Loudness and short-term annoyance of Low Sonic Boom signatures

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LOUDNESS AND SHORT-TERM ANNOYANCE OF LOW SONIC BOOM SIGNATURES

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ABSTRACT

Supersonic aircraft produce a sonic boom when flying faster than the speed of sound. In order to rule out detrimental effects for inhabitants of overflown areas, civil supersonic flights (like the Concorde) were allowed to fly over water only. Due to progress in aircraft design, the supersonic boom may be reduced considerably in the future. Such low sonic boom signatures will potentially be quieter and sound very different compared to conventional sonic booms. For an assessment of human responses to low sonic boom signatures, a sonic boom simulator has been built at the University of Oldenburg. Listening tests were carried out in the simulator and volunteers rated the loudness and the short-term annoyance of a variety of simulated and recorded boom signatures, differing in the shape of the time signal, the maximum overpressure and the A-weighted sound exposure level.

1. INTRODUCTION

Supersonic aircraft produce a sonic boom when flying faster than the speed of sound. In order to rule out detrimental effects for inhabitants of overflown areas, civil supersonic flights (like the Concorde) were allowed over water only. Due to progress in aircraft design, the sonic boom created by future supersonic aircraft may be reduced considerably. Such Low Sonic Boom-signatures will potentially be quieter and sound different compared to conventional sonic booms [1]. Although a lot of research was carried out to better understand the effects of classical sonic boom on humans, the sensation and subjective response of humans to future low sonic boom signatures is currently under investigation [2,3]. An acoustic measure for the acceptability of low sonic booms is not available at the moment and it is the question how to define it such that the effects on humans are reflected [1,4].

In the framework of the EU-project RUMBLE [1], different simulators have been built for a collection of human responses to low sonic boom signatures [5]. As a part of this activity, an indoor sonic boom simulator has been built at the University of Oldenburg [6]. In the present study, the indoor simulator at the University of Oldenburg,

Figure 1. Inside the pressure chamber of the indoor simulator at University of Oldenburg. [6]

shown in Fig. 1, is used for listening tests with volunteer participants. Different recorded and simulated sonic boom signatures from conventional aircraft designs and from a low boom designs were rated in terms of the perceived loudness and short-term annoyance in laboratory listening tests. Each signature was presented at three different signal levels to achieve a broad coverage of peak overpressure values around 20 Pa and corresponding A-weighted sound exposure levels (ASELs) around 60 dB(A). The aim of this study is a first look into the relationships between loudness and annoyance ratings and ASEL values.

2. METHODS

2.1 Simulator Setup

The listening tests took place in an indoor simulator designed specifically to accurately reproduce (low) sonic boom signatures. Figure 1 shows a picture of the inside of the simulator. The simulator is constructed in a small room that acts as a pressure chamber similar like facilities at NASA [7] and at JAXA [8]. A neighboring room acts as a loudspeaker enclosure for two 18” speakers. The loudspeaker chassis are mounted in a thick wooden plate that is installed in the doorframe between the two rooms. The

[1] http://www.rumble-project.eu

pressure chamber is accessed by another door with an air-tight sealing to the outside. The electro-acoustic system is equalized with a digital filter for an accurate reproduction of the time signals at the listening position in the simulator. More details on the construction, technical systems and specs of the indoor simulator can be found in [6].

The average background noise level in the simulator room is only $L_{\mathrm{Aeq}} = 21$ dB(A). However, occasional background sounds like closing doors from a neighboring staircase and laboratories can be heard and are not completely isolated from the simulator room. The reverberation time of the chamber averaged over octave bands from 63 Hz to 8 kHz is $T_{20} = 0.2$ seconds. The background noise level and the reverberation time are similar to different sonic boom simulators at NASA [7, 9, 10].

2.2 Participants

A total of 16 volunteers (10 female, 6 male) participated in the listening tests. The participants had a average age of 24 years (age range from 19 to 29 years). About 56 percent of the participants (8 female, 1 male) had prior experience with other listening experiments. The other 44 percent had no prior experience with listening tests. All of the participants declared that they had no hearing problems. Each participant was paid a compensation of 20 € for the two sessions (10 € per hour). The commission for research impact assessment and ethics of the University of Oldenburg had no objections regarding the listening experiments of this study (ethics application EK/2018/104).

2.3 Stimuli

Different recorded and simulated sonic boom signatures from smaller and larger aircraft together with a simulation of a recent low boom design (NASA C25D, middle curve in subfigure (h) in Fig. 2) were used as stimuli in the listening tests. Some of the signals which originally had an overpressure greatly above 20 Pa were attenuated so that they were in a similar level range as the low boom simulations. Each of the eight signatures was varied in level in 3 dB steps over a 6 dB range. In this way, a broad coverage of A-weighted sound exposure levels from 55.5 dB(A) to 69.8 dB(A) and peak overpressures from 4.25 Pa to 28.63 Pa was achieved. Figure 2 shows the time signals of the eight different boom signatures for the three levels each. Table 1 summarizes the values of the A-weighted sound exposure level (ASEL) and the peak overpressure for the overall 24 stimuli. Signatures with a very short rise time, like signature (d), have a higher amount of high frequency content compared to those signatures with a longer rise time. Together with the A-weighting in the ASEL calculation, the higher amount of high frequencies can lead to rather high values of the ASEL even if the peak overpressure is quiet low.

2.4 Experimental Procedure

The 24 sonic boom signals were rated with respect to the loudness and the short-term annoyance in separate listening tests. A single participant sat on a rigid wooden chair on a wooden platform that can be used to provide whole-body vibration. In the present study, no vibratory stimuli were played back. The participants were not able to see the loudspeakers during the listening tests because of a visual shield installed on the right side of the loudspeakers (shown in Fig. 3). In this way, a visual impression from the excursion of the loudspeaker membranes was excluded.

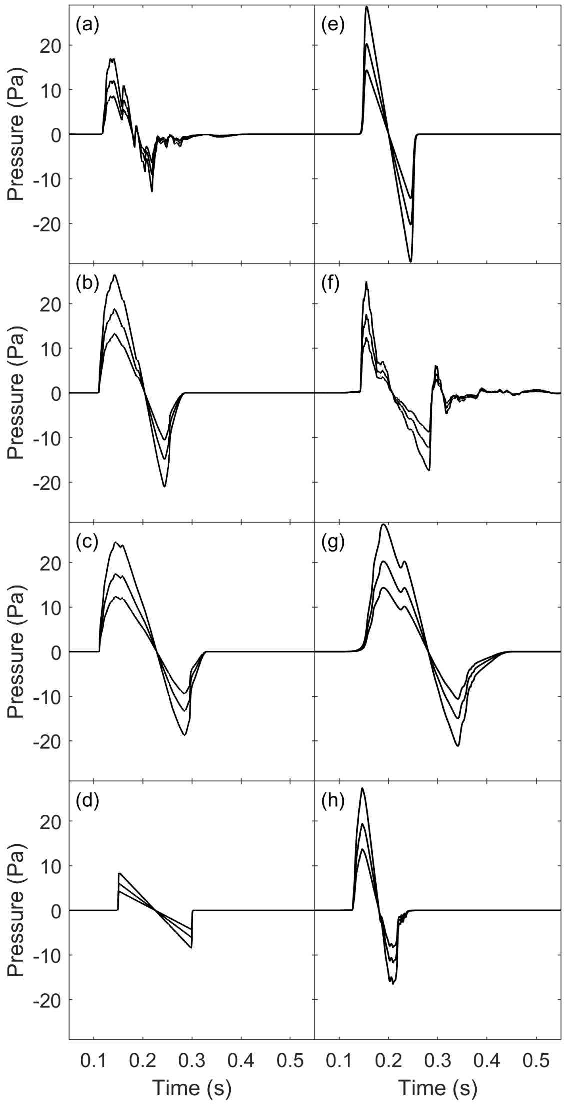

Figure 2. Time signals of the pressure for the eight different boom signatures used as input to the simulator. Each subfigure contains three curves for three different levels.

The participants were asked to give their annoyance rating for each of the 24 stimuli on a 11-point categorical scale. The categories had numerical labels from 0 to 10 and the ends of the scale had additional verbal labels "not at all annoying" (0) and "extremely annoying" (10). The verbal scale labels were chosen to be similar to laboratory studies investigating indoor rattle noise [13] and chair vibration [14] in combination with sonic booms heard indoors. Similar scales were also used in studies on the an-

Table 1. Values of the A-weighted sound exposure level (ASEL) and max overpressure ($p_{\max}$) for the 24 signals. Each of the eight different signtaures (a)-(h) was varied threefold in level in 3 dB steps.

Signal	ASEL (dB(A))	$p_{\max}$ (Pa)
(a)	67.5	17.01
	64.5	12.04
	61.5	8.52
(b)	61.5	26.56
	58.5	18.80
	55.5	13.31
(c)	64.0	24.53
	61.0	17.37
	58.0	12.30
(d)	69.8	8.49
	66.8	6.01
	63.8	4.25
(e)	66.2	28.63
	63.2	20.27
	60.2	14.35
(f)	69.1	25.01
	66.1	17.71
	63.1	12.54
(g)	57.9	28.55
	54.9	20.21
	51.9	14.31
(h)	64.5	27.41
	61.5	19.41
	58.5	13.73

noyance of impulsive sounds of fire arms [11] and tramway noise [12]. This measured short-term annoyance does not necessarily reflect the annoyance effect in real life but it is more closely related to the perceived unpleasantness of the sounds [15]. To clearly distinguish the results of the present laboratory experiments from field test data we will use the term short-term annoyance instead of annoyance in the following.

The loudness ratings for each of the 24 stimuli were collected in a separate task, asking the participants “How loud was the sound that you just heard?” The loudness ratings were given on a 11-point categorical scale from 0 (not loud at all) to 10 (extremely loud). The labels at the ends of the scale were similar to the annoyance scale and laboratory studies of effects of sonic boom shaping [16]. The original questions and scale labels were in German language for both tasks because all participants were native German speakers.

A listening session started by giving the participant general information about the listening experiments and collected written informed consent. Then the first listening experiment, either loudness of short-term annoyance, took place in the simulator. Each experiment started with written instructions and an orientation phase. In the orientation phase, each of the 24 signals was played back to give the

Figure 3. View of the participants inside the simulator during the listening experiments.

participants a complete overview of the stimuli. Then, the first experiment started and all 24 signals were rated by the listener in a random order. Directly after each experiment, the participant took a short break with some questions from the investigator. The first open questions was asking for the first impressions after the experiment, the second open question was asking for associations with the sounds and identified sound sources. After a short break the second experiment started again with the orientation phase. One group of about half of the participants did the loudness task first and the short-term annoyance task second in each session. The other half carried out the two task the other way round. The ratio of female and male participants was balanced over the two groups of participants.

The listening tests were divided into two sessions on different days. In the first session, the participants received as little information about the background of the study as possible prior to the listening tests. Only after having finished both listening tests, each participant was debriefed and finally informed about the background of the study and potential sources of the sounds. The second session was a repetition of the same listening experiments. Between the first and the second session was a gap of at least two days (one weekend) and in most cases about one week. The order of the two tasks was kept the same as in the first session for each participants but the order of the signals was newly randomized for each task. The same information that was used for the debriefing at the end of the first session was given at the start of the second session to ensure that all participants had the same amount of prior knowledge present.

3. RESULTS

In the following, the average results from the first session are presented. Further analyses about the effect of providing information about the nature of the sounds may be presented in a future publication.

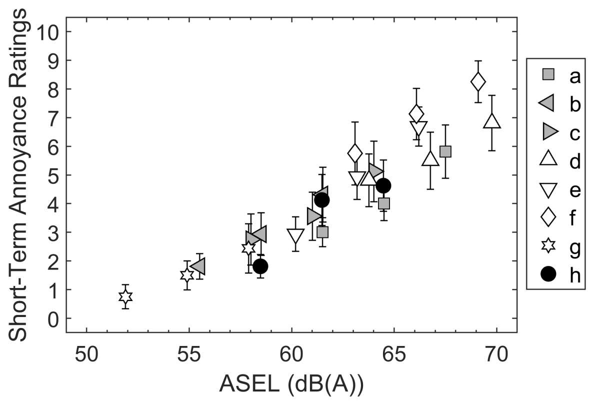

Figure 4. Average short-term annoyance ratings (N=16) from the first session plotted over the A-weighted sound exposure level (ASEL) for the 24 stimuli. Error bars indicate the 95% confidence interval.

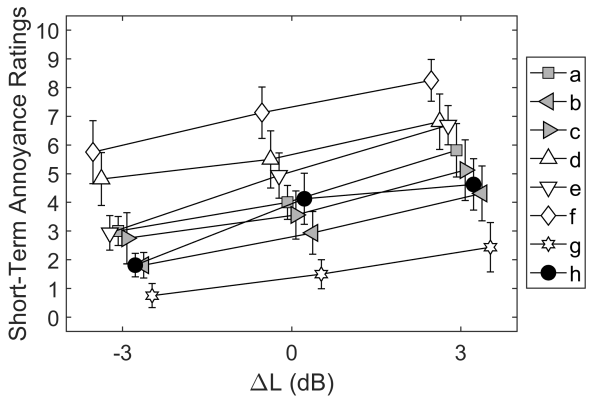

Figure 5. Average short-term annoyance ratings (N=16) from the first session plotted over relative levels for each of the 24 stimuli. Error bars indicate the 95% confidence interval.

3.1 Average Short-Term Annoyance Ratings

The results of the short-term annoyance ratings from the first session averaged over all 16 participants are shown in Fig. 4 plotted over the A-weighted sound exposure level (ASEL) of the signals. The average annoyance ratings cover a broad range of scale values between 1 and 8.5 scale units. In general, the annoyance ratings increase with rising ASEL values for each of the signatures. Signal (f) is the most annoying signal among the other signals with similar ASEL values. Signal (h), which is the C25D low boom simulation, is found among the other signals when having the same ASEL. Figure 5 shows the average short-term annoyance ratings plotted over the relative levels for each of the signatures. For each of the signatures, a relative increase in level by 6 dB results in a rise of the average short-term annoyance values by 2 to 3 scale units.

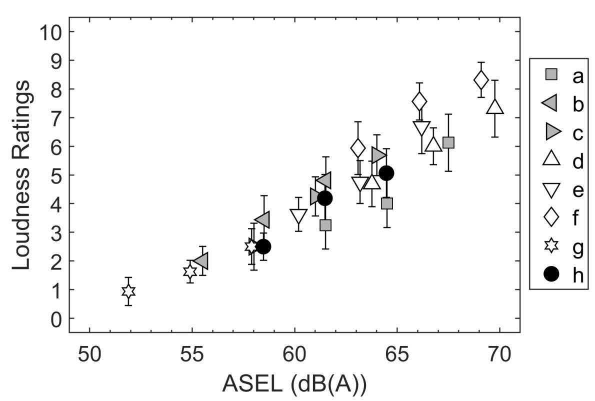

Figure 6. Average loudness ratings (N=16) from the first session plotted over the A-weighted sound exposure level (ASEL) for the 24 stimuli. Error bars indicate the 95% confidence interval.

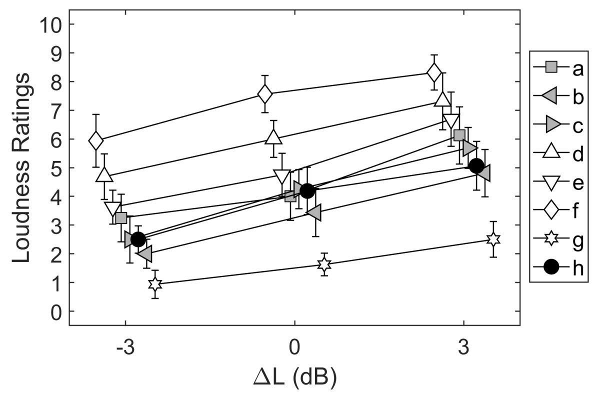

Figure 7. Average loudness ratings (N=16) from the first session plotted over relative levels for each of the 24 stimuli. Error bars indicate the 95% confidence interval.

3.2 Average Loudness Ratings

The results of the loudness ratings from the first session averaged over all 16 participants are shown in Fig. 6 plotted over the ASEL values of the signals. In general, the loudness ratings increase with rising ASEL values for each of the signatures. The loudness ratings do cover a similar range of scale values as the short-term annoyance ratings. Signal (f) is the loudest signals compared to others signatures at similar ASEL values. Similar like for the short-term annoyance ratings, a relative increase in level by 6 dB results in a rise of the loudness rating between 2 and 3 scale units for each of the signatures (Fig. 7).

3.3 Relationships between loudness and short-term annoyance ratings

Figure 8 shows the relationship between the average loudness and short-term annoyance ratings from the first session. The average short-term annoyance ratings are tightly linked to the loudness judgments and the average values

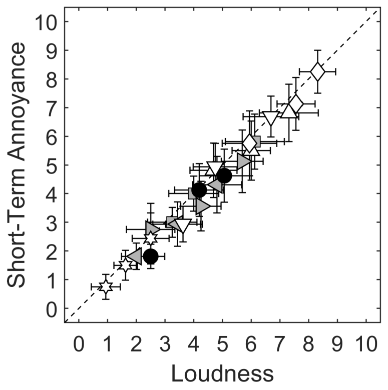

Figure 8. Relationship between the average loudness and short-term annoyance ratings for all 24 stimuli. Shown are average values across participants (N=16) from the first session. Error bars indicate the 95% confidence interval. The dashed line indicates identical ratings.

for short-term annoyance and loudness are nearly identical with and without background information given to the participants. The correlation coefficient between the average loudness and short-term annoyance ratings of $\rho = 0.990$ was statistically highly significant ($p < 0.0001$). Only some of the average short-term annoyance values are slightly lower than the corresponding loudness values.

4. DISCUSSION

In the present study,a close relationship between annoyance ratings and ASEL values (cf. Fig. 4) as well as between loudness ratings and ASEL values (cf. Fig. 6) is observed. The finding is in overall agreement with relationships reported in the literature. Leatherwood and Sullivan investigated the effectiveness of boom shaping for overpressure values between 50 Pa and 125 Pa and ASEL values between 62 dB(A) and 90 dB(A) [16]. They found correlation coefficients around 0.96 between the A-weighted sound exposure level and loudness ratings depending on the set of sounds. In their study the level range was considerably larger and the absolute values were considerably higher than in the present study. This large range of tested ASEL values might have contributed to the high correlation coefficients in their study. In another study, the same authors reported very high correlation coefficients between ASEL values and loudness and annoyance values obtained from magnitude estimation experiments also for a similar range of ASEL values like in the present study [17].

In the present study, a relative increase in level by 6 dB resulted in a higher average short-term annoyance rating by 2 to 3 scale units for each of the signatures. Due to the close link of the short-term annoyance and the loudness ratings, this relationships is similarly found for the loudness ratings.

5. ACKNOWLEDGEMENT

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