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DEVELOPMENT AND PSYCHOACOUSTIC EVALUATION OF A CURVING NOISE CLASSIFICATION METHOD

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ABSTRACT

An objective evaluation method for the acoustic quality of train pass-by sounds is introduced, focusing on the perceptual attributes of two curve phenomena: flanging and squealing. Objective psychoacoustic parameters were found to be insufficient for accurately assessing these phenomena, which exhibit high spectrotemporal complexity, prompting the development of novel metrics. It should be noted that these phenomena are currently evaluated on-site only subjectively during the measurement process. To test the proposed approach, a laboratory psychoacoustic experiment was conducted with 18 subjects, consisting of two listening tests. The experiment was designed and executed in the PsychoPy environment, using 26 train pass-by recordings. In the first listening test, subjects rated their short-term perceived annoyance from the train pass-bys on the 11-point ICBEN scale. In the second listening test, after a short training session, subjects rated their perceived degree of flanging and squealing, each on a 4-point scale. Results showed strong associations between subjects' evaluations and the corresponding objective measures for flanging and squealing. Furthermore, higher perceived degrees of squealing and flanging were associated with increased annoyance. While these findings confirm the effectiveness of the novel approach for assessing the curve phenomena, future developments are proposed to further refine the measures.

Keywords: *Train noise, Squealing, Flanging, Annoyance, Psychoacoustics*

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1. INTRODUCTION

Curving noise is one of the loudest and most annoying types of train noise [1–3], occurring when a train negotiates a sharp curve. Two types of phenomena are particularly relevant: Squealing, and flanging. The nomenclature, definition, formation mechanisms and distinction of these phenomena have been subject to discussion and sometimes confusion [4–6]. Tab.1 gives a simplified summary of the two phenomena.

Table 1: Qualitative descriptions and mechanisms of the curving noise phenomena.

	Qualitative description	**Underlying mechanism**
Squealing	Tonal, high-frequency noise (250 Hz – 5 kHz) according to [2]	Lateral creepage of the train wheels, causing stick-slip excitation of wheel eigenmodes according to [3]
Flanging	Broadband, high-frequency noise (5 kHz – 10 kHz) according to [7]	Tarnishing of the wheel flange on the track head according to [8]

Several publications (e.g. [1, 2, 9, 10]) highlight the complexity of these phenomena. In particular, they name

- different, sometimes multiple mechanisms causing the different phenomena,
- stochastic, rather than deterministic behavior in their occurrence,
- the difficulty of clearly separating phenomena, and
- different frequency bandwidths for the phenomena.

Due to different research questions and goals, various categorizations and threshold of when a noise event is considered to be squealing or flanging have been defined. While some definitions are purely qualitative, without giving any clearly defined frequency ranges or sound level pressure thresholds (e.g. [3, 4]), others add an indication of frequency range (e.g. [6, 7]). Some publications additionally indicate the maximum sound pressure levels (SPL) measured during squeal noise events (e.g. [1, 9, 11]. A few publications give specific, technical definitions and thresholds for categorizing squealing and flanging noise [12–15]. However, justification for the values of these thresholds in all cases is the subjective experience of the authors. A large study on the perception of annoyance and tonality in train noise events (including but not limited to curving noise) has been conducted by Salz [16]. The proposed model for tonality correlates highly with tonality perception by the study participants. Apart from tonality, sharpness was found to be another relevant parameter for the evaluation of train noise events. The study could also link higher tonality in trains to higher discomfort (German "Unangenehmheit"). This study contributes to the perception-based classification of curving noise events and their link to annoyance, by presenting results of a participant study, investigating the perception of different curving noise phenomena.

2. METHODS

2.1 Data collection

A measurement system featuring a Class 2 SPL sensor (according to IEC 61672) was set up at a height of $1.8\,\mathrm{m}$ and a horizontal distance of $0.5\,\mathrm{m}$ from the outer rail on the outside of a meter-gauge curve with a radius of $150\,\mathrm{m}$. Additional sensors, including an accelerometer, were integrated into the measurement system. A-weighted SPL values (L_{AFmax}, L_{AS}, and L_{A95}) in one-second resolution, as well as spectral data in the ISO 266 [17] frequency bands ($6\,\mathrm{Hz}$–$16\,\mathrm{kHz}$), were collected. In addition to the measurement data, lossless audio recordings (FLAC format) of train passbys were obtained. Data collection was conducted from March 20, 2023, to December 18, 2023, capturing a total of approximately 62'000 train passages. The curve, located in an inhabited area, is prone to squealing and flanging noise events.

2.2 Preliminary curving noise classification

Train passbys were identified through an empirically found threshold value in the accelerometer data. As an indicator of possible squealing noise, a tonality metric ΔL_i was calculated for each second and each frequency band, based on [18]:

$$\Delta L_i = 2 * L_{pi} - L_{pi-1} - L_{pi+1} \tag{1}$$

where:

ΔL_i	The tonality value in the frequency band i
L_{pi}	SPL in frequency band i
L_{pi-1}	SPL in the frequency band below i
L_{pi+1}	SPL in the frequency band above i

After listening to train passages with a variety of tonality values, a preliminary detection threshold value $\Delta L_i = 30\,\mathrm{dB}$ in the frequency bands $f > 1\,\mathrm{kHz}$ for squealing events was chosen. For flanging noise events, a similar approach as in [14] was used, where the mean sound pressure level across frequency bands $5\,\mathrm{kHz}$-$16\,\mathrm{kHz}$ was calculated in a first step. As with the squealing noise detection, after listening to a number of train passages with different amounts of flanging noise (as to the perception of the authors), a preliminary detection threshold value of $L_{5-16k} > 65\,\mathrm{dB}$ was chosen. For both types of events, the maximum value within the second-resolution data of a train passby was used as indicative, whether the noise event is considered to be squealing and/or flanging.

2.3 Psychoacoustic experiment

As a first step, two additional threshold levels were defined for both squealing and flanging noise, in order to differentiate between no, minor, moderate, and strong occurrences (see Tab. 2). The thresholds were subjectively chosen by the authors and a subset of 42 recordings from the data set mentioned in section 2.1 was extracted, such as to have all intensity variations of the phenomena (from no squealing/flanging noise to strong squealing/flanging noise, including mixed intensities). This subset was tested with four expert listeners, who have several years of experience in either noise research or wheel/rail interaction phenomena. The 26 recordings showing the least deviation to the experts' categorization were then cut to a uniform length of $17\,\mathrm{s}$ and a raised-cosine fade-in and fade-out window of $1\,\mathrm{s}$ was applied to all signals.

The experiment was conducted in German. The study was designed to investigate the subjective auditory per-

Table 2: Threshold values for different intensities of squealing/flanging noise

	Squealing threshold values	**Flanging threshold values**
none	$\Delta L_i < 20\,\mathrm{dB}$	$L_{5-16k} < 41.7\,\mathrm{dB}$
minor	$20\,\mathrm{dB} < \Delta L_i < 30\,\mathrm{dB}$	$41.7\,\mathrm{dB} < L_{5-16k} < 65\,\mathrm{dB}$
moderate	$30\,\mathrm{dB} < \Delta L_i < 45\,\mathrm{dB}$	$65\,\mathrm{dB} < L_{5-16k} < 70\,\mathrm{dB}$
strong	$\Delta L_i > 45\,\mathrm{dB}$	$L_{5-16k} > 70\,\mathrm{dB}$

ception of train curving noise. In the first part, the focus was on evaluating the annoyance caused by curving noise. In the second part, each recording was evaluated on two separate four-point scales. Participants indicated their perception of the squealing noise ("Kreischen") and the flanging noise ("Zischeln") intensity present in the recording. Eighteen participants, aged 21 to 62 years (mean age 36; six women and twelve men), took part in a controlled study conducted in a room measuring approximately $14.9\,\mathrm{m}$ by $9.3\,\mathrm{m}$ with a reverberation time of $RT_{60} \approx 0.8\,\mathrm{s}$. The room was arranged to minimize reflections from tables (see Fig. 1): a full-range loudspeaker was positioned at a distance of $5\,\mathrm{m}$ from the participants, and a laptop was set on a table directly in front of them, with walls and seating configured to minimize extraneous reflections. The playback levels were initially calibrated to match the original train pass-by levels using an NTi XL2 measurement device, but since these levels would have been excessively loud and potentially harmful to participants, they were reduced by approximately 12 decibels to ensure auditory safety. The experiment was fully automated using PsychoPy [19], a python based experiment software. Before the experiment began, the participants were provided with a printed briefing that clearly outlined the procedure of the experiment and their roles.

In part 1 of the experiment, participants underwent a training phase with five practice train pass-by sounds before rating the overall annoyance on the 11-point ICBEN scale, with twenty-six recordings presented in a random order under a complete block design to ensure consistency across subjects. In part 2, the focus shifted to assessing intensities of the specific curving noise events. After a training session, including pronounced examples of both *squealing noise events* ("Kreischen") and *flanging noise events* ("Zischeln"), as well as a baseline recording with no squealing and flanging noise, participants rated these events on two separate four-point scales (0 indicating no presence of squealing/flanging, 3 indicating strong squealing/flanging) . Recordings had estimated L_{Aeq} values in the range $69\,\mathrm{dB(A)}$ to $82.3\,\mathrm{dB(A)}$, while estimated L_{AFmax} values were between $76.5\,\mathrm{dB(A)}$ and $96.6\,\mathrm{dB(A)}$.

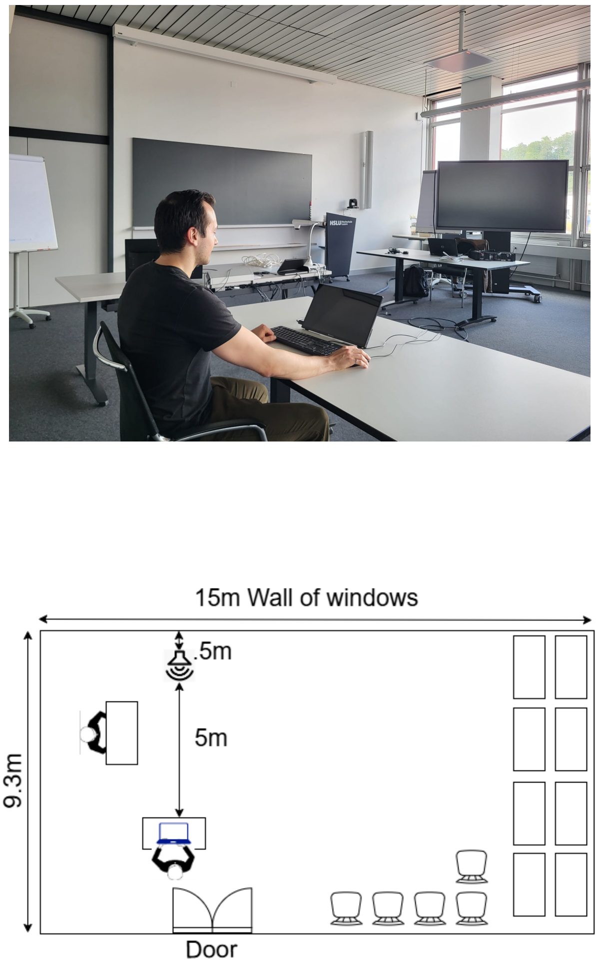

Figure 1: Experiment room. Top: Participant position, Bottom: Diagram of the experiment room with loudspeaker to the top, participant to the bottom and experimenter to the left side.

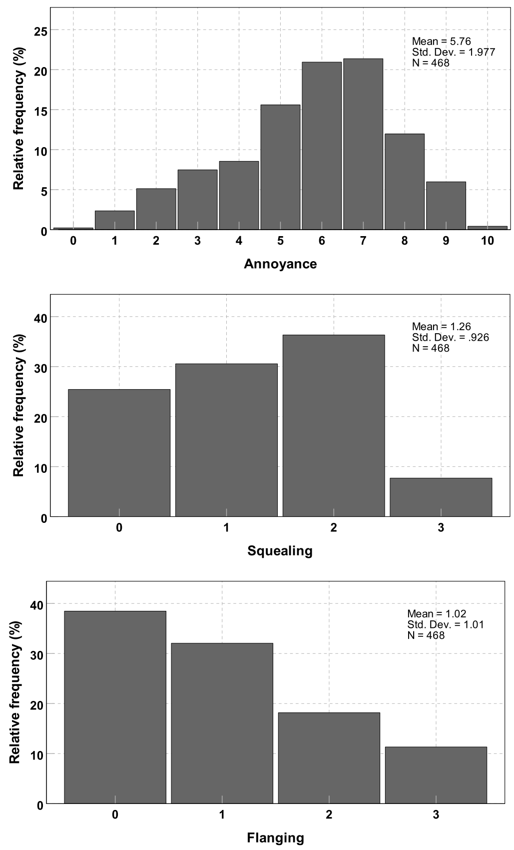

Figure 2: Histograms showing relative frequency of perceived annoyance (top), squealing (middle), and flanging (bottom) ratings in percent.

3. RESULTS

3.1 Psychoacoustic experiment

Fig. 2 shows the histograms of perceived annoyance (top), squealing (middle), and flanging (bottom) ratings as relative frequencies in %.

3.1.1 Annoyance

As shown in Fig. 3, the perceived annoyance ratings correlated strongly with the perceived squealing and flanging ratings. The perceived annoyance was also correlated bilaterally with L_{Aeq} and with L_{AFmax}. A linear mixed-effects model showed that both perceived flanging and perceived squealing, as well as their interaction could be used (indirectly) as predictors of perceived noise annoyance (all $p < .001$). The model shows that both squealing and flanging are independently associated with increased

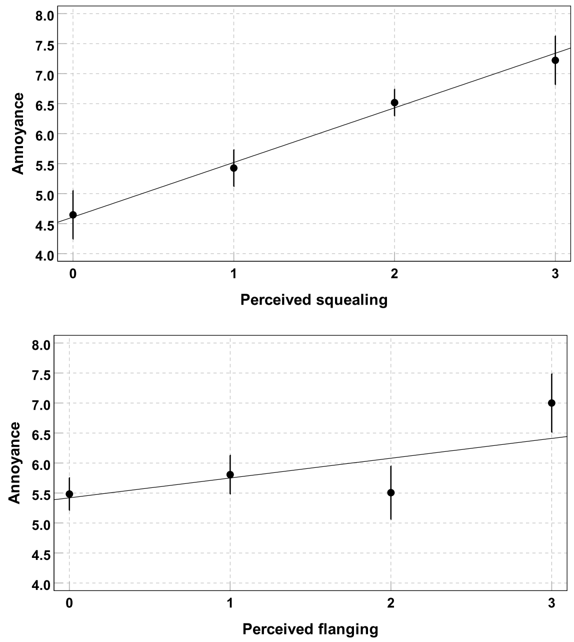

Figure 3: Perceived annoyance as a function of perceived squealing noise (top) and perceived flanging noise (bottom). Circles and whiskers represent mean values and 95% confidence intervals, respectively.

train noise annoyance, with squealing being a stronger predictor (both $p < .001$). However, the significant interaction ($p < .001$) shows that their co-occurrence does not amplify annoyance as much as expected from their individual contributions alone. The combined annoyance is slightly less than the sum of their individual effects. In the presence of squealing and flanging, L_{Aeq} or L_{AFmax} did not contribute significantly in any established model. Furthermore, the playback order of train noise stimuli showed a marginal and non-significant tendency to increase perceived annoyance.

As shown in Fig. 4, the thresholds for squealing and flanging noise detection proposed by the authors, corresponded to a clear difference in subjective annoyance ratings. Events defined as squealing or flanging show a difference of more than 1.5 points in short-term annoyance on the 11-point ICBEN scale. Flanging noise events were associated with slightly higher overall annoyance levels (mean: 6.9 points) than squealing noise events (mean: 6.6 points).

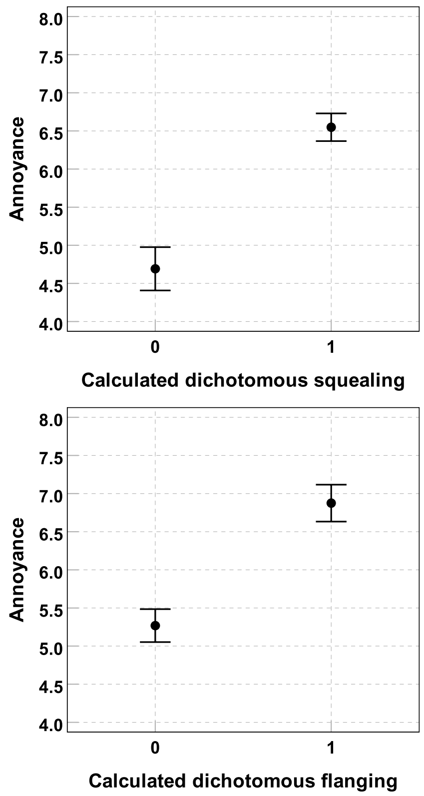

Figure 4: Annoyance as a function of proposed squealing (top) and flanging (bottom) noise thresholds. Circles and whiskers represent mean values and 95% confidence intervals, respectively.

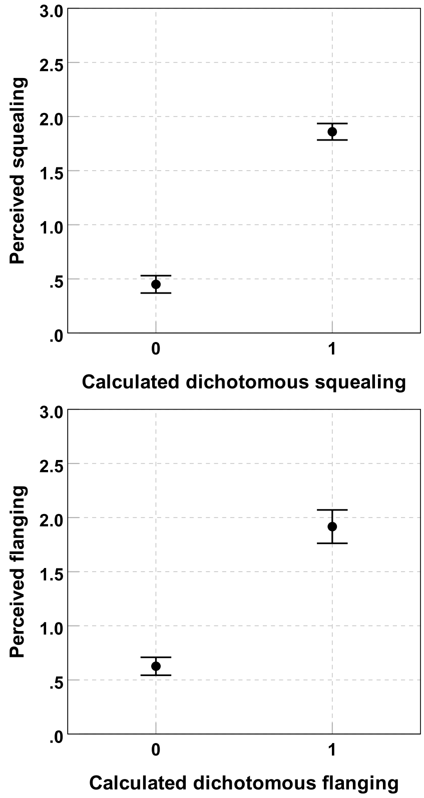

Figure 5: Subjective flanging/squealing vs. proposed squealing (top) and flanging (bottom) noise thresholds. Circles and whiskers represent mean values and 95% confidence intervals, respectively.

3.1.2 Squealing and flanging noise intensity

Fig. 5 shows, that the decision thresholds for squealing and flanging events, chosen by the authors, correspond well with the squealing/flanging noise intensity perception of participants. Events under the detection threshold had an average intensity perception of around 0.5 for squealing (between no and minor squealing) and around 0.6 for flanging (between no and minor flanging). Events over the detection threshold have an average intensity perception of around 1.9 (moderate squealing/flanging).

Tab. 3 (top) shows the distribution of the perceived squealing noise intensity perception, grouped by the squealing detection proposed by the authors. Events determined as non-squealing by the proposed threshold were mostly perceived as containing no squealing (58.6%) or minor squealing (38.4%). Only 3% of the events classified as non-squealing by the authors, were considered to contain moderate or strong squealing. As for events determined as squealing by the proposed threshold, these were mostly (98.9%) considered as squealing by participants as well, among which most events (61.1%) were considered to be moderately squealing.

Similarly, Tab. 3 (bottom) shows the distribution of the perceived flanging noise intensity perception, grouped by the flanging detection proposed by the authors. Events determined as non-flanging by the proposed threshold were mostly perceived as containing no flanging (52.5%) or minor flanging (34.3%). 13.3% of the events classified as non-flanging by the authors, were considered to contain moderate or strong flanging. As for events determined as flanging by the proposed threshold, these were mostly (93.0%) considered as flanging by participants as well.

Table 3: Comparison of calculated dichotomous squealing/flanging and perceived squealing/flanging.

			Perceived squealing			
			0	1	2	3
Calculated dichotomous squealing	0	Count	116	76	5	1
		Percentage	58.6%	38.4%	2.5%	0.5%
	1	Count	3	67	165	35
		Percentage	1.1%	24.8%	61.1%	13.0%
			Perceived flanging			
			0	1	2	3
Calculated dichotomous flanging	0	Count	170	111	37	6
		Percentage	52.5%	34.3%	11.4%	1.9%
	1	Count	10	39	48	47
		Percentage	6.9%	27.1%	33.3%	32.6%

3.1.3 Experts' vs. subjects' ratings

It was investigated whether railways and noise control experts' and subjects' squealing/flanging ratings were comparable. Fig. 6 compares the two datasets. Note that the actual linear regression lines (solid lines) are shown alongside hypothetical perfect matches (diagonal dashed lines). Experts rated squealing and flanging slightly more harshly than the participants in the experiment. This may be due to the reduced noise levels used during the experiment compared to the original recordings made beside the railway tracks. In other words, squealing and flanging noises are more prominent in real-world conditions than they were in the experimental setting.

4. DISCUSSION

Results of the presented psychoacoustic experiment suggest higher annoyance by train pass-by events, which were perceived as squealing or flanging. The more perceived squealing an event exhibited, the more annoying it was. As for events perceived as flanging, no strong difference in annoyance was visible for minor and moderate flanging, compared to no flanging. However, strong flanging was associated with a steep rise in subjects' annoyance.

Similar results were observed, when comparing perceived annoyance with the grouping of squealing and flanging noise events, proposed by the authors. Events classified as containing either squealing or flanging noise, were perceived as more annoying. When comparing the classification of the curving noise phenomena by subjects with the classification proposed by the authors, a good agreement was visible.

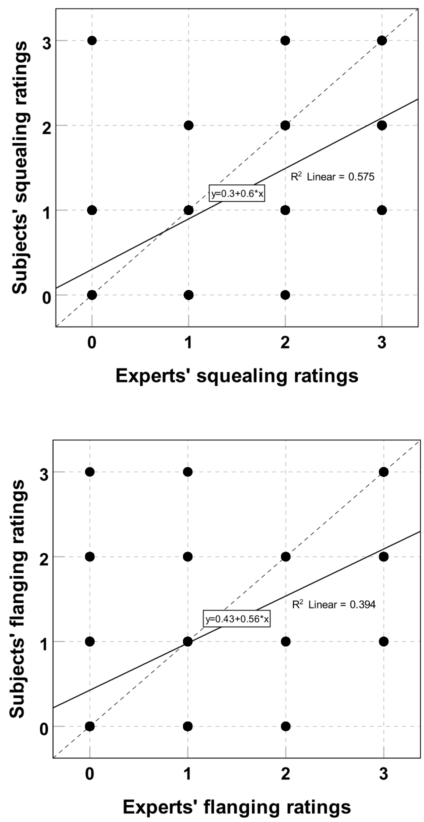

Figure 6: Subjective flanging/squealing vs. proposed four-level squealing noise thresholds (top) and flanging noise thresholds (bottom)

4.1 Limitations and further research

The detection and classification of squealing and flanging noise events in this study was executed on measurement data with a resolution of 1 s, where an event was classified as squealing or flanging, even when a single 1 s value was above the threshold. Therefore, no information about the duration of the phenomenon is contained in this classification. Presumably, there is a difference in the perception of prolonged squealing/flanging noise events, compared to short "bursts" of these phenomena. The influence of the duration on the annoyance and intensity perception is a subject for further studies.

Recordings used in this psychoacoustic study were gathered in close proximity to the wheel/rail interface with a single microphone. The recorded audio was played back with a single loudspeaker with a distance of 5 m to the participants in a normal meeting room, adding reverberation through its surfaces. No outdoor sound propagation effects were added to the stimuli. A more realistic representation of train pass-by events could be achieved through the use of binaural or ambisonic recording and playback techniques in a more representative distance to the train tracks and with the addition of video material. An even more controlled experiment could be achieved, using auralization of the phenomena. Playback in an anechoic room would prevent the potential influence of room characteristics.

Future research should include more advanced descriptors for tonality (e.g. as described in [16]) and possibly other psychoacoustic metrics to better represent human perception of curving noise phenomena. Larger subject sample sizes combined with high-resolution descriptors would allow for the research and definition of a perception based threshold for these phenomena or perception based correction factors in the calculation of train noise immissions. In addition, physiological variables, describing subliminal stress reactions to curving noise should be included. The effect of curving noise phenomena on sleep quality and cognitive tasks is yet another research gap to be filled.

5. CONCLUSIONS

A tonality-based approach for the detection of squealing noise and a level-based approach for the detection of flanging noise were implemented and compared to perceptual data collected in a psychoacoustic experiment. Events containing either squealing or flanging noise were perceived as more annoying. The proposed detection method and thresholds show a good separation of curving noise events, considering perceived annoyance. The proposed thresholds also correspond well to the intensity perception of participants. Future research should use more sophisticated, continuous psychoacoustic metrics so as to tailor threshold and correction factors closer to human perception. The measurement of physiological variables as well as the influence of curving noise phenomena on sleep and cognitive capabilities should further be included in future analysis.

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