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Pleasantness judgements of air diffuser noise and their relation to psychoacoustic parameters

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Abstract – This study investigates the subjective pleasantness of airflow noise generated by five air diffusers used in building ventilation systems and how it can be modelled by psychoacoustic parameters. Recordings were made in a hemi-anechoic chamber at various volume flow rates and subsequently auralised in a simulated room for a listening experiment. Thirty normal hearing participants compared the air diffuser stimuli using a paired comparison method across five blocks defined by equal sound pressure levels (35, 40, 45 dB(A)) or equal volume flow rates (400, 600 m^3/h). Additionally, psychoacoustic parameters were analysed for all stimuli. Results reveal differences in pleasantness between air diffuser stimuli in all blocks. While participants were able to determine consistent rank orders individually, a concordance analysis indicated only limited agreement across participants, except for the 600 m^3/h block where agreement was comparatively higher. Regression analyses revealed that both loudness and sharpness exhibited negative associations with subjective pleasantness, indicating that higher values of these psychoacoustic parameters reduced pleasantness. Combining these two descriptors slightly improved model performance compared with loudness alone, at the cost of increased model complexity. These findings highlight that even when sound pressure level or volume flow rate is held constant, subjective evaluation differences between air diffuser noises persist and can be explained by psychoacoustic factors. The study concludes that loudness is the dominant descriptor of subjective pleasantness of air diffuser noise, while sharpness may provide additional information. Therefore loudness and sharpness should be considered in future product assessment and design.

Keywords. Air diffuser noise, Pleasantness, Psychoacoustic modelling

1 Introduction

In industrialised countries, people spend most of their time indoors [1, 2]. The improvement of insulation standards results in more airtight construction. To ensure a constant supply of fresh air and maintain good indoor air quality, buildings are increasingly equipped with mechanical ventilation systems [3]. However, a side effect of these systems is the generation of airflow noise when air is transferred into rooms using, e.g., air diffusers. Even at low volume flow rates, the resulting sound pressure levels can exceed those usually found in quiet indoor environments. This can harm well-being and reduce acoustic comfort for occupants. Moreover, it is well known that indoor noise can have negative health effects [4]. In particular, ventilation noise has been shown to adversely affect alertness, speech production, and subjective acoustic comfort [5]. Consequently, regulatory standards limit the permissible noise emissions of technical systems in workplaces by setting specific threshold values [6].

To date, noise emissions have mainly been assessed using the A-weighted sound level (e.g. [7]). Whether the A-weighted sound level alone is sufficient for a valid assessment of how pleasant the noise from air diffusers is, or if additional psychoacoustic analyses are required, needs to be evaluated. This study uses pleasantness as the subjective assessment instead of annoyance or preference as often found in psychoacoustic studies. Here, pleasantness is an operational term for the integral evaluative judgement of the sound under controlled listening conditions. It may subsume multiple perceptual attributes into a single appraisal of how agreeable a sound is. Pleasantness differs from noise annoyance, which has been described as a multifaceted concept comprising evaluative aspects (notably nuisance and unpleasantness) as well as

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disturbance- and interference-related aspects, and which is additionally shaped by situational and individual factors [8, 9]. In contrast, preference refers to comparative choices between alternatives and depends on the judgement criterion, which may, for instance, be pleasantness. Such choice outcomes can be modelled as preference probabilities with respect to the specified target attribute [10]. A number of studies have investigated how noise from air supply sources is perceived by combining psychoacoustic analyses with participant-based assessments. Töpken and van de Par [11] analysed the acoustic quality of fans. Pairs of adjectives used to describe fan noises were identified using a semantic differential, and a principal component analysis (PCA) revealed three dominant perceptual groups – unpleasant, humming, and shrill – even though all noises had the same A-weighted sound pressure level. Based on specific loudness ratios, they proposed new parameters, which were shown to capture these perceptual distinctions more effectively than classical psychoacoustic parameters. In a subsequent study, they demonstrated that sharpness together with the introduced parameter N_{ratio} significantly influence the preference for fan noise [12]. Schneider and Feldmann [13] examined fan noise annoyance and confirmed loudness as the dominant factor. They also noted that tonality and fluctuation strength can be relevant factors. A psychoacoustic study by Susini et al. [14] characterised the preference for air-conditioning noise by using paired comparison methods, multidimensional scaling, and acoustic parameters. They found that preference judgements were associated not only with loudness but also with spectral characteristics.

Hohls et al. [15] analysed preference ratings for heating, ventilation, and air conditioning (HVAC) noise and identified loudness as the dominant parameter. They emphasised, however, that sharpness and roughness should not be overlooked in noise assessment. Scouarnec and Bennouna [16] investigated annoyance caused by electric vehicle fan systems. While loudness was the best indicator of subjective annoyance, the study highlighted that additional parameters like tonality are necessary for a comprehensive evaluation. However, tonality alone did not fully account for perceptual differences. Bennouna et al. [17] compared standard objective noise metrics (e.g., overall A-weighted levels and one-third-octave spectra) with psychoacoustic parameters for automotive HVAC systems. It was concluded that standard objective noise metrics are insufficient to represent annoyance. In particular, tonality, roughness, and sharpness were found to offer additional explanatory power in complex noise environments. Ma et al. [18] examined the psychological effects of HVAC noise. They found that loudness had a significant correlation with subjective ratings and cognitive performance, while sharpness had less impact. A study by Davies et al. [19] included a wide range of HVAC sounds with varying acoustic characteristics. It was found that loudness alone explained most of the variance in subjective annoyance assessments. Ayr et al. [20] focused on noise indices based on sound pressure level or loudness for air-conditioning noise in offices and found that these align with participants' judgements on loudness and annoyance. Overall, loudness is identified as the dominant factor in the evaluation of HVAC and ventilation noise. However, most of those studies show that additional psychoacoustic parameters are required to account for differences in subjective evaluations, but the specific parameters identified differ across studies.

The aforementioned studies focused on HVAC or ventilation noise, which necessarily includes noise generated by fan operation. Ostmann et al. [21, 22] recently conducted simulation-based investigations of swirl and slot diffusers, identifying dominant geometric regions as the main sources of aeroacoustic emission. However, these studies did not address how such emissions are perceived by listeners. The present study, therefore, investigates airflow noise generated by five different air diffusers, recorded in a hemi-anechoic chamber at varying volume flow rates. Fan noise was effectively suppressed in the experimental setup through the use of silencers and long duct segments. These recordings were used in a listening experiment employing dominance paired comparison as the scaling method, as described, e.g., by Wickelmaier et al. [23]. The paired comparison dominance procedure was chosen because it is especially effective for detecting subtle auditory differences between stimuli while yielding lower inter-participant variance than ranking or direct scaling methods [23]. In the present study, pleasantness is deliberately chosen as the evaluative construct used in the paired comparison dominance procedure, unlike much of the existing literature, which focuses on annoyance or preference. Participants made discrete pairwise judgements indicating which of two stimuli was perceived as more pleasant. Pleasantness was chosen as it reflects that air diffuser noise is not primarily expected to be disturbing but rather should, ideally, contribute to a comfortable and unobtrusive indoor environment. Accordingly, the listening task targets pleasantness as an immediate evaluative judgement under controlled conditions, rather than annoyance. And in contrast to preference, which is commonly used in related work, pleasantness reflects an immediate perceptual judgement that integrates multiple perceptual attributes into an overall appraisal of agreeableness. Therefore, pleasantness is specified here as the judgement criterion in the paired-comparison task.

This study adopts a two-step approach that first establishes evaluative differences in pleasantness from paired comparison dominance judgements and then quantifies their relation to psychoacoustic parameters. Given that loudness is widely recognised as the dominant perceptual factor in the evaluation of ventilation noise, maintaining a constant sound pressure level allows the identification of other perceptual characteristics that may influence the pleasantness of air diffuser noise independently of the level. In practical applications, air diffusers are typically operated at a prescribed volume flow rate; therefore, differences in pleasantness between air diffusers

operating at the same volume flow rate are also investigated. Correspondingly, the research questions are:

(RQ1) Are there differences in the subjective pleasantness of noises from different air diffusers even when presented at equal sound pressure level or equal volume flow rate?
(RQ2) To what extent can psychoacoustic parameters model subjective pleasantness from air diffuser noise?

To address RQ1, block-wise rank orders of the air diffuser stimuli are derived from the paired comparison data and inter-listener concordance is assessed. To address RQ2, linear regression analyses are conducted with subjective pleasantness rankings as the dependent variable and psychoacoustic parameters as descriptors.

2 Method

2.1 Measurements

The assessment of the acoustic emissions from various air diffusers under controlled conditions was conducted in the hemi-anechoic chamber of the Institute for Hearing Technology and Acoustics, RWTH Aachen University, Germany. Sound power measurements were carried out in accordance with DIN EN ISO 3745 [24]. For this purpose, a hemispherical microphone array consisting of 20 Sennheiser KE 4-211-2 microphones was arranged on six metal struts around the sound source, forming a measurement surface with a radius of 1.86 m. The array was mounted on an inverted ceiling panel structure ($4.2 \times 4.2\,\mathrm{m}^2$), thereby directing the airflow upwards. Wind screens were attached to the microphones to prevent flow-related disturbances. An overview of the measurement setup is shown in Figure 1. In addition, the air diffuser noise was recorded using a low-noise measurement microphone (1/2″ G.R.A.S. 40 HL) placed at the centre of the array, to ensure high-quality recordings for the listening experiment. The measurements with the hemispherical microphone array were used for sound power determination, whereas the stimuli for the listening experiment were based on the recordings from the low-noise measurement microphone.

A total of five ceiling air diffusers from three different manufacturers, varying in sizes and outlet designs, were analysed. In the following, the air diffusers are labelled D1 to D5. D1 and D2 are slot diffusers, with outlet sizes of $1000 \times 190\,\mathrm{mm}^2$ and $1300 \times 161\,\mathrm{mm}^2$, respectively. D3 to D5 are swirl diffusers with an outlet size of $600 \times 600\,\mathrm{mm}^2$, but different rectangular plenum box sizes: $570 \times 570\,\mathrm{mm}^2$ for D3 and $470 \times 470\,\mathrm{mm}^2$ for D4 and D5. During the measurement, volume flow rates were varied from 150 to $600\,\mathrm{m}^3/\mathrm{h}$ in $50\,\mathrm{m}^3/\mathrm{h}$ increments; additionally, all air diffusers except D2 were measured at 700 and $800\,\mathrm{m}^3/\mathrm{h}$.

To deliver a precise and quiet air supply, a mobile unit equipped with a speed-controlled fan was designed. The volume flow rate was recorded through active pressure measurement via an orifice. To reduce noise emissions from the supply system, several silencers were installed both upstream and downstream of the fan. Only smooth spiral ducts were used, and the airflow was directed through the longest feasible straight pipe section, limited by the laboratory space, to minimise turbulence. Additional silencers were installed in the long pipe section to further reduce airflow noise within the duct. This design ensured that the recorded stimuli were dominated by diffuser-generated airflow noise, while fan noise was effectively suppressed.



Figure 1. Measurement setup in the hemi-anechoic room of the Institute for Hearing Technology and Acoustics, RWTH Aachen University, Germany. In the middle of the ceiling panel construction, the air diffusers are inserted. The hemispherical microphone array is centered above the air diffuser outlet.

2.2 Auralisation

For the listening experiment, the recorded air diffuser noises were auralised in a virtual cuboid room ($V = 168\,\mathrm{m}^3$) using the room acoustics simulation software RAVEN [25, 26], which generates binaural room impulse responses. Auralisation was chosen to place the controlled source recordings in a defined room-acoustic context, providing a plausible, controlled, and repeatable listening scenario. To obtain binaural stimuli – the sounds a listener would perceive at the investigated position – the simulated impulse responses were convolved with the recorded air diffuser noises. Binaural reproduction was used to provide a natural headphone-based presentation that more closely approximates real-world listening than monaural reproduction. Figure 2 shows the room layout, indicating the positions of the source and receiver. The source is depicted as a loudspeaker on the ceiling, while the receiver is shown as a head model at the listening position. The source was positioned 0.5 m to the left, 1.0 m in front, and 1.5 m above the receiver. The room featured a carpeted floor, plastered walls, and an installed acoustic ceiling. The simulation was carried out at a room temperature of 20 °C, with a relative humidity of 50%, and

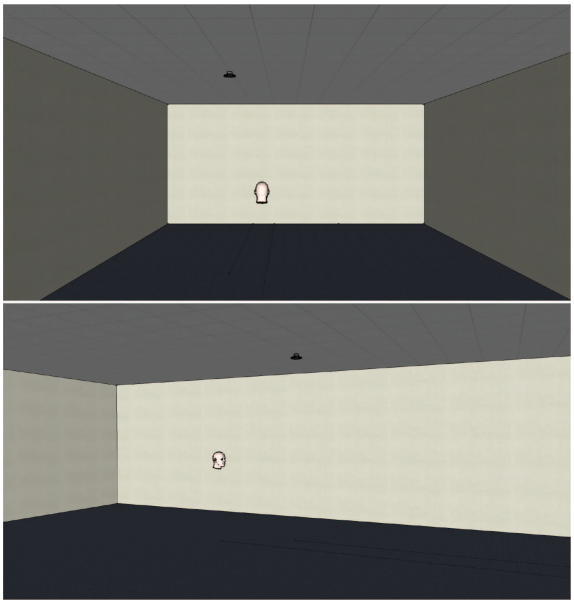


Figure 2. Simulated room for the auralisation. The loudspeaker on the ceiling represents the air diffuser as the source, and the head model represents the receiver.

an air pressure of 1013.25 hPa. The reverberation time of the room was set to $T_{30} = 0.65$ s.

2.3 Stimuli

After the auralisation, all stimuli were shortened to 3 s and smoothed with a 5 ms fade-in and fade-out using a Hann window. They were then grouped into five blocks based on either sound pressure level or volume flow rate. Table 1 summarises the selected stimuli for each block along with their volume flow rate and sound pressure level. Three blocks were defined by target sound pressure levels: 35 dB(A), 40 dB(A), and 45 dB(A). The stimuli in these blocks have approximately equal sound pressure levels (maximum deviation ±2 dB), as shown in Table 1. These level deviations occurred because the stimuli were not level-normalised, but reflect the actual measured levels at the respective volume flow rate after auralisation. The remaining two blocks, 400 m^3/h and 600 m^3/h, contained stimuli with the same volume flow rate but different resulting sound pressure levels. Figure 3 shows the A-weighted sound pressure levels of the air diffuser stimuli at all measured volume flow rates. These levels correspond to the sound pressure at the left ear of the receiver through headphones, considering the auralisation. The stimuli used in the listening experiment are highlighted: in yellow for the 35, 40, and 45 dB(A) blocks, and in red for the 400 and 600 m^3/h blocks. Figure 4 offers a representative comparison of the frequency spectra of the air diffuser stimuli between the 40 dB(A) and 400 m^3/h blocks. It can be seen that the frequency spectra align more closely when stimuli are grouped by sound pressure level and show greater variation when grouped by volume flow rate.

2.4 Psychoacoustic parameters

The stimuli used in the listening experiment were also examined for their psychoacoustic parameters using the ArtemiS Suite 13.1 software from Head acoustics GmbH. The analysis covered loudness in sone (DIN 45631 [27]), sharpness in acum (DIN 45692 [28]), roughness in asper (ECMA-418-2 [29]), and tonality in tu_{HMS} (ECMA-74 [30] and ECMA-418-2 [29]). Additionally, the parameters N_{low} and N_{ratio} were assessed for each stimulus [11]. N_{low} represents the ratio of specific loudness from 0 to 2.5 Bark relative to the total loudness N of the stimulus. N_{ratio} reflects the ratio of specific loudness in the range from 2 to 5 Bark to that in the range from 10 to 24 Bark. All values were calculated for the left ear and are provided in Table 1. The psychoacoustic parameters indicate that there are measurable and audible differences between the stimuli generated by different air diffusers. This interpretation is supported by the just noticeable differences (JNDs) reported by You and Jeon [31], which are 0.5 sone for loudness, 0.08 acum for sharpness, and 0.04 asper for roughness. For tonality, N_{low} and N_{ratio} no JNDs have been reported. For loudness, the differences between stimuli within a block did not consistently exceed the JND. In each block, at least one pair of stimuli fell below this threshold, yet in every block there were pairs exceeding the JND, with maximum within-block values ranging from 0.6 sone in the 35 dB(A) block up to 8.5 sone in the 600 m^3/h block. A comparable pattern emerged for sharpness: only in the 600 m^3/h block did all stimuli differ by more than the JND, while in the other blocks differences between some stimuli remained below the JND. For roughness and tonality, the standard ECMA-418-2 [29] defines threshold values of 0.2 asper and 0.4 tu_{HMS}, respectively. As detailed in Table 1, for air diffuser noise the values for both parameters stayed below these thresholds, suggesting that the stimuli were not perceived as prominently rough or tonal. It is noteworthy that stimuli with the same sound pressure level did not necessarily have the same loudness, and vice versa. For example, in the 45 dB(A) block the stimuli from air diffuser D2 and D3 had a sound pressure level of 44.8 dB(A) yet their loudness differed by 1.17 sone. Conversely, in the 35 dB(A) block the stimuli of D3 and D4 had a loudness of 1.54 sone but differed in sound pressure level by 0.6 dB.

2.5 Listening experiment

Thirty participants took part in the listening experiment, including 22 women, 7 men, and 1 non-binary person, aged between 18 and 38 years (mean age 23 years). Data collection was conducted at the Work and Engineering Psychology, RWTH Aachen University, Germany. All participants had normal hearing, confirmed through audiometric screening at 500, 1000, 2000, and 4000 Hz with thresholds ≤20 dB HL, and were included in the data analysis.

Participants sat in a listening booth and evaluated the air diffuser stimuli, presented via Sennheiser HD 650

Table 1. Volume flow rate $\dot{V}$, A-weighted sound pressure level, and the values for the psychoacoustic parameters loudness N, sharpness S, roughness R, and tonality T, as well as for the parameters N_{low} and N_{ratio} for the stimuli of the air diffuser D1 to D5 in the blocks 35 dB(A), 40 dB(A), and 45 dB(A), 400 m^3/h, and 600 m^3/h, calculated for the left ear after the auralisation.

Block	Air Diffuser	$\dot{V}$ [m^3/h]	SPL [dB(A)]	N [sone]	S [acum]	R [asper]	T [tu_{HMS}]	N_{low}	N_{ratio}
35 dB(A)	D1	300	35.5	1.99	0.99	0.13	0.05	0.22	1.29
	D2	400	35.6	2.15	1.13	0.10	0.05	0.21	1.07
	D3	350	34.6	1.54	0.93	0.05	0.10	0.48	1.76
	D4	450	35.0	1.54	0.92	0.05	0.13	0.45	1.97
	D5	450	35.6	1.88	0.93	0.08	0.07	0.37	1.42
40 dB(A)	D1	350	39.6	3.09	1.05	0.14	0.07	0.20	0.98
	D2	500	41.5	4.03	1.46	0.10	0.07	0.17	0.63
	D3	500	40.0	2.59	0.93	0.07	0.17	0.45	1.61
	D4	550	39.4	2.48	0.79	0.10	0.17	0.43	2.02
	D5	550	41.2	3.54	1.00	0.09	0.17	0.31	1.05
45 dB(A)	D1	400	43.5	4.40	1.23	0.11	0.08	0.16	0.75
	D2	550	44.8	5.31	1.68	0.06	0.07	0.14	0.54
	D3	600	44.8	4.14	1.00	0.08	0.18	0.40	1.37
	D4	800	46.2	5.48	1.20	0.11	0.16	0.30	0.88
	D5	600	43.0	4.29	1.18	0.07	0.14	0.27	0.85
400 m^3/h	D1	400	43.5	4.40	1.23	0.11	0.08	0.16	0.75
	D2	400	35.6	2.15	1.13	0.10	0.05	0.21	1.07
	D3	400	36.6	1.82	0.89	0.05	0.18	0.47	1.91
	D4	400	33.0	1.29	1.02	0.04	0.09	0.45	1.65
	D5	400	33.4	1.49	0.98	0.05	0.09	0.40	1.59
600 m^3/h	D1	600	56.2	11.5	2.03	0.10	0.12	0.12	0.44
	D2	600	47.7	6.73	1.86	0.11	0.09	0.14	0.48
	D3	600	44.8	4.14	1.00	0.08	0.18	0.40	1.37
	D4	600	41.1	2.97	0.81	0.11	0.17	0.39	1.80
	D5	600	43.0	4.29	1.18	0.07	0.14	0.27	0.85

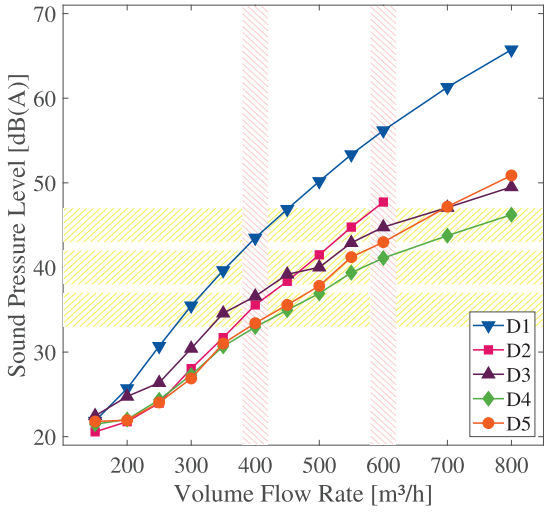


Figure 3. Sound pressure level in dB(A) for the volume flow rate, measured in steps of 50 m^3/h, for each air diffuser D1 to D5. The stimuli for the listening experiment in the 35, 40, and 45 dB(A) blocks are highlighted in yellow, and those in the 400 and 600 m^3/h blocks are highlighted in red.

headphones. A paired comparison dominance procedure was used as the experimental method because it is particularly suitable for detecting subtle auditory differences that are difficult to assess through absolute judgements. In this method, stimuli are presented in direct pairs, and participants are asked to indicate which stimulus they found more pleasant. In the presented experiment, the question posed in German was *Welches Geräusch ist angenehmer?*, which translates into English as *Which sound is more pleasant?*. After three practice trials, the five stimuli, one from each air diffuser, were paired in all possible combinations within each block, resulting in 50 experimental trials. To prevent order effects, the presentation order of the blocks, the stimulus pairings within each block, and the sequence of stimuli within each pair were randomised across participants using a predefined seed variable and an associated stimulus list.

3 Results

3.1 Consistency analysis

The results first address RQ1, examining whether air diffuser noises presented at equal sound pressure level or equal volume flow rate differ in subjective pleasantness. Due to the limited number of five stimuli per block, a classical consistency analysis or the use of point probabilities was not applicable. Classical consistency approaches in paired comparison research typically rely on repeated

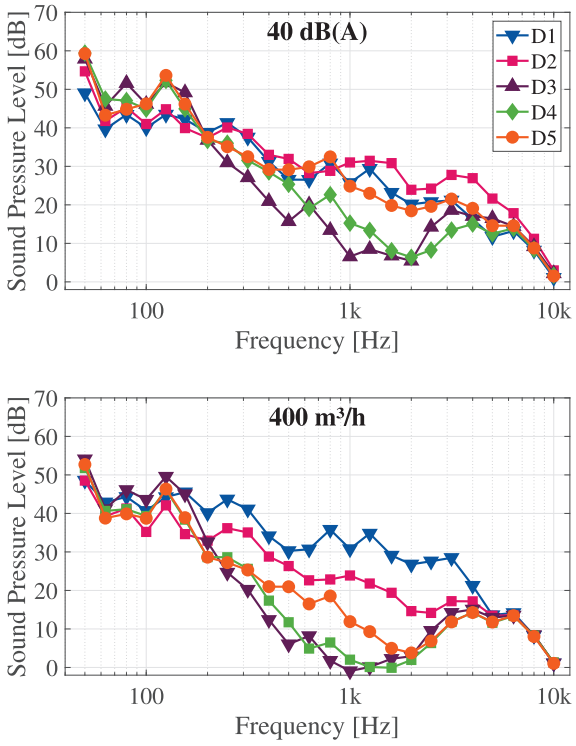


Figure 4. Comparison of the frequency spectra of the air diffusers at similar sound pressure level of 40 dB(A) (top) and at the same volume flow rate of 400 m^3/h (bottom).

comparisons or on estimating choice probabilities across stimulus pairs to assess agreement with a fully transitive ordering. With only five stimuli per block and no repeated pairings, such approaches would yield unstable estimates. Instead, the consistency of the participant's pleasantness judgements was assessed based on the number of circular triads each participant exhibited. Circular triads describe intransitive relations within a set of paired comparisons, that is, situations in which the observed relations cannot be represented by a single transitive ordering of the stimuli. The occurrence of circular triads, therefore, indicates inconsistent judgements and provides a commonly used measure of internal consistency in paired comparison data [32]. Figure 5 shows the distribution of circular triads among participants for each block. Across all blocks, most participants showed no circular triads, indicating high internal consistency. The 600 m^3/h block had the highest number of participants with no circular triads, while the 35 dB(A) block had the fewest. The higher number of circular triads in the 35 dB(A) block may be explained by reduced perceptual discriminability between the stimuli, as their acoustic characteristics are more similar, which is reflected in a more limited value range of the psychoacoustic parameters compared to the other blocks (cf. Tab. 1). With only five stimuli per block, a maximum of five circular triads is possible; this maximum was reached by one participant in the 40 dB(A) block. To ensure reliable pleasantness judgements, participants

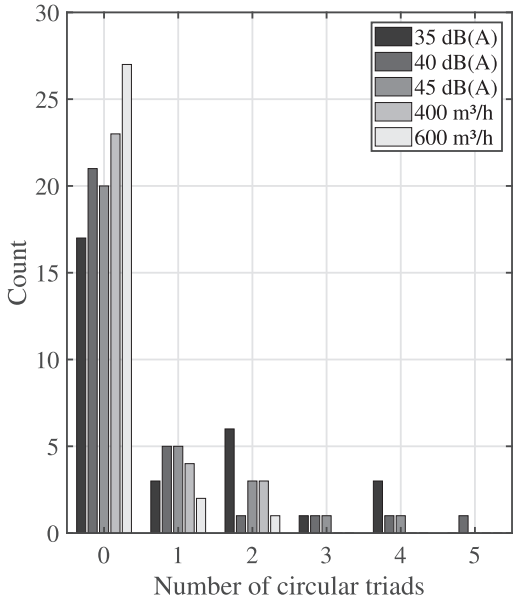


Figure 5. Count of participants for the number of circular triads in each block.

Table 2. Number of consistent participants m and Kendall's coefficient of concordance u, including the theoretical minimum of concordance u_{min} for each block.

Block	35 dB(A)	40 dB(A)	45 dB(A)	400 m^3/h	600 m^3/h
m	20	26	25	27	29
u	0.40	0.44	0.44	0.48	0.79
u_{min}	−0.053	−0.040	−0.040	−0.037	−0.034

with more than one circular triad per block were excluded from further analysis.

Table 2 lists the resulting number of participants m per block, along with Kendall's coefficient of concordance u for paired-comparison data, as defined by Kendall and Smith [32]. Kendall's coefficient of concordance u quantifies the overall agreement across all participants within a block and equals 1 in the case of complete agreement. The theoretical minimum value of u, denoted u_{min}, reflects total disagreement and varies by the number of participants. For comparability across blocks, both u and u_{min} are reported in Table 2. Across blocks, concordance u ranged from 0.40 to 0.79, with the lowest concordance in the block with the quietest stimuli (35 dB(A)) and the highest concordance in the block with the highest volume flow rate (600 m^3/h).

3.2 Pleasantness ranking

Tables 3 to 7 display the result matrices for each block. Each cell indicates how many participants rated the stimulus in the row as more pleasant than the one in the column. The last column lists, for each stimulus, the total

Table 3. Result matrix for the 35 dB(A) block.

	D1	D2	D3	D4	D5	∑
D1		15	4	2	9	30
D2	5		2	2	2	11
D3	16	18		14	17	65
D4	18	18	6		17	59
D5	11	18	3	3		35

Table 4. Result matrix for the 40 dB(A) block.

	D1	D2	D3	D4	D5	∑
D1		23	5	4	14	46
D2	3		2	2	3	10
D3	21	24		9	22	76
D4	22	24	17		23	86
D5	12	23	4	3		42

Table 5. Result matrix for the 45 dB(A) block.

	D1	D2	D3	D4	D5	∑
D1		25	5	19	8	57
D2	0		2	4	1	7
D3	20	23		20	13	76
D4	6	21	5		4	36
D5	17	24	12	21		74

Table 6. Result matrix for the 400 m^3/h block.

	D1	D2	D3	D4	D5	∑
D1		0	3	2	2	7
D2	27		9	3	2	41
D3	24	18		8	14	64
D4	25	24	19		21	89
D5	25	25	13	6		69

Table 7. Result matrix for the 600 m^3/h block.

	D1	D2	D3	D4	D5	∑
D1		1	1	0	0	2
D2	28		4	0	0	32
D3	28	25		2	15	70
D4	29	29	27		29	114
D5	29	29	14	0		72

number of times it was judged as more pleasant. To visualise pleasantness, the sums of the matrices (Tabs. 3–7) were normalised to a range between 0 and 1 and plotted in Figure 6 as normalised pleasantness ranking PL. The following results are reported descriptively and aim to highlight qualitative patterns in the paired comparison outcomes. Statistical tests were not applied as the limited number of stimuli does not support reliable statistical inference. Differences in pleasantness patterns can be observed between blocks defined by sound pressure level (35, 40, and 45 dB(A)) and those defined by volume flow rate (400 and 600 m^3/h), resulting in different rank orders of stimuli.

As only pairwise comparisons within blocks were conducted, effects of varying operating states within a single air diffuser cannot be analysed. Pleasantness rankings, however, vary between blocks. For example, stimuli from air diffuser D2 are consistently rated as the least pleasant in the level-defined blocks but are rated more pleasant than stimuli from D1 in the volume-flow-rate-defined blocks. Stimuli from air diffuser D4 are the second or the most pleasant across all blocks except for the 45 dB(A) block, likely due to their higher sound pressure level and volume flow rate in this block, cf. Table 1.

Stimuli from D3 rank among the most pleasant in the level-defined blocks but score lower in the volume-flow-rate-defined blocks. Identical stimuli appearing in two blocks further illustrate shifts. For instance, the stimulus from D1 is identical in the 45 dB(A) and 400 m^3/h block (cf. Tab. 1) but ranks mid-range in the former but

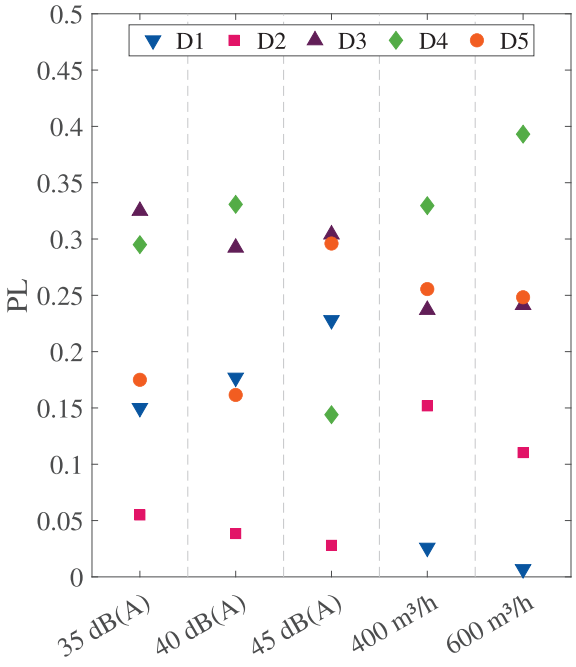


Figure 6. Normalised pleasantness ranking PL for the air diffusers D1 to D5 in each block, resulting from the pleasantness ratings by normalising the sums of the results matrices (Tabs. 3–7) to a range between 0 and 1.

lowest in the latter. Similarly, the identical D2 stimulus ranks lowest at 35 dB(A), but exceeds D1 at 400 m^3/h. Identical stimuli from D3 and D5 appear in the 45 dB(A) and 600 m^3/h block. While their relative positions remain similar, both are outperformed by the pleasantness ranking of the stimulus from D4 in the 600 m^3/h block. Overall, the observed changes in ranking across the level-defined blocks may suggest that sound characteristics in addition to loudness influence the pleasantness rating, whereas larger loudness differences in the volume-flow-rate-defined blocks may dominate the pleasantness ranking, resulting in the same ordering.

Table 8. Block-wise linear regression results for five candidate predictor sets (N, S, $N+S$, N_{low}, and N_{ratio}) for the normalised pleasantness ranking PL (cf. Fig. 6) . Reported are the estimated coefficients (β_0 and slopes), RMSE, adjusted R^2, the overall model F-test and its p-value (p_{model}), and the Bayesian information criterion (BIC). The Total column gives the aggregated BIC across all blocks ($\text{BIC}_{\text{total}}$). For loudness N and sharpness S the linear regressions are plotted in Figure 7.

		35 dB(A)	40 dB(A)	45 dB(A)	400 m³/h	600 m³/h	Total
N	β_0	0.93	0.75	0.98	0.39	0.44	
	β_N	−0.40	−0.17	−0.16	−0.09	−0.04	
	RMSE	0.02	0.03	0.06	0.04	0.06	
	R^2_{adj}	0.97	0.94	0.71	0.86	0.83	
	F-test	151.0	67.6	10.7	25.8	20.7	
	p_{model}	0.001	0.004	0.047	0.015	0.020	
	BIC	−25.4	−21.0	−12.9	−16.5	−13.2	−73.0
S	β_0	1.22	0.65	0.71	0.94	0.56	
	β_S	−1.04	−0.43	−0.41	−0.71	−0.26	
	RMSE	0.07	0.05	0.06	0.08	0.05	
	R^2_{adj}	0.63	0.84	0.73	0.52	0.89	
	F-test	7.7	22.5	11.9	5.3	32.6	
	p_{model}	0.069	0.018	0.041	0.104	0.011	
	BIC	−12.1	−16.0	−13.3	−10.4	−15.2	−50.8
$N+S$	β_0	0.99	0.74	0.99	0.48	0.53	
	β_N	−0.37	−0.12	−0.10	−0.08	−0.02	
	β_S	−0.13	−0.15	−0.25	−0.10	−0.17	
	RMSE	0.02	0.02	0.03	0.05	0.05	
	R^2_{adj}	0.97	0.96	0.94	0.80	0.88	
	F-test	60.9	47.5	30.2	9.1	15.1	
	p_{model}	0.016	0.021	0.032	0.100	0.062	
	BIC	−24.8	−23.1	−20.9	−15.2	−15.2	−74.9
N_{low}	β_0	−0.08	−0.05	0.02	−0.04	−0.06	
	$\beta_{N\text{low}}$	0.80	0.81	0.70	0.72	0.98	
	RMSE	0.05	0.06	0.10	0.06	0.08	
	R^2_{adj}	0.82	0.75	0.21	0.74	0.71	
	F-test	18.9	13.1	2.1	12.2	11.0	
	p_{model}	0.023	0.036	0.245	0.040	0.045	
	BIC	−15.7	−13.7	−7.9	−13.3	−10.6	−45.1
N_{ratio}	β_0	−0.24	−0.05	−0.04	−0.10	−0.03	
	$\beta_{N\text{ratio}}$	0.29	0.20	0.27	0.21	0.23	
	RMSE	0.04	0.03	0.09	0.07	0.07	
	R^2_{adj}	0.88	0.92	0.37	0.68	0.79	
	F-test	28.9	45.6	3.4	9.4	15.6	
	p_{model}	0.013	0.007	0.163	0.055	0.029	
	BIC	−17.6	−19.2	−9.0	−12.3	−12.0	−54.0

3.3 Psychoacoustic modelling

While RQ1 addresses whether differences in pleasantness between air diffusers persist under controlled conditions, it does not provide insight into the factors influencing these judgements. Subsequently, RQ2 is addressed, examining to what extent psychoacoustic parameters model subjective pleasantness. To formally quantify these relationships, separate linear regression models were fitted for each block and predictor set. The corresponding parameter estimates, model statistics, and Bayesian information criterion (BIC) are summarised in Table 8. A comparison of the parameter estimates shows that loudness N and sharpness S reveal a negative association with the normalised pleasantness rankings PL, while N_{low} and N_{ratio} have a positive association with PL. Therefore, stimuli with higher N or S generally receive lower PL, as illustrated by the block-wise linear regression results in Figure 7. The steepness of the regression fits vary per block depending on the inter-stimulus variance of loudness and sharpness. Table 8 also shows the statistical results for a multiple linear regression combining loudness and sharpness $N+S$.

Comparing the results of the multivariate model $N+S$ with the univariate models N and S, $N+S$ achieves a lower BIC in three out of five blocks compared to N, and in four out of five blocks compared to S. BIC [33] was used to compare models within each block, as it accounts for both model fit and complexity. BIC values are only comparable when models are estimated on the same dependent variable, which is satisfied here. Lower BIC values indicate a better balance between

explanatory power and simplicity, with the model exhibiting the smallest BIC considered the preferred predictor set. The improvement from the univariate model N to the multivariate model $N + S$ is small and block-dependent, and also the values of the root mean squared error (RMSE) and the adjusted R^2 are generally similar. The multivariate model $N+S$ yielded the lowest $\mathrm{BIC}_{\mathrm{total}}$. $\mathrm{BIC}_{\mathrm{total}}$ represents the aggregated BIC across all blocks, combining model fit and complexity for each block, with lower values indicating a better overall predictor set.

A predictor set combining N or S with N_{low} or N_{ratio} was not used, due to the coefficients attempting to explain the same information in opposite directions, which can lead to unstable estimates or inflated standard errors. Further, N_{low} and N_{ratio} are calculated from the total loudness N and are therefore not independent from it, which makes their combination prone to multicollinearity. Looking at their statistical results from the linear regression fits, it can be seen that the model using N_{low} has the highest $\mathrm{BIC}_{\mathrm{total}}$, and the model using N_{ratio} has a lower $\mathrm{BIC}_{\mathrm{total}}$ than the model using S but a higher $\mathrm{BIC}_{\mathrm{total}}$ than the model using N. Therefore, N_{low} and N_{ratio} performe worse than the models using N or $N+S$.

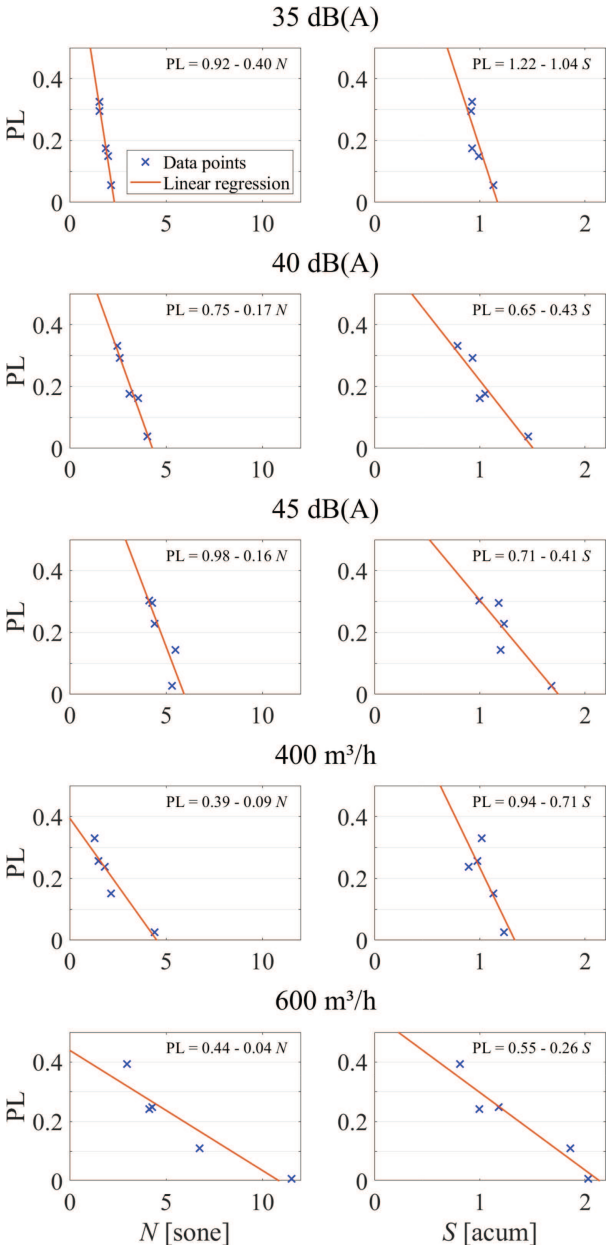


Figure 7. Normalised pleasantness ranking PL plotted against loudness N in sone and sharpness S in acum, including linear regression fits for each block, cf. Table 8.

4 Discussion

The finding that pleasantness decreases as loudness increases aligns with previous studies on HVAC and ventilation noise. In the present study, pleasantness is used as an integral evaluative judgement under controlled listening conditions, while many related studies focus on annoyance or preference. Pleasantness differs from annoyance, which is a broader, context-dependent construct shaped by disturbance- and interference-related aspects [8, 9]. Preference, in contrast, reflects comparative choices based on a specified judgement criterion, such as pleasantness in the present study [10]. Hohls et al. [15], Bennouna et al. [17], and Davies et al. [19] consistently identified loudness as the dominant perceptual factor in the evaluation of HVAC noise. Scouarnec and Bennouna [16], Ma et al. [18], and Schneider and Feldmann [13] likewise demonstrated that loudness is the key predictor of pleasantness or annoyance in fan and ventilation noise.

While loudness is frequently identified as the dominant factor in the perception of HVAC and ventilation noise, which aligns with the results of this study for air diffuser noise, many of these studies also show that additional psychoacoustic parameters are needed to explain subjective responses. Sharpness and roughness were identified as relevant secondary factors for annoyance and preference by Hohls et al. [15] and Bennouna et al. [17]. Susini et al. [14] found that while the preference judgements of one group depend primarily on loudness, the other group's judgements are based on spectral characteristics. Spectral characteristics as a secondary criterion were also identified by Davies et al. [19], who listed them alongside fluctuation characteristics and tonality. Tonality was mentioned as a secondary factor by Scouarnec and Bennouna [16] and by Schneider and Feldmann [13]. Whereas, Ma et al. [18] reported a significant correlation between pleasantness and sharpness. This aligns well with the findings of Töpken and van de Par [11], who observed that stimuli with lower sharpness are generally judged as more preferred.

It is important to note, however, that all of the aforementioned studies analysed HVAC or ventilation noise that inherently includes fan operation noise. This study differs in this regard, as only airflow noise from air diffusers was investigated, whereby fan noise was effectively

suppressed through the use of silencers and long duct segments in the experimental setup. By excluding fan operation noise from the acoustic signal, this study enables a more targeted evaluation of pure airflow noise. Complementary to this, Ostmann et al. [21, 22] analysed the aeroacoustic source mechanisms of swirl and slot diffusers using numerical simulations, identifying plenum eigenmodes, guide elements, and recirculation zones as dominant contributors to the emitted noise. These results emphasise that even without fan noise, air diffuser design can strongly shape the emitted sound, offering a technical basis for the subjective evaluation differences examined in the present work.

With regard to RQ1, the results suggest that when sound pressure level or volume flow rate is held constant across stimuli, participants can consistently rank them in terms of pleasantness, indicating that pleasantness can be meaningfully assessed under controlled conditions. However, Kendall's coefficient of concordance indicates only moderate agreement between participants, except for the block with $600\,\mathrm{m}^3/\mathrm{h}$ where the agreement is sufficient. These low coefficient values might be due to several stimuli being perceived as equally pleasant (e.g., D1 and D5 at 35 and 40 dB(A); D3 and D5 at 45 dB(A), 400 and $600\,\mathrm{m}^3/\mathrm{h}$, see Fig. 6).

If volume flow rate is the dominant design constraint, the present findings suggest that diffuser D4, one of the swirl diffusers, would be a favourable choice. Overall, the swirl diffuser (D3-D5) yield higher pleasantness than the slot diffuser (D1-D2). The consistently lower pleasantness ratings of the slot diffusers D1 and D2 compared to the swirl diffusers can be related to their acoustic characteristics. As shown in Table 1, D1 and D2 exhibit higher sharpness S than the other diffusers across conditions. In addition, when operated at the same volume flow rate, D1 and D2 also show higher psychoacoustic loudness N, and this trend is likewise observed in the 35 dB(A) block. The frequency spectra presented in Figure 4 further support this interpretation. D1 and D2 exhibit elevated sound pressure levels in the mid-frequency range compared to the swirl diffusers, particularly relative to D3 and D4. This provides a consistent acoustic explanation for the lower pleasantness ratings of the slot diffusers relative to the swirl diffusers.

Concerning RQ2, linear regressions demonstrated that both loudness N and sharpness S are negatively associated with normalised pleasantness rankings PL, such that higher values correspond to lower rankings, while N_{low} and N_{ratio} associate positively with PL. N_{low} and N_{ratio}, which describe specific loudness distributions, did not outperform the model based on loudness (cf. $\mathrm{BIC}_{\mathrm{total}}$ in Tab. 8). The univariate model with N performed best compared to the univariate models based on S, N_{low}, or N_{ratio}. Overall, the present results confirm that lower loudness and lower sharpness are associated with higher pleasantness ratings (cf. Fig. 7), which is consistent with previous findings in the literature. Combining N and S in a multiple linear regression model $N + S$ did slightly improve model performance compared to univariate model N. For most stimuli, sharpness increases with increasing loudness (cf. Tab. 1), indicating that both parameters may not vary independently, which limits the interpretability of their combined use in the regression model. Additionally, with only five observations per scenario, any statistical estimate is inherently unstable, as small variations in the data can have a large effect. Including multiple predictors in the model further reduces the residual degrees of freedom (here, from three in a univariate model to two in a two-predictor model with five observations), thereby increasing estimation uncertainty and leading to inflated standard errors and less stable coefficient estimates. Therefore, the slight improvement in model performance of $N+S$ compared to the univariate model using N should be interpreted with caution. Under the present conditions, loudness represents the dominant predictor of pleasantness, while sharpness may provide additional, but limited, information.

Roughness and tonality were not considered suitable as model predictors because they remained below their respective perception threshold in all stimuli (cf. Tab. 1).

From a practical perspective, the results indicate that loudness is decisive when selecting or designing air diffusers, even when equalising the stimuli by sound pressure level. Bringing in sharpness as an additional parameter might be worthwhile, even though as a standalone parameter its explanatory power is not enough.

A limitation of this study is the between-listener variability in pleasantness judgements. While participants provided consistent pairwise pleasantness judgements, the resulting agreement across participants was only moderate in most blocks, which may reduce the robustness of the rankings derived from these judgements. The $600\,\mathrm{m}^3/\mathrm{h}$ block represents an exception, where higher concordance between air diffuser stimuli indicates more reliable results, possibly reflecting greater perceptual differences between the stimuli in this block. Another key limitation is the small sample size per block, with only five air diffuser stimuli. This restricts the statistical power of the regression models and may prevent smaller, but meaningful effects from being detected. Moreover, given the limited number of stimuli, the apparent benefit of combining loudness and sharpness in a predictive model is uncertain and may be either under- or overestimated.

5 Conclusion

This study demonstrated that differences in pleasantness can be observed and related to loudness and sharpness, even when the sound pressure level or volume flow rate is held constant. Overall, the results confirm that lower loudness and lower sharpness are associated with higher pleasantness. In addition, the results indicate that the psychoacoustic parameter loudness is a suitable predictor of pleasantness beyond sound pressure level. Accordingly, psychoacoustic parameters should be incorporated in product design and assessment of air diffusers,

complementing conventional level- or volume-flow-rate-based criteria. Under comparable operating conditions defined by volume flow rate, swirl diffusers were found to be more pleasant than slot diffusers, which can be associated with their lower loudness and sharpness.

Future research should include a broader set of air diffuser noise, especially under controlled loudness conditions, to test whether the findings can be generalised. In particular, it would be interesting to examine whether a combination of loudness and sharpness yields greater explanatory power when applied to a larger and more diverse dataset.

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Conflicts of interest

The authors declare no conflict of interest.

Data availability statement

The research data associated with this article are available in Zenodo, under the reference https://doi.org/10.5281/zenodo.20273423

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