Title: Evaluation of an Indoor Sonic Boom Subjective Test Facility at NASA Langley Research Center

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Abstract:

A sonic boom simulator at NASA Langley Research Center has been constructed for research on human response to low-amplitude sonic booms heard indoors. Research in this facility will ultimately lead to development of a psychoacoustic model for single indoor booms. The first subjective test was designed to explore indoor human response to variations in sonic boom rise time and amplitude. Another goal was to identify loudness level variability across listener locations within the facility. Finally, the test also served to evaluate the facility as a laboratory research tool for studying indoor human response to sonic booms. Subjects listened to test sounds and were asked to rate their annoyance relative to a reference boom. Measurements of test signals were conducted for objective analysis and correlation with subjective responses. Results confirm the functionality of the facility and effectiveness of the test methods and indicate that loudness level does not fully describe indoor annoyance to the selected sonic boom signals.

1 Introduction

Civil supersonic flight over land is currently prohibited in the United States due to human annoyance to sonic booms. Research has shown, however, that shaping the aircraft can affect the sonic boom waveform that is received at the ground and can result in a decreased loudness level. As NASA and aircraft manufacturers are developing new low-boom aircraft designs based on this shaping concept, NASA is also researching the potential impact of low-amplitude shaped sonic booms, or "low booms", on community residents. An understanding of indoor human response to sonic booms is one important factor in the determination of the acceptability of low booms. With the goal of providing information to regulatory agencies to enable replacement of today's prohibition of civil supersonic over-land flight with a noise-based standard for supersonic aircraft certification, NASA is developing a model that describes and predicts people's annoyance to the low booms experienced indoors.

Developing a psychoacoustic model of human response to low booms involves identifying the best metric or combination of metrics to predict human annoyance. Subjective tests to aid in the single-event model development and validation are being conducted in the laboratory, as opposed to a field environment. In the laboratory, greater control over the interior sound exposure can be achieved, which allows for investigation of the contribution of specific parameters to human annoyance, such as loudness level, spectral content, presence of secondary rattle noises and vibration, and room acoustics. In the laboratory relative levels of annoyance are measured, which can be used to develop the predictive model for human annoyance to isolated sonic booms.

In order to develop this prediction model, NASA Langley Research Center has designed and constructed a sonic boom simulator capable of reproducing a realistic indoor sound environment for subjective testing [3]. This simulator, known as the Interior Effects Room (IER), consists of a living-room-sized structure with loudspeaker systems installed to create a controlled acoustic environment. The human-rated facility is used as an environment in which to assess people's perception of the sonic boom noise, whereby test subjects listen to the sounds inside the "living room" and rate their annoyance to the various sounds.

1.1 New Laboratory Evaluation Test

The first subjective test in the IER, reported here, was designed to evaluate the operational procedures of the facility and to investigate the relationship between indoor annoyance, loudness level, and sonic boom rise time. Additional objectives included definition of loudness level variation across listener locations in the room and comparison of noise metric correlations with indoor annoyance. It was envisioned that insight gained from this preliminary study would guide the design of future subjective tests.

2 Sonic Boom Subjective Test Facility Overview

Sonic boom simulators have been used effectively to study human annoyance to a broad range of boom signals under controlled conditions. Subjective testing in previous simulators, in homes, and in the field [5] have shown that human annoyance to sonic booms outdoors is best predicted by the loudness level metric Perceived Level (PL) [8, 9]. Indications that human response may differ when experiencing sonic booms in an indoor environment [10]

motivated construction of the Interior Effects Room (IER) at NASA Langley Research Center [3]. The unique capabilities of this facility include a realistic indoor soundscape within the context of a residential living room environment.

The IER, shown in Fig. 1, consists of a living-room-sized structure built with typical modern American home construction methods and materials. The interior dimensions are 4.1 m by 3.5 m with a 2.5 m-high ceiling, and the room includes typical living room furnishings. The facility includes the capability to simulate the booms realistically by employing two arrays of subwoofers and mid-range loudspeakers (52 of each) coupled to two adjacent exterior walls of the simulator. The sound transmits through the facility walls as a boom would transmit through a home's walls, and the resulting interior boom approximates that which would be received from a real supersonic overflight. The human-rated facility is used as a controlled environment in which to assess people's perception of sonic booms indoors. The facility allows for controlled and repeatable playback of recordings of sonic booms, synthesized boom sounds that emphasize different sound characteristics, and simulated booms from supersonic aircraft designs.

Figure 1. Interior view of Interior Effects Room subjective test facility.

For the present study, only one exterior loudspeaker array was installed and used to play back the sonic booms. A floor plan of the IER depicting the active array is included in Fig. 2. Microphone locations M1-M3 are also illustrated, where M1, M2, and M3 correspond to subject seat locations 1, 2, and 3, respectively. Seat 1 corresponds to the armchair, and seats 2 and 3 correspond to seats on the couch.

The IER also includes the capability to simulate contact-induced rattle noises [6] inside the room that would be expected from low-frequency excitation of a house. This is accomplished with seven small loudspeakers and a subwoofer located inside the room. The preliminary study described here concentrated solely on subjective reactions to transmitted sonic booms and did not utilize the rattle playback capability.
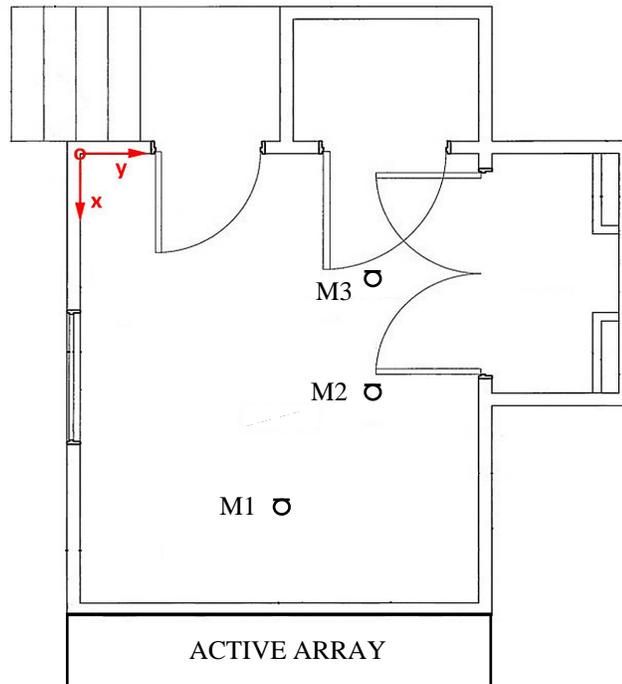
Figure 2. IER floor plan with indoor microphone locations. M1, M2, and M3 correspond to subject seat locations 1, 2, and 3, respectively.

3 Sonic Boom Test Sounds

3.1 Sonic Boom Parameters

The evaluation study included classic N-wave sonic booms synthesized with variations in amplitudes and shock rise times. All boom durations were set to 200 ms before applying a hyperbolic tangent function for smooth shock transitions [1]. Rise times of 3, 6, and 12 ms were included, as shown in Fig. 3. Each of these boom shapes was played back at seven different amplitudes, for a total of 21 unique signals. The amplitudes were chosen to span a range of PL, from approximately 70 to 90 dB at the exterior of the structure.

3.2 Measurement of Signals at Facility Exterior and Interior

Prior to playback, the sonic boom waveforms were high-pass filtered at 6 Hz to fall within the facility's usable bandwidth. When measured at the interior, the waveforms exhibit the effects of this high-pass filtering, as well as the effects of structural transmission and indoor radiation. Example waveforms measured at a representative indoor location are included in Fig. 4. Note that the signals are labeled with the shock rise times (3, 6, and 12 ms) corresponding to their respective exterior waveforms.
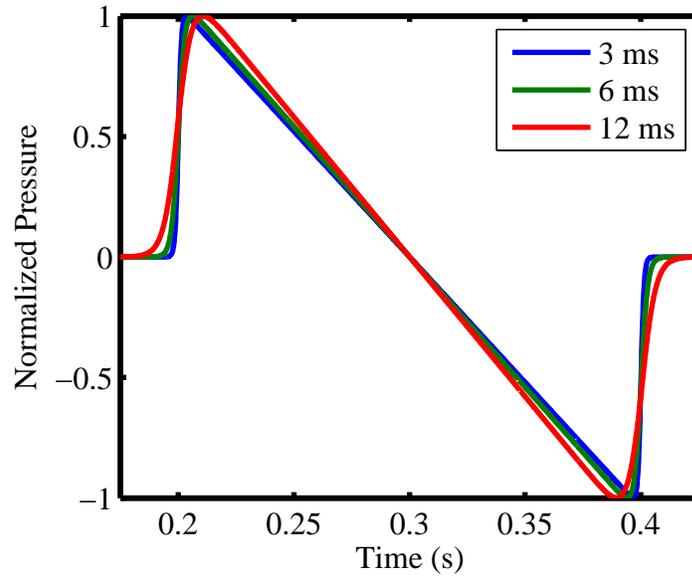
Figure 3. Synthesized sonic boom signals with shock rise times of 3, 6, and 12 ms.
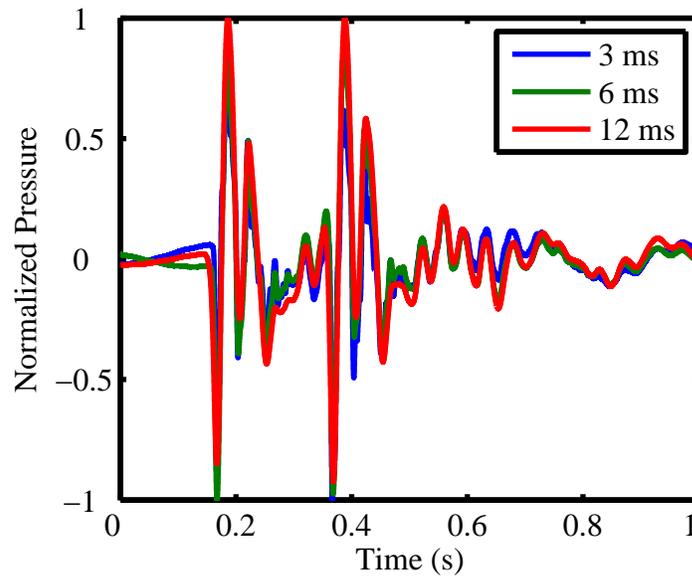

Figure 4. Measured sonic boom signals at a representative indoor location in the IER. The signals are labeled with the shock rise times (3, 6, and 12 ms) corresponding to their respective exterior waveforms.

The energy spectral density for the exterior and interior signals are given in Fig. 5. Included are the three rise time types for an outdoor PL of 78 dB. For equivalent PL, the signals must be played back at different amplitudes, due to the difference in spectral shape between the three rise time types. The interior boom spectra are calculated from measurements at seat 2 near the center of the room (see Fig. 2) and show a PL reduction of $25 - 30$ dB from the exterior levels.
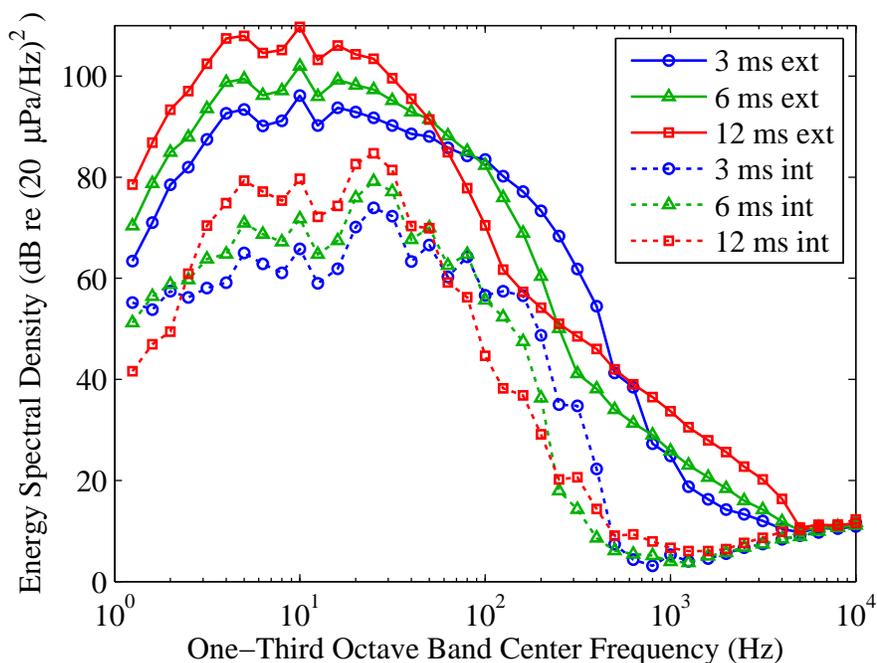

Figure 5. Energy spectral density of measured sonic boom signals at the exterior and at the seat 2 indoor location in the IER. The signals are labeled with the shock rise times (3, 6, and 12 ms) corresponding to their respective exterior waveforms.

4 Evaluation Test Description and Analysis

4.1 Test Description and Objectives

The IER evaluation test was designed to evaluate the operational procedures of the facility and to investigate the effect of basic sonic boom parameters on indoor annoyance. Four specific objectives were identified for analysis of the data:

1. Relationship between indoor annoyance and loudness level

2. Relationship between indoor annoyance and sonic boom rise time

3. Loudness level variation with listener locations in the room

4. Comparison of noise metric correlations with indoor annoyance

For the first two items, previous studies with outdoor booms [4] have shown that annoyance increases with increasing loudness level and decreasing rise time. The objective of the current test was to confirm that these relationships remain the same in the IER indoor environment, where the sonic boom signal is distorted by transmission and re-radiation. The third item was conceived to document expected variations in a small room and whether annoyance would vary depending on location. The fourth item was introduced to begin investigations into the efficacy of different loudness and sound quality metrics for prediction of indoor annoyance, given the limited set of sonic boom waveforms presented. It was envisioned that insight gained from this preliminary study would guide the design of future subjective tests. One such test has been documented in Ref. [7].

Test subjects were recruited from the community and were compensated for their participation. Subjects received an audiometric test beforehand to confirm that their hearing was within 40 dB of reference hearing threshold levels [2]. Thirty subjects participated in the test in groups of three.

The 21 test booms were presented along with a reference boom, the 6 ms boom with an exterior PL of 83 dB. Each comparison was presented in two orders (A-B and B-A) for a total of 42 pairs presented to the subjects for judgment in each session. Subjects rotated among seats and repeated the 42-pair test session at each of the three seat locations. Thus a total of 126 pairs were presented to the subjects for judgment. An example of the judgment screen for the paired comparison is included in Fig. 6. This paired comparison to a reference method allows for determination of an equality point for each signal. The equality point is defined as the signal's metric level resulting in the same annoyance as the reference signal.


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    First          Second
If the first sound is more annoying depress the button labeled 'First'.
If the second sound is more annoying depress the button labeled 'Second'.
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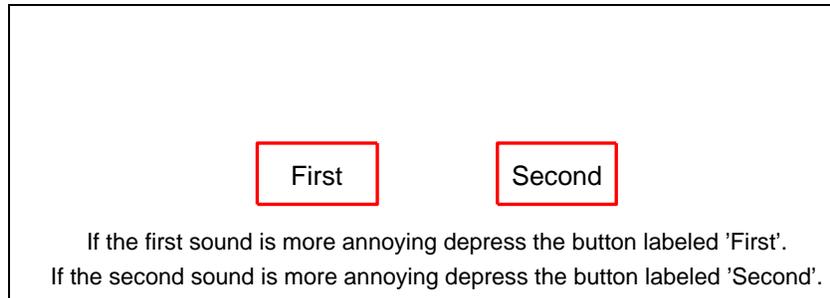
Figure 6. Example judgment screen presented to subjects for paired comparison test.

4.2 Relationship Between Indoor Annoyance and Loudness Level

Results of the subjective test show the percent of subjects more annoyed by the test boom than by the reference boom as a function of noise metrics. The results for an analysis with Perceived Level (PL) of all 21 booms are given in Fig. 7. The percent of subjects more annoyed by the test booms increases with exterior PL, with an equality point at 82 dB (Fig. 7a). The percent more annoyed also increases with interior PL, yielding an equality point at 55 dB (Fig. 7b). The annoyance and PL values from all three seats are included, for a total of 63 data points. Both plots confirm that subjects become more annoyed by the test booms as the loudness level increases.
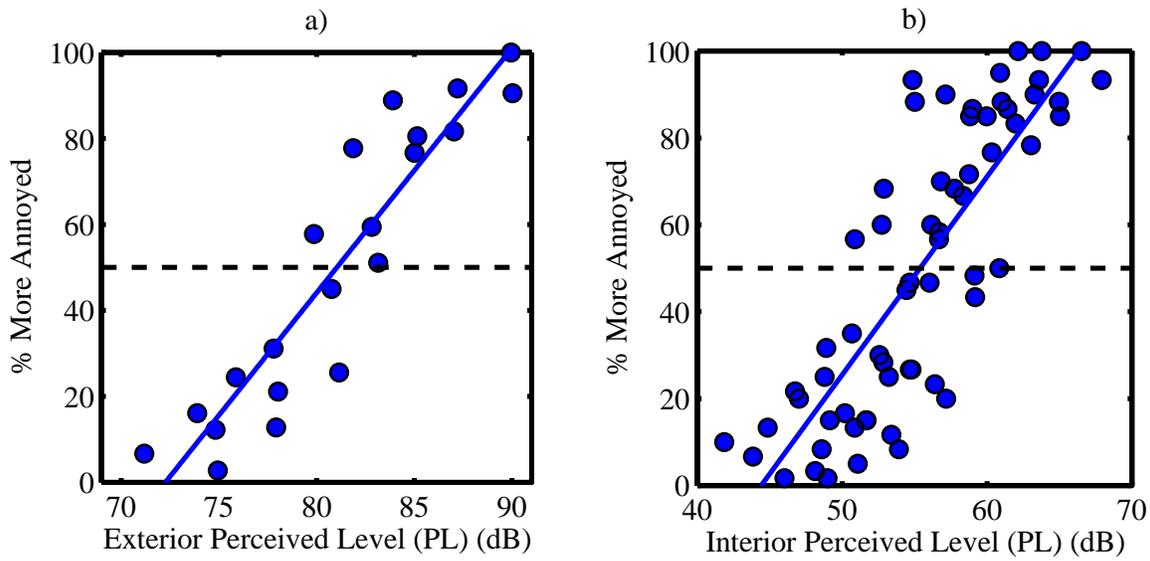
Figure 7. Percent of subjects more annoyed by test booms than by the reference boom as a function of: a) exterior PL and b) interior PL.

4.3   Relationship Between Indoor Annoyance and Rise Time

The annoyance results are also analyzed as a function of peak exterior shock overpressure. This allows for a comparison of annoyance to waveforms of the same amplitude but different rise times. When the data are separated by rise time, it becomes apparent that the relationship with annoyance follows a sigmoidal shape, as opposed to linear. Annoyance to the test booms relative to the reference increases more rapidly as values approach 50%, and then begins to level off as values approach 100%, producing a flattened S shape.

Logistic regression curves are fitted to the data and presented in Fig. 8. A comparison of the logistic curves at a particular peak overpressure, indicated by the dashed line, shows that indoor annoyance caused by a given exterior boom overpressure is greatest for the smallest (3 ms) rise time, and the annoyance is least for the longest (12 ms) rise time. Thus for a given overpressure, indoor annoyance is inversely proportional to rise time.

4.4   Loudness Level Variation with Listener Location

It was expected that indoor loudness levels would vary with location, due to distance from the excited wall and due to room acoustic modes. Acoustic measurements and calculations of PL were performed for the sonic boom waveforms at the exterior and at the three interior subject locations. The relationships between interior and exterior PL for the different waveforms and locations are given in Fig. 9. Loudness level variations for a given waveform type are typically $5 - 7$ dB. Loudness levels at seat 1, the location closest to the excited wall, are consistently highest, while loudness levels are lowest at seat 2 for 12 ms booms and at seat 3 for 3 and 6 ms booms.
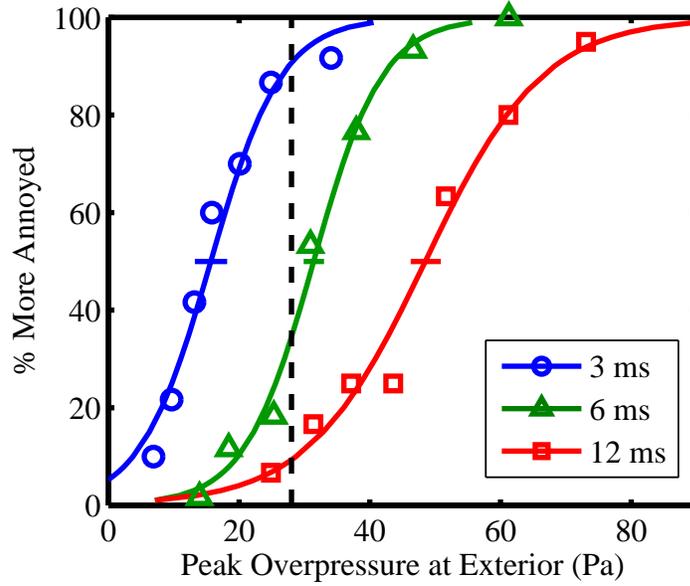
Figure 8. Percent of subjects more annoyed by test booms than by the reference boom as a function of exterior peak overpressure and rise time.
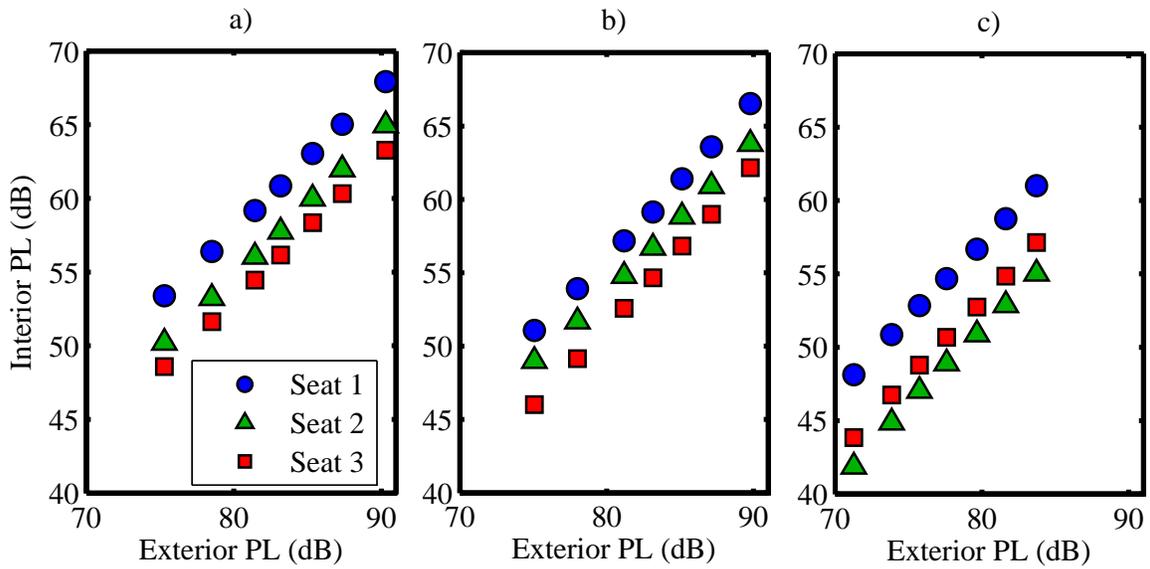

Figure 9. Variations in interior PL by seat location as a function of exterior PL for a) 3 ms booms, b) 6 ms booms, and c) 12 ms booms.

4.5 Comparison of Noise Metric Correlations with Indoor Annoyance

Because the PL variation with seat location is greater than the PL difference between test booms, the analysis of noise metric correlations is performed separately for each seat location. Fig. 10 shows the logistic-regression curves and percent-more-annoyed data as a function of interior PL for the three different seat locations. Equality points and their 95% confidence intervals are denoted by a horizontal line on each curve where it crosses 50%. Although the equality point PL values may be different at the three seat locations, the trend is the same. It is shown that the equality points for the 12 ms boom always occur at a lower PL value than for the 3 or 6 ms booms. A corollary to this observation is that for a given PL value, the 12 ms boom is more annoying than the other two boom shapes. This finding differs from that of the peak overpressure analysis due to PL's frequency weighting that approximates the behavior of the human auditory system. PL, however, still does not fully account for indoor human annoyance to the different boom shapes tested.
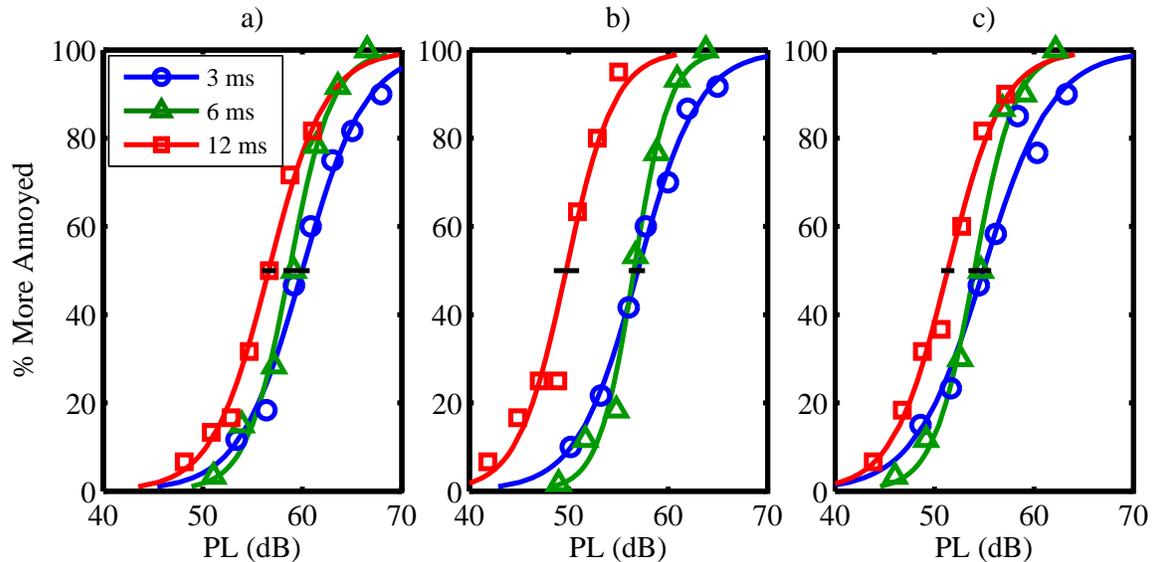

Figure 10. Percent of subjects more annoyed by test booms than by the reference boom as a function of rise time and interior PL for a) seat 1, b) seat 2, and c) seat 3.

An "ideal" metric would group the three curves together, so that annoyance could be predicted by the metric regardless of boom shape (see Fig. 11). An analysis of the correlations for various sonic boom noise metrics was performed to determine whether any metric would perform better than PL. Using a logit transformation to form a linear relationship, correlation coefficients and their 95% confidence intervals were computed for the loudness and sound quality metrics (see App. D in Ref. [6] for a list of metrics). Of the 34 metrics analyzed, 13 metrics (including PL) are identified as being reasonable predictors of annoyance ($r > 0.7$), although not one can be singled out as the clear best metric.
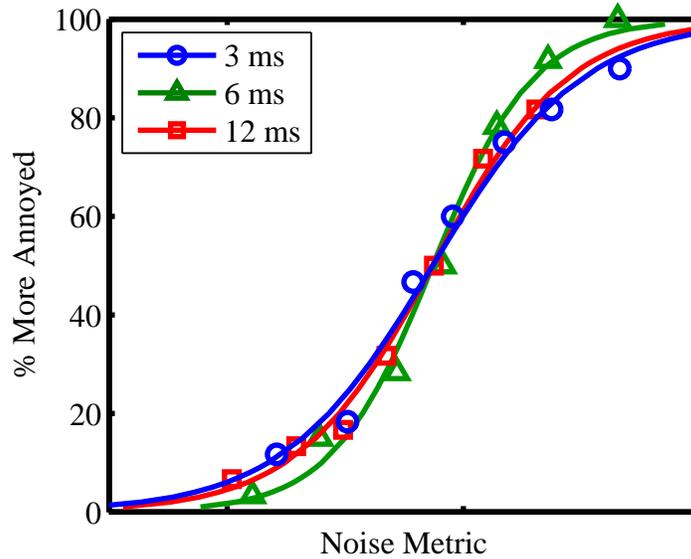
Figure 11. Example logistic regression curves for an "ideal" noise metric that predicts the same equality point regardless of boom shape.

5   Summary and Conclusions

The subjective study described in this paper serves as an initial assessment of the Interior Effects Room facility at NASA Langley Research Center. The IER has been evaluated and validated as a laboratory research tool for studying indoor human response to sonic booms. Analyses relating to the four study objectives confirm the expected trends in annoyance with variations in sonic boom parameters and characterize the facility for use in future test planning. The main conclusions of the test are:

1. Indoor annoyance is proportional to the sonic boom loudness level.

2. Indoor annoyance is inversely proportional to the sonic boom rise time.

3. The loudness level variation with listener locations in the room is typically $5-7\,\mathrm{dB}$ for the sonic booms tested when the 24-element loudspeaker array is used alone. The test method used here allows for separate evaluation of metrics with seat location, since test subjects repeated the test at each location. This repetition limits the number of waveforms that can be evaluated within the allocated 1-hour test period, so that it may be useful to identify alternate locations with decreased variation for future tests (see Ref. [7]). Using both loudspeaker arrays to play back the sonic boom waveforms has subsequently been shown to mitigate this issue by decreasing loudness level variations across the room.

4. Noise metric correlations with indoor annoyance identify a set of best metrics, and no single metric performs significantly better than PL. Only three waveform shapes were

included in this study, and it has subsequently been shown that a greater diversity of waveforms allows for a more rigorous evaluation of noise metrics [7].

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