance was measured for each sound by question: "*How much does the sound bother, disturb, or annoy you*?" The 11-step response scale was from 0 as "Not at all" to 10 "Extremely annoying". The participants were instructed to use the full scale and try to make their responses as consistent as possible. The participants had to listen the sound for 8–18 seconds, depending on Experiment, before the response scale became visible.

Laboratory. Experiments A–C were conducted in the psychophysics laboratory of TUAS within 2016–2018. The background noise level was close to hearing threshold level or below it (19 dB L_{Aeq}). The sounds were presented using headphones (Sennheiser HD580) and the SPLs presented to the participants were measured using head-and-torso simulator (B&K

4100).

Experimental procedure. Each experiment had similar procedure consisting of the following phases: hearing threshold test, familiarizing to sounds (5–10 example sounds), rehearsal of annoyance rating with 5–10 sounds, and final experiment.

Penalty determination. AP was determined in Experiments A–C using a protocol developed for this project. The protocol of Experiment A is described in **Fig. 2**. The protocol was similar in Experiments B–C except for the spectrum and the L_{Aeq} range of reference sounds.

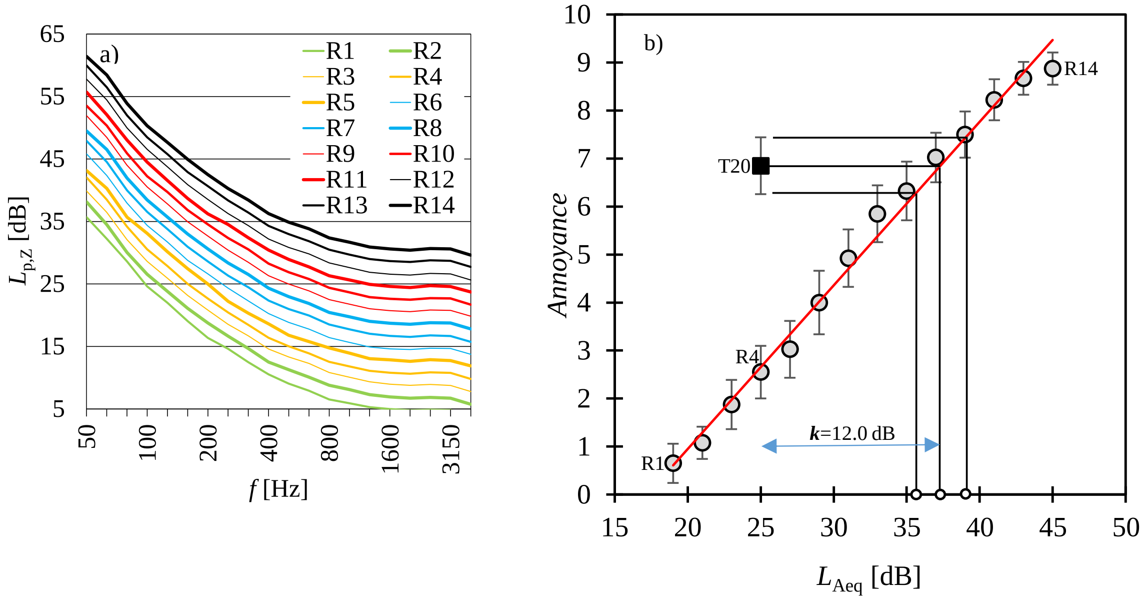

Fig. 2. Penalty determination in Experiment A. (a) Fourteen reference sounds, R1–R14, had steady-state spectrum and they were played in 2 dB steps at 19–45 dB L_{Aeq}. (b) The annoyance (mean and 95% confidence intervals of 40 participants) of the reference sounds R1–R14 and one tonal sound, T20, is shown. The penalty, k=12.0 dB, was determined by projecting the annoyance of T20 to the regression line based on reference sounds.

RESULTS

The experimental results of Experiments A–C are summarized in **Fig. 3**.

DISCUSSION

AP due to tonality (**Fig. 3a**) increases with increasing tonal audibility. The largest tonal audibility level, 25 dB, led up to 8–12 dB penalty values. The dependence of penalty on tonal audibility was expected. However, it was unexpected that the penalty was absent for low tonal frequencies (50, 110 Hz) while the dependency of penalty on tonal audibility was quite similar for middle and high frequency tones (290, 850, and 2100 Hz). One potential explanation for that was the extremely low overall level of the tones, 25 dB L_{Aeq}. The 50 Hz tones exceeded the hearing threshold at all four tonal audibility levels but since the SPLs of masking on the critical band (1 Bark, 50 Hz, bandwidth 100 Hz) defined by ISO 1996-2 was far below the hearing threshold, the tonal audibility values assigned to 50 Hz tones could be misleading from perception point of view. Although the experimental finding may be valid at low frequencies, there is still an obvious need to develop the objective assessment method of tonality for low level tones, where masking is below hearing threshold.

AP due to impulsiveness (**Fig. 3b**) increases with increasing onset rate and level difference. The largest penalty values, around 8 dB, were reached when the onset rate exceeded 200 dB/s and level difference exceeded 30 dB. On the other hand, penalty is not needed, when onset rate is under 40 dB/s and level difference is under 25 dB. In overall, the results look logical, and no unexpected findings are found. However, the penalty values predicted by Nordtest (2002) overestimated the findings of this experiment at large onset rates. The penalty model of Nordtest (2002) was adopted to ISO/PAS 1996-3 (ISO, 2022), although it lacks scientific peer-reviewed psychophysical evidence. Therefore, the penalty model of ISO/PAS 1996-3 should be revised and applied with preservations.

AP due to amplitude modulation (**Fig. 3c**) increases with increasing modulation frequency and increasing modulation depth. The largest penalty values, 11–12 dB, were obtained with large modulation depth and modulation frequency higher than 1 Hz. The lowest modulation frequency, 0.25 Hz, was probably associated to seacoast waves, and the sounds were not rated as annoying, even with the largest D_m (14 dB). AP appeared first time at 0.5 Hz and reached the maximum at 2 Hz and showed similar values within 2–16 Hz. Modulation depth of 1 dB did not lead to penalty at any f_m so that the limit of penalty is around 2 dB.

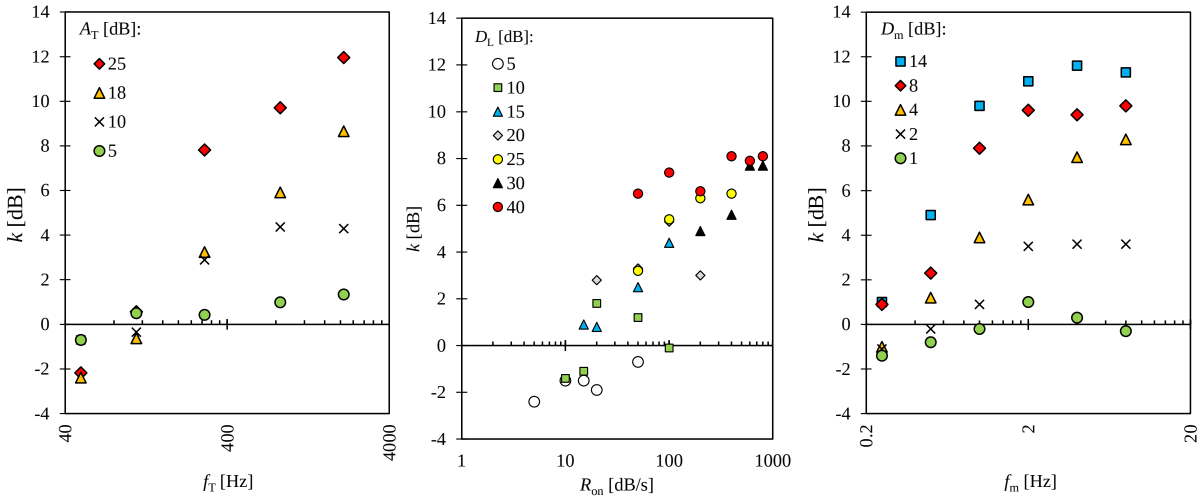

Fig. 3. Dependence of penalty *k* on the objective descriptors of sounds in Experiments A–C. (a) Experiment A (tonal sound): dependence of penalty on tonal frequency, f_T, and tonal audibility, A_T. (b) Experiment B (impulsive sound): dependence of penalty on onset rate, R_{on}, and level difference, D_L. (c) Experiment C (amplitude-modulated sound): dependence of penalty on modulation frequency, f_m, and modulation depth, D_m. In each experiment, the 95% confidence interval of each penalty observation was usually ±2 dB. Therefore, penalty differences smaller than 2 dB were usually non-significant (as well as values k< 2 dB).

Hongisto et al. (2019) showed that the AP of Experiment A could be predicted with high accuracy by a simple, analytic model, where the input parameters are A_T and f_T. Similar simple models would be useful also for Experiments B and C. Such models can be directly applied for noise measurements when the parameters describing the specific feature are known.

The Experiments A–C represents a unique and systematic analysis over the AP of noise carrying tonal, impulsive, or amplitude-modulated features. Similar coordinated research has not been previously done. It is quite clear, that penalty can be up to 8–12 dB. They suggest that constant penalty models are not justified: AP depends on the microstructure of the sound.

All sounds of Experiments A–C were synthetic because the properties had to be systematically controlled. It would be useful to test these findings using recorded real sounds.

CONCLUSIONS

This work summarizes the findings of three independent psychoacoustic Experiments A–C, which investigated the annoyance penalty (AP) due to tonality, impulsiveness, and amplitude modulation. In all three Experiments, the AP was determined using similar method, so that an overview between the Experiments was justified. The AP values ranged from 0 to 12 dB, depending on the feature. The AP clearly depends on the microstructure of the sound. The results can be applied in the assessment of AP in cases when scientifically justified methods rather than constant penalty models (found in many noise regulations) are needed. The results can also be used in the development of future penalty models.

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