Relationships between loudness and preference judgments for fan sounds as a function of the reference sound pressure level

Eike Claaßen[1]
Acoustics Division, Department of Medical Physics and Acoustics, Excellence Cluster Hearing4all
Carl von Ossietzky University Oldenburg, Carl-von Ossietzky-Str. 9-11, 26129 Oldenburg, Germany

Stephan Töpken
Acoustics Division, Department of Medical Physics and Acoustics, Excellence Cluster Hearing4all
Carl von Ossietzky University Oldenburg, Carl-von Ossietzky-Str. 9-11, 26129 Oldenburg, Germany

Steven van de Par
Acoustics Division, Department of Medical Physics and Acoustics, Excellence Cluster Hearing4all
Carl von Ossietzky University Oldenburg, Carl-von Ossietzky-Str. 9-11, 26129 Oldenburg, Germany

ABSTRACT

In a prior study, the level of fan test sounds was adjusted in a listening test using an adaptive procedure, until they became equally loud or equally preferred as a reference sound at a fixed level. Depending on the test sound, level reductions of up to 15 dB compared to the 60 dB(A) reference level were necessary to reach equal loudness or preference compared to the reference sound. It turned out that the preference-equivalent levels were highly correlated with the loudness-equivalent levels, indicating that the preference decision and the loudness judgment were closely related to each other.
In a follow-up study, the measurements were extended towards a higher reference level of 75 dB(A) and a lower reference level of 45 dB(A). The preference-equivalent levels obtained at 75 dB(A) were again closely related to the loudness-equivalent levels.
For the lower reference level of 45 dB(A), the preference-equivalent levels deviate from the loudness-equivalent levels by 3.5 dB on average and also the inter-individual variability increased. This result suggests an increasing effect of additional fan-noise characteristics to play a role for the preference decisions on top of the perceived loudness especially at low absolute sound pressure levels.

1. INTRODUCTION

Fans are a common noise source in people's everyday life because they are necessary in many technical applications and systems. To acoustically quantify fan noise, the A-weighted sound pressure level is an established measure, which is also part of standards and regulations. With respect to the pleasantness or annoyance of fan noise, the A-weighted sound pressure level is often limited

[1]eike.claassen@uol.de

and psychoacoustic parameters can be beneficial to characterize and predict the evaluation of fan sounds [1], [2].
In order to enhance the A-weighted sound pressure level to better reflect the annoyance and effects of sounds, level adjustments (penalties) can be a useful extension [3], [4], [5]. For a better characterization of the effects of noise, rating levels including level adjustments are also used in some international standards, e.g. ISO1996 [6]. Level adjustments are also proposed for tonal components in noise by the German DIN45681 [7].

In previous studies loudness- and preference-judgments of fan sounds were determined in listening tests [5], [8]. In two experiments, loudness- and preference equivalent levels were measured using an adaptive procedure in which the level of a test stimulus is adjusted until it is equally loud or equally preferred as a fixed reference stimuli. The resulting level differences between the test- and the reference sound at the point of subjective equality (PSE) can be interpreted as a level penalty or level adjustment.
The results of the previous study showed strong similarities of loudness- and preference-judgments at reference levels of 60 and 75 dB(A) [8]. Recent listening tests carried out by the authors at a lower reference of 45 dB(A) showed that the preference judgments differ from the loudness judgments considerable.Therefore, this paper shows the relationship of relative loudness- and preference-judgements measured for reference levels of 75, 60 and 45 dB(A) in more detail.

2. METHOD

The method in the present study is closely related to that of the prior study [5] but with a reduced set of sounds compared to the prior study.

2.1. Participants

Twenty-four participants (12 female, 12 male) with a mean age of 24 years (ranging from 20 to 30) for the reference level of 75 dB(A) and a mean age of 25.1 ranging from 20 to 35) for the reference level of 45 dB(A) volunteered to participate in this study. The data at a reference level of 60 dB(A) is based on a randomly drawn sample of 24 participants (12 female, 12 male) from a previous study [5]. The mean age of the sample was 23.4 years (ranging from 20 to 29).
The participants were mainly students from the University of Oldenburg and stated that they do not suffers from any kind of hearing impairment. The participants were compensated with 50 € (10 € per hour). Ethic approval was granted by the committee for research impact assessment and ethics of the University of Oldenburg (ethics application Drs EK/2020/007).

2.2. Procedure

The loudness-equivalent levels were determined using an adaptive procedure. In each trial, pairs of sounds consisting of a test sound and a common reference sound were presented in random order. Participants had to decide which sound is perceived louder. Based on the subject's response, the level of the test signal was varied using an adaptive method while the level of the reference sound remained fixed. The adaptive measurements were realized as using a 2-Interval, 2-Alternative Forced Choice (AFC) method changing the level of the test signal with a on a one-up, one-down rule, which converges at the PSE. At the start of each adaptive track, the level of the test sound was the same as the respective reference sound level. The initial step size of the level change for the loudness experiment was 3 dB. After the second upper reversal the step size was reduced to 1.5 dB. The measurement phase consisted of four reversals with a step size of 1.5 dB for each adaptive track. The PSE was always calculated as the mean value over the last four reversal points of the adaptive track. The procedure for the determination of the preference-equivalent levels (Preference-Task) was essentially the same as in the loudness experiments. The level of the test sound was reduced when the reference was preferred and it was increased when the test sound was preferred. The underlying assumption here is that a reduction of the sound pressure level reduces the loudness and increases the pleasantness of a stimulus, which increases the probability to be preferred compared to the fixed reference sound. The preference experiment started with an initial step size of 6 dB which was halved after each upper reversal to a final step size of 1.5 dB. The adaptive track is terminated after 4 reversals with a step width of 1.5 dB. A custom AFC framework was used for implementing both adaptive measurement procedures in Matlab (The Mathworks) [9]. The overall experimental design was balanced out with respect to gender (female/male), the start sound-set (1-3) as well as the starting-task for every session (Loudness-Task / Preference-Task). The collection of the judgments is divided into three appointments on different days, each separated by a week. At an appointment, each participant carried out two separate experiments to determine the loudness- and preference-equivalent levels.

2.3. Stimuli

Three sound-sets with seven stimuli each were compiled from the sounds of the previous study [5]. Twelve sounds were modified based on the base-signals B1 and C4 including a threefold variation with respect to the parameter N_{ratio} and a twofold variation of N_{low} for the two different base-signals, each. The rest of the signals were different recorded fan sounds, which are not included in the presented results, here. The reference sound was always a band-limited white noise between 200 and 500 Hz as in the prior study [5]. All stimuli had a duration of 3 s and were calibrated to the reference level of the specific experiment (75, 60 or 45 dB(A)).

2.4. Apparatus

The listening experiments were conducted in a single-walled (L_{ref} = 75 and 60 dB(A)) or double-walled (L_{ref} = 45 dB(A)) listening booth. The background noise level inside both listening booths with a silent person present was 20.5 dB(A) and therefore close to the self noise level of 18 dB(A) of the used sound level meter (Norsonic Nor140).

The stimuli were presented diotically with open headphones (Sennheiser HD 650) driven by the headphone output of an audio interface (RME Fireface UC) that was connected to a computer. The experimental task was visualized using a graphical user interface. Subjects could answer using a mouse, keyboard or a touchscreen in front of them. The calibration was carried out using a B&K 4134 microphone capsule in an Artificial Ear (B&K Type 4153) that was powered by a B&K Type 2669 microphone pre-amplifier and connected to a B&K Type 2610 measurement amplifier.

3. RESULTS

In the following, the relationship of relative loudness-equivalent levels (ΔL_{loud}) and relative preference-equivalent level ΔL_{pref} compared to the reference levels of 75, 60 and 45 dB(A) will be presented based on the individual data in Section 3.1. The evaluation of the median values of the loudness- and preference-equivalent levels for all stimuli averaged across all participants is discussed in Section 3.2. An evaluation of the correlation coefficients for both, individual and median values is discussed in Section 3.3.

3.1. Relationships between preference and loudness PSEs for individual data

The relationship between ΔL_{loud} and ΔL_{pref} at the reference levels of 75, 60 and 45 dB(A) is shown in the three subfigures of in Figure 1. The scatter plots show the individual data for both base signals B1 and C4 for all 24 subjects. Each subfigure includes an individual regression line shown as a solid grey line and a one-to-one agreement is indicated by the dashed grey line. The median values calculated

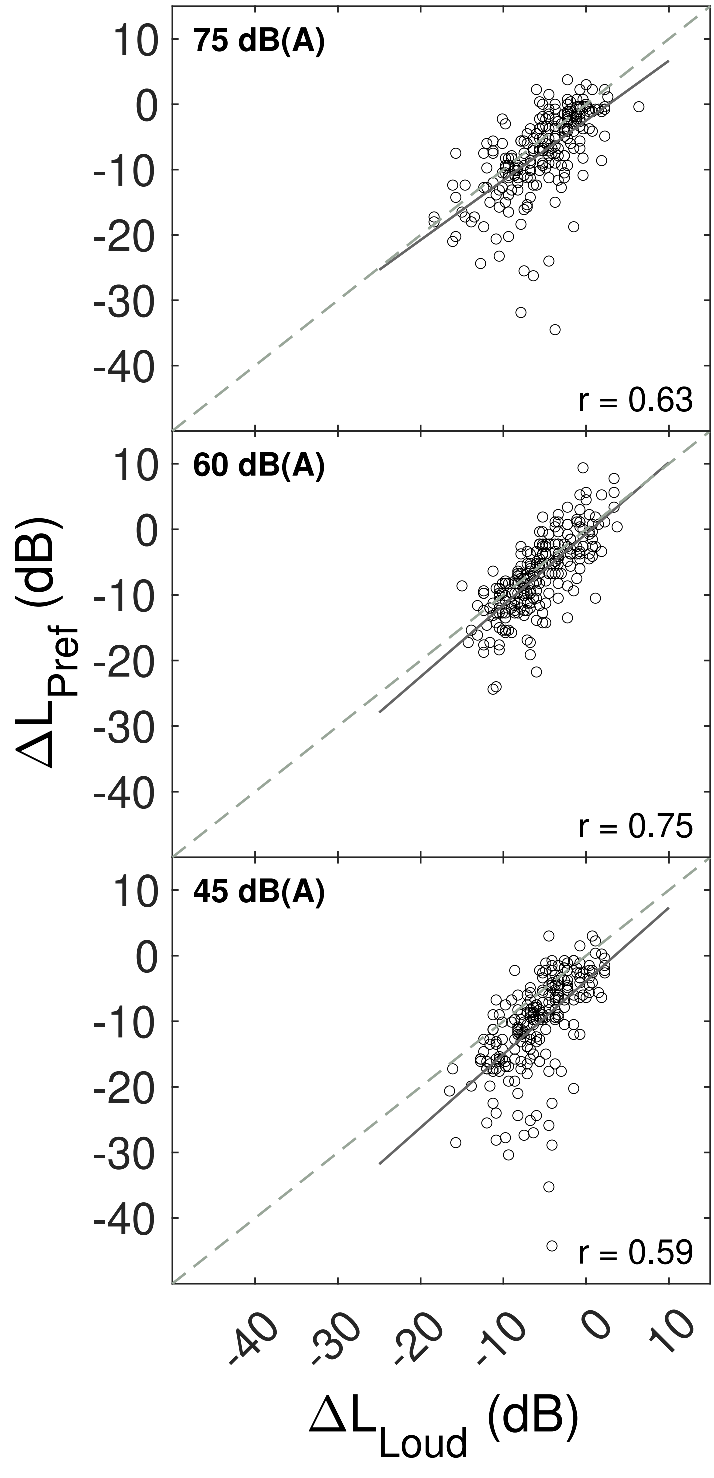

Figure 1: Scatter plots of individual data of relative preference-equivalent levels ΔL_{pref} and loudness-equivalent levels ΔL_{loud} for reference levels of 75, 60 and 45 dB(A) and both base signals B1 and C4 using open circles. The solid grey line indicates a linear regression and a one-to-one agreement is indicated by the dashed grey line.

Table 1: Median values and interquartiles for ΔL_{pref} and ΔL_{loud} based on the individual data for the reference levels of 75, 60 and 45 dB(A).

L_{ref}	ΔL_{pref}			ΔL_{loud}		
	Median	Lower quartile	Upper quartile	Median	Lower quartile	Upper quartile
75 dB(A)	-6.75 dB	-10.88 dB	-2.25 dB	-4.88 dB	-8.25 dB	-2.25 dB
60 dB(A)	-6.75 dB	-10.88 dB	-2.63 dB	-5.63 dB	-8.63 dB	-2.81 dB
45 dB(A)	-9.19 dB	-14.81 dB	-4.88 dB	-5.63 dB	-8.25 dB	-3.38 dB

over all data points for each reference level and the corresponding lower and upper quartiles are given in Table 1.

For ΔL_{pref} the median values and lower and upper quartiles for the reference levels of 60 dB(A) and 75 dB(A) are of similar magnitude. In comparison to this, the median value for a reference level of 45 dB(A) is about 2.5 dB lower. Similarly, the lower quartile is about 4 dB lower and the upper quartile is about 2.5 dB lower than for the higher reference levels. The median values of ΔL_{loud} are similar for reference levels of 45 and 60 dB(A), while the median for a reference level of 75 dB(A) is approximately 1 dB higher. The lower and upper quartiles of ΔL_{loud} have approximately the same values for the three tested reference levels.

Overall, the median attenuation values of ΔL_{pref} are higher compared to ΔL_{loud} for all reference levels, indicating that different criteria were used for the two different tasks. Furthermore, the interquartile ranges for ΔL_{pref} are larger compared to ΔL_{loud} at all reference levels, suggesting higher inter-individual differences for the preference than for the loudness task.

Especially at a reference level of 45 dB(A) some outlier data points for ΔL_{pref} are visible in Figure 1. Level reductions of up to 45 dB suggest that the adaptive tracks for these data points converged by accident because they are very close to or even below the absolute threshold of hearing. However, strong level reductions of more than 20 dB are also present for ΔL_{pref} at a reference level of 75 dB(A), which is well above the absolute threshold of hearing and for a different group of participants. For ΔL_{loud} no extreme outliers are apparent in the data for all reference levels. Due to no obvious systematic behind the outliers in terms of a single participant or a single sound being responsible for the outliers, we decided to retain these data points.

3.2. Relationships between preference and loudness PSEs for median data

The relationships of the median values across participants for the relative loudness-equivalent levels (ΔL_{loud}) and relative preference-equivalent levels (ΔL_{pref}) at the reference levels of 75, 60 and 45 dB(A) are presented in Figure 2. Each symbol shows the median value and the corresponding interquartiles for the signals B1 (diamond marker) or C4 (circular marker) for 24 subjects. A linear regression is plotted as a solid grey line and a one-to-one agreement is indicated by the dashed grey line. Regarding their values of ΔL_{loud} and ΔL_{pref} no systematic differences are apparent between the base signal B1 and C4 at any reference level.
The regression lines for the reference levels of 60 and 75 dB(A) have a similar slope of about 1. The data obtained at a reference level of 45 dB(A) exhibits a slightly flatter slope of 0.9 between the preference and the loudness PSEs.

Lager differences occur for the intercepts of the regression lines. For 75 and 60 dB(A) the intercept

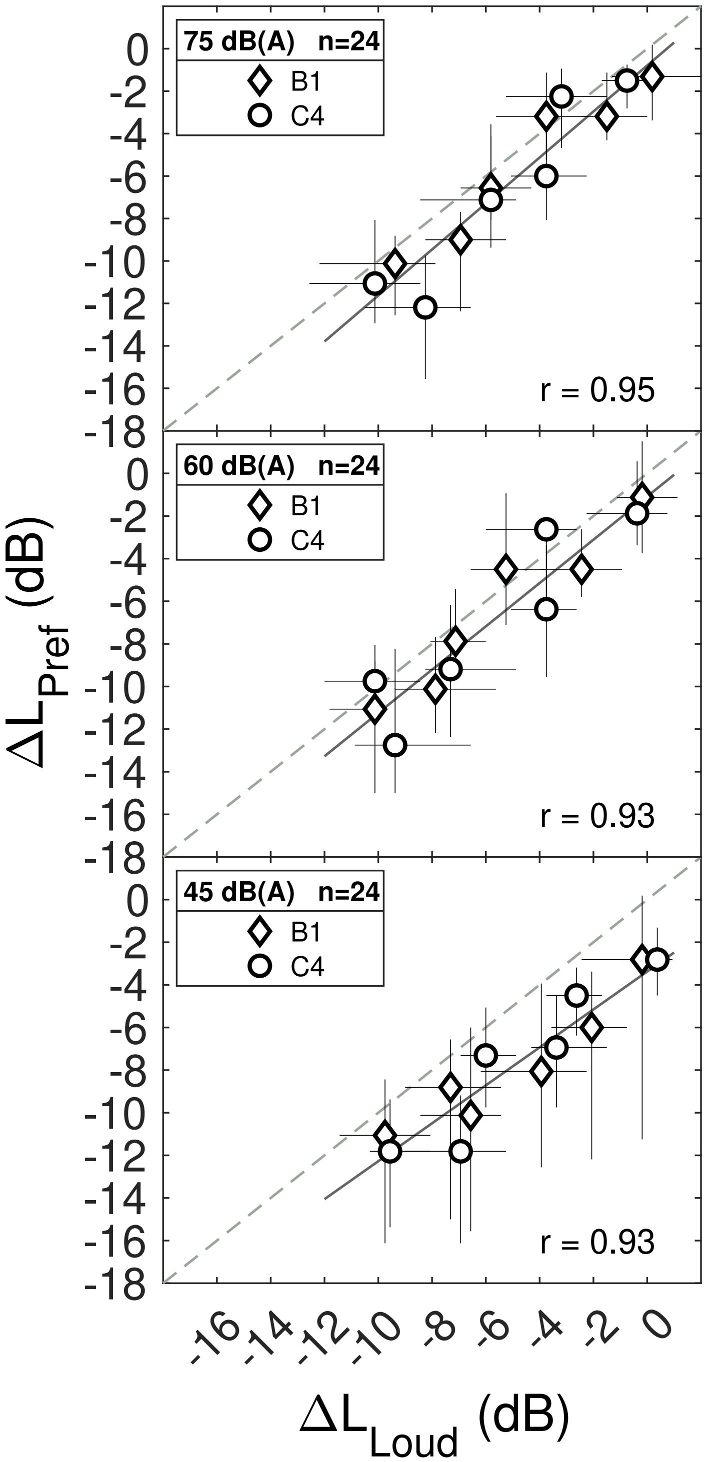

Figure 2: Scatter plots of median values for the relative preference-equivalent levels ΔL_{pref} and loudness-equivalent levels ΔL_{loud} across the participants. Subplot show the data for the three reference levels of 75, 60 and 45 dB(A). The median values are based on the base sounds B1 (diamond markers) and C4 (circular markers). A linear regression line is shown by the solid grey line and a one-to-one agreement is indicated by the dashed grey line.

Table 2: Correlation coefficients r (Pearson) between ΔL_{pref} and ΔL_{loud} and the corresponding p-Values for the individual data (Figure 1) and the median data (Figure 2) for reference levels of 75, 60 and 45 dB(A).

L_{ref}	Individual data		Median values	
75 dB(A)	$r = 0.63$	$p < 0.001$	$r = 0.95$	$p < 0.001$
60 dB(A)	$r = 0.75$	$p < 0.001$	$r = 0.93$	$p < 0.001$
45 dB(A)	$r = 0.59$	$p < 0.001$	$r = 0.93$	$p < 0.001$

is -0.8 dB and -1.1 dB while for 45 dB(A) an intercept of -3.4 dB is observed. For a reference level of 45 dB(A), all median data points are also well below the dashed line indicating the one-on-one agreement. Apparently, the preference judgments differ in overall magnitude from the loudness judgements especially for a low reference level of 45 dB(A), although the correlation coefficients are of similar magnitude for all three reference levels.

3.3. Correlation coefficients for individual and median results

An overview of the correlation coefficients and the corresponding p-values for the three reference levels is shown in Table 2. Based on the individual data for ΔL_{loud} and ΔL_{pref}, correlation coefficients of 0.63 for a reference level of 75 dB(A), 0.75 for 60 dB(A) and 0.59 for 45 dB(A) are obtained. For the median values across participants, the correlation coefficients are considerably higher and of similar magnitude for all three reference levels. Although differences in the intercepts could be identified for the low reference level, the loudness and preference PSEs seem to be closely linked to each other for all reference levels.

4. CONCLUSION

For the investigated set of stimuli a close link between loudness and preference judgments was found for all three reference levels of 45, 60 and 75 dB(A). At a lower reference level of 45 dB(A) the preference judgments seems to decouple from the loudness judgments resulting in a shift of the regression line from the one-to-one agreement by more than 3 dB. The inter-individual differences for ΔL_{pref} increase for reference levels of 45 dB(A) while the inter-individual differences for ΔL_{loud} remain consistent for all reference levels.

The results of the present study suggest that additional factors on top of the loudness play a role for the lower reference level compared to the higher reference levels. We assume that tonality might have an increasing influence on the preference judgment.

ACKNOWLEDGMENTS

The present study is part of a larger project dealing with the psychoacoustic characterization of fan noise, which was initiated by the Research Association for Air and Drying Technology (FLT e.V.) from Germany. The project is supported in the context of the program for industrial collective research by the German Federal Ministry for Economic Affairs and Climate Action (BMWK) on the basis of a decision by the German Bundestag.

REFERENCES

[1] Roland Sottek and Klaus Genuit. Sound quality evaluation of fan noise based on advanced hearing-related parameters. *Noise Control Engineering Journal*, 57(4):384–390, 2009.

[2] Patrick Susini, Stephen McAdams, Suzanne Winsberg, Ivan Perry, Sandrine Vieillard, and Xavier Rodet. Characterizing the sound quality of air-conditioning noise. *Applied acoustics*, 65(8):763–790, 2004.

[3] David Oliva, Valtteri Hongisto, and Annu Haapakangas. Annoyance of low-level tonal sounds–factors affecting the penalty. *Building and Environment*, 123:404–414, 2017.

[4] Valtteri Hongisto, Pekka Saarinen, and David Oliva. Annoyance of low-level tonal sounds–a penalty model. *Applied Acoustics*, 145:358–361, 2019.

[5] Stephan Töpken and Steven van de Par. Determination of preference-equivalent levels for fan noise and their prediction by indices based on specific loudness patterns. *The Journal of the Acoustical Society of America*, 145(6):3399–3409, 2019.

[6] ISO1996-1:2016. Acoustics - description, measurement and assessment of environmental noise - part1: Basic quantities and assessment procedures. *International Organisation for Standardisation*, pages pp. 1–32, 2016.

[7] DIN 45681:2005. Acoustics—Detection of tonal components of noise and determination of tone adjustment for the assessment of noise immisions. *Beuth, Berlin, Germany, German industry standard*, 2005.

[8] Eike Claaßen, Stephan Töpken, and Steven van de Par. Loudness-and preference-equivalent levels of fan sounds at different absolute levels. *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, 263(4):2304–2312, 2021.

[9] Stephan D Ewert. AFC— a modular framework for running psychoacoustic experiments and computational perception models. In *Proceedings of the international conference on acoustics AIA-DAGA*, pages 1326–1329, 2013.