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Effects of chair vibration on indoor annoyance ratings of sonic booms

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Abstract

The effects of perceptible whole-body vibrations on annoyance ratings of sonic booms and other impulsive environmental sounds experienced indoors were studied. Fifteen pairs of test subjects made annoyance ratings while seated in a living room environment. There were two chairs, one isolated from floor vibrations and the other not isolated, and every test subject rated all signals in both chairs. Halfway through each test session, subjects changed seats. Subjects who sat in the isolated chair first gave lower mean annoyance ratings in both halves of the test than subjects who sat in the non-isolated chair first. Annoyance predictions from models using both sound and vibration measures were closer to average annoyance ratings than predictions from a model using sound measures alone. Reformulation of the annoyance model revealed that the presence of perceptible vibration is equivalent to increasing Perceived Level by 4.8 dB when calculated on exterior signals and by 5.6 dB when calculated on interior signals.

I. INTRODUCTION

Commercial supersonic flight was banned over land in the 1970s because traditional sonic booms caused unacceptable annoyance in overflown communities. The two shocks of a traditional N-wave sonic boom result in a very loud “double bang” sound on the ground.

Also, acoustic energy below 50 Hz can cause building vibrations and rattle sounds, which may increase annoyance indoors beyond that of the transmitted sound alone.

In the coming years, however, advancements may lead to quiet supersonic aircraft that are allowed to fly supersonically over land. Through careful aircraft design, both the peak amplitude of the “shaped” sonic boom waveform and the steepness of the shocks can be reduced (Fig. 1(a)), which greatly attenuates audibility at ground level (Fig. 1(b)). NASA is working with the Federal Aviation Administration (FAA) and the International Civil Aviation Organization (ICAO) to determine whether shaped sonic booms will be publicly acceptable. When considering changes in noise regulations, the FAA and ICAO will rely on a combination of community survey data from quiet supersonic demonstrations and validated predictive models to assess public acceptability. Determining the right factors to include in predictive models, and the relative importance of those factors, is the subject of ongoing research.

Conflicting conclusions are found in the literature on the effects of vibration on indoor sonic boom annoyance. In Nixon and Borsky’s sonic boom field study², 93% of subjects reported interferences with ordinary living activities due to house shaking, and 38% reported annoyance due to house shaking. By contrast, Kryter’s 1968 study³ in which houses were overflowed by supersonic aircraft found no difference in annoyance ratings between subjects seated on an inflatable vibration isolation pad and subjects not seated on the pad. Others have also concluded that indoor annoyance is governed by the acoustic stimulus and vibration does not contribute in a meaningful way⁴. However, this finding may not hold for shaped sonic booms where high frequency content has been attenuated significantly but low frequency content has not (Fig 1(b)).

The effect of perceptible vibration on indoor annoyance for other transportation noise sources is well-documented. For example, adding a vibration predictor to a sound predictor improves annoyance models for lab studies of annoyance from railway events⁵ and for determining passenger discomfort due to ride quality⁶. However, in these studies the vibration signals had peak amplitudes an order of magnitude greater than the vibration signals expected from shaped sonic booms. The lack of consensus from previous research, as well as the comparatively low vibration amplitudes expected for shaped sonic booms, motivated this investigation.

To identify the separate roles that whole-body vibration and low frequency sound play in subjective judgments, impulsive environmental sounds, including shaped sonic booms, were presented to subjects in the NASA Langley indoor sonic boom simulation facility⁷. These sounds induced varying levels of vibration in the facility floor. Vibration isolators were installed to reduce the vibration transmitted from the facility floor to one of two chairs. The locations of the two chairs in the room were chosen because the sound levels at the two locations were very similar. Care was taken to eliminate contact-induced rattle noises from the impulsive sounds. Three questions are posed in this research. First, does changing the vibration exposure affect annoyance ratings of sonic booms when heard indoors? Second, when vibration is present, does an annoyance model that combines a vibration descriptor with an acoustic descriptor perform better than a model with only an acoustic descriptor?

Third, what is the approximate magnitude of the vibration penalty for the range of sounds and vibrations in this study?

In the next section, the test facility, the signals, and the test procedures are described. Results of the study are presented in Section III along with an analysis of annoyance models that include both sound and vibration descriptors. The paper ends with a summary of the research findings.

II. TEST SETUP

Below are descriptions of the indoor sonic boom simulation facility, the isolated and non-isolated chairs in which subjects sat, and how vibration and sound exposures were estimated. The test procedure, test signals, and subject pool are also described.

A. Test Facility

A plan view of the Interior Effects Room (IER), an indoor sonic boom simulation facility at the NASA Langley Research Center, is shown in Fig. 2. This single-room facility, built using typical U.S. residential construction methods and materials, is surrounded on adjacent sides by two arrays of loudspeakers in close proximity to the exterior surface of the walls (shown at the bottom and on the left side of Fig 2). The two arrays, containing a total of 52 subwoofers and 52 mid-range speakers, have a usable bandwidth of 3 Hz to 5 kHz and sufficient output to allow study of sonic boom noise. These arrays are used to mimic the time dependent exterior pressure loading that would occur if a sonic boom were to impact the exterior facade of a residential house and transmit into a room located at the corner of the house.

The interior dimensions of the furnished test space are 3.45 m by 4.09 m with a 2.54 m high ceiling. Walls are of wooden 2×4 stud construction, nominally 0.4064 m (16 in) on center, with a 1.27-cm plywood exterior sheathing and 1.27-cm gypsum board interior finish. Exterior finishing materials typical of residential construction, such as stucco or siding, were not used on the exterior façade. The larger wall containing speaker array #2 also contains a double hung window with an outside frame measuring 1.22 m wide by 1.52 m tall. The facility floor is framed with 2×10 wood joists nominally 0.4064 m (16 in) on center and is built atop a raised, wooden foundation that provides a 0.533 m high crawl space. This allows the floor to vibrate naturally in response to indirect excitation from the speaker arrays. The subfloor is 1.91 cm plywood, and is finished with a floating laminate flooring system. Carpeting can be added to the room; however, in this study carpeting was not used. The room includes two closets (Fig. 2) with louvered doors, which can be filled with acoustically absorptive material to alter the room reverberation. However, these closets were empty for this study. While the reverberation time was not specifically measured for the room as-configured for this study, the reverberation time for a similar configuration was measured and is listed in Table I. The mean T60 reverberation time from 40 to 4000 Hz is 0.52 s and the Schroeder frequency of the room is approximately 190 Hz.

1. Chair vibration isolation—Two wooden chairs were placed in the simulator. Test subjects seated in these chairs experienced both tactile and whole-body vibration. The

vibration results from indirect excitation from the exterior speaker arrays, which causes motion in the facility floor that transmits into the chairs. Compliant seating surfaces (seat cushions) were not used. To vary subjective exposure to the vibration stimulus, the chair construction and placement within the facility were manipulated to maximize the vibration response of one chair while minimizing the vibration response in the other, all while maintaining similar acoustic levels at the two listener locations.

Pneumatic elastomeric vibration isolators, model SLM-1A from Barry Controls, were mounted to the legs of one test chair (Fig. 3) to reduce the transmitted chair motion. Due to the static load limit for these isolators, which includes the weight of the chair, only test subjects who weighed less than 90.7 kg (200 lbs) were allowed to participate in the study. When appropriately loaded and inflated, these isolators have an expected resonance of 3 to 5 Hz, which is well below the first vibration mode of the facility floor. The modal response of the floor was measured, and the first three dominant modes were at 12, 23 and 32 Hz, which are in the range where the isolators are expected to attenuate the transmitted vibration. The second chair was placed in the facility with the legs in direct contact with the floor with no isolators installed (Fig. 4). In addition, the chair placement was selected so the isolated chair sat near a nodal line of the expected low-frequency mode shapes of the facility floor while the non-isolated chair was placed near a modal maximum. This placement further increased the disparity in vibration amplitudes between chairs.

The effectiveness of the chair isolation was assessed by playing several sonic boom waveforms through the exterior arrays while measuring the vibration of both chairs while a person was seated in them. Accelerometers were attached directly to the underside of the chair seats. In Fig. 5(a), the w_k -weighted time domain waveforms and corresponding peak w_k -weighted levels are shown for both the isolated and non-isolated chairs and are compared to both the ambient vibration of the chairs and the perception threshold¹⁰. In the example shown in Fig 5(a), a reduction of the peak acceleration amplitude by a factor of 4.8 is observed when comparing the isolated and non-isolated chairs. The isolated chair average vibration amplitudes were always below the peak w_k -weighted perception threshold of 0.015 m/sec², while average amplitudes in the non-isolated chair were always above this threshold (Fig. 5(b)). These vibration exposure estimates will be discussed in the next sub-section.

2. Vibration exposure—Vibration exposure will be described in two ways: 1) using a binary descriptor, according to the presence or absence of chair vibration isolators, or 2) using a continuous descriptor, the average chair seat vibration amplitude. Ideally all subjects would experience comparable vibration amplitudes for each test signal. This was difficult to ensure because chair vibrations were a secondary effect of the acoustic excitation and not controlled directly. The mass (subject weight and distribution across the chair seat) varied among subjects, which affected the vibration amplitude transmitted from the ground through the chair. Additionally, the isolators were always inflated to 37 psi inflation pressure, which implies a constant spring rate. Therefore, for the same excitation signal and chair, some variation in vibration amplitude across the pool of test subjects was expected.

In an attempt to bound the range of vibration exposure, three sample subjects were selected whose weights of 51.3 kg (113 lbs), 73.9 kg (163 lbs) and 94.8 kg (209 lbs) spanned the

anticipated weight range of the test subjects. The range of vibration amplitudes experienced by these three people of disparate weights was considered a good estimate of the range of vibration amplitudes that would be experienced by a pool of test subjects.

Quantifying the actual vibration experienced by a test subject in a chair was complicated because subjects tend to shift their weight in the chairs throughout signal playback. These small motions by the seated subject introduced noise into the vibration signal, particularly on the isolated chair, which is more likely to rock due to the isolators. Therefore, instead of measuring the transient chair vibration directly due to each test signal, the vibration was predicted using a frequency response function estimated from accelerometer measurements for each of the three sample subjects. Pink noise was reproduced at the facility exterior using the speaker arrays, and the frequency response function (FRF) between this exterior acoustic pressure excitation (input in units of Pa) and resulting vibration of the occupied chair (output in units of m/s^2) was computed using an H1 estimate. The H1 estimator was used to reduce the effect of the uncorrelated vibration “noise” generated by movements of the subject seated in the chair. A total of 115 averages with 50% overlap and a Hanning window were used in the H1 estimate, where each window had a period of 2.5833 s. The resulting six FRFs were inverse Fourier transformed to yield an impulse response function for each sample subject and each chair. The impulse response functions were convolved with the desired exterior test waveforms to estimate the transient vibration experienced in each chair by the three sample subjects for each signal.

These transient vibration estimates were filtered using a w_k -weighting infinite impulse response (IIR) filter¹⁰ and the peak absolute value of the filtered transient (Fig. 5(a)) was selected to describe vibration exposure in each chair for each sound (Fig. 5(b)). The three peak w_k -weighted exposure predictions for each chair were averaged to estimate the range of vibration exposure across all test subjects in that chair for each signal. This average vibration amplitude in the isolated and non-isolated chairs is shown in Fig 5(b) and is compared to both the perception threshold and the ambient vibration of the non-isolated chair when the facility is not excited. The acceleration exposure averaged across the three people in the isolated chair was always below the perception threshold of 0.015 m/s^2 and varied from 0.0017 to 0.0147 m/s^2 (Fig. 5(b)). In the non-isolated chair the average exposure estimates varied from 0.0151 to 0.0874 m/s^2 (Fig. 5(b)), which are above the perception threshold and an order of magnitude (20 dB) or more above the facility ambient.

In addition to the average amplitude, the range in exposure across these three sample subjects for each test sound and each chair is shown as a vertical bar in Fig 5(b). Exposure variability was higher in the isolated chair than in the non-isolated chair, possibly due to changes in the compliance of the pneumatic isolators when loaded with subjects of different weights. In the isolated chair, the range typically remained below the perception threshold except for five of the signals with high vibration amplitudes. These signals were kept because the average vibration is below threshold and because the isolated chair vibration was well below the vibration in the non-isolated chair. The large observed variability of vibration in the isolated chair (Fig. 5(b)) should have minimal effect on analysis because vibration amplitudes are below the perception threshold. By contrast, the small variability in

exposure observed in the non-isolated chair (Fig. 5(b)) indicates that exposure in the chair where vibrations could be felt can be estimated with higher confidence.

The Maximum Transient Vibration Value (MTTV)¹⁰ was also computed for consideration as a continuous vibration exposure descriptor, in addition to peak w_k -weighted acceleration. The MTTV values were compared to the peak w_k -weighted acceleration. The coefficient of determination between descriptors was $R^2 = 0.91$ (or $R = 0.95$), suggesting that either would be suitable to describe vibration exposure. Given the desire to relate vibration exposure to the perception threshold, peak w_k -weighted acceleration is chosen instead of MTTV. No other vibration predictors were considered.

3. Acoustic Exposure—To characterize the noise environment, pressure time histories were measured at two locations: the exterior surface of the IER walls, exposed directly to the impulsive sound waveform from the speaker arrays, and inside the test space (Fig. 2). Exterior measurements were made with 38 microphones placed flush against the exterior facade of the facility, 18 of these locations were in array #1 and 20 were in array #2. The interior measurements were made at approximately ear height at both the isolated and non-isolated chairs while subjects were not present. Each of the test signals was recorded ten times. The set of ten waveforms at each measurement location were time aligned and then averaged in the time domain to reduce effects of microphone self-noise and ambient background noise. The averaged exterior waveforms were averaged again across microphones to produce a single pressure time history estimate for each array for each test signals. These time and spatially averaged exterior signals are used for the calculation of exterior acoustic exposure. The reasoning behind using exterior, instead of interior, measurements to quantify exposure is discussed in Section III(B).

Acoustic loudness levels inside the test space can vary by almost 10 decibels depending on the measurement location. Despite attempts to select chair locations with identical sound exposure, the isolated chair had slightly higher values, as shown in Fig. 6. The mean difference and standard deviation of Perceived Level between chair locations was 1.45 ± 1.14 dB. The study was conducted despite the difference in acoustic exposure for two reasons. First, the observed sound level differences are relatively small. Second, sound levels are slightly higher at the isolated chair, where lower annoyance is expected. If lower average annoyance ratings are observed in the isolated chair, it will mean that any potential annoyance increase with slightly higher sound levels was overshadowed by the annoyance decrease with the absence of perceptible vibrations.

B. Audio playback and facility response

The audio hardware, signal playback, and test flow are controlled by Labview software. Each mid-range, subwoofer pair in the two exterior speaker arrays is independently controlled by a separate 24-bit digital to analog converter (D/A). Each D/A channel is routed to an analog-to-digital-to-analog audio processor that provides some parametric equalization and also acts as a crossover, splitting the full bandwidth analog signal into separate low and high frequency signals that are amplified and sent to each subwoofer and mid-range speaker, respectively.

Corrections for the variation in the magnitude and phase of the frequency response of the exterior arrays is accomplished partially by using parametric equalizers in the audio processors and also by predistorting the transient excitation using an finite impulse response filter designed using a Wiener filter approach⁷. The deviations between measured and desired array response magnitudes in each one-third-octave band from 6.3 Hz to 4 kHz are shown in Table I. The deviation shown is the difference between the measured exterior level, found from an average over multiple microphone locations at the exterior wall surface, and the desired exterior pink noise level. The deviation is shown for both Array #1 and Array #2. However, the first three one-third-octave band estimates are excluded for Array #1 because the frequency range of the microphones used for this characterization of Array #1 did not include these bands. The error averaged over the bands from 12.5 Hz to 4 kHz is 0.03 dB and -0.09 dB for Array #1 and Array #2, respectively.

The exterior pressure loading transmits through the walls, resulting in reduced acoustic levels inside the test space similar to the noise reduction that would occur in a residential house. The space-averaged exterior-to-interior noise reduction, found from the interior level averaged over several interior microphones, is shown in Table I for pink noise excitation of the arrays and a room configuration similar to that used in this subjective study. The observed noise reduction varies from about 9.4 dB at 25 Hz to more than 50 dB above 3 kHz.

C. Test Signals

There were 45 signals of interest for the current research questions. The signals include 29 synthetic shaped sonic booms, eight conventional sonic booms, four door slams, three blast waveforms, and one gunshot. The range in exterior Perceived Level⁹ was 72 to 107 dB. Subjects experienced an additional 35 signals to address research questions not described here, including comparison with a headphone study conducted at Purdue University.

D. Subjects

The subject pool consisted of thirty subjects from the Hampton, Virginia area, recruited via flyers posted in public places, via an online signup form, and via word of mouth. There were eighteen female subjects and twelve male subjects, ages 18–61 years. The average age was 27 years and the median age was 22 years. To screen for normal hearing, subjects were checked for auditory acuity within 30 dB of audibility thresholds for tones from 125 Hz to 8 kHz. A second audiogram was given after the test to ensure that hearing thresholds did not change during the test. Institutional Review Board (IRB) approval at the NASA Langley Research Center was obtained prior to testing.

Upon arriving at the facility, subjects were given a consent form to sign, and the pretest audiogram was administered. Two subjects at a time were escorted into the facility, one seated in the vibration isolated chair and one in the non-isolated chair. A verbal description of the testing sequence was then given: familiarization, practice, first half of the test, switch chairs, second half of the test. For familiarization, subjects were asked to experience ten signals without rating them. Subjects then practiced using the rating input procedure described below by responding to another six signals. After this practice, the first half of the

test commenced, consisting of 80 acoustic signals and the corresponding induced floor vibration. On completion of the first half of the test, the two subjects switched chairs to experience the same sequence of 80 signals and accompanying vibrations in the other chair. The order of signals was randomized for each subject pair to reduce playback ordering effects such as learning and fatigue. Note that there are two groups of subjects: the subjects who sat in the non-isolated chair first (Group I), and the subjects who sat in the isolated chair first (Group II).

After each signal, an image of a categorical line scale was presented to subjects (Fig. 7) using a laptop computer set on a table attached to the chair. Subjects were asked to rate their annoyance by placing a mark anywhere along this line using a rotary dial input device to move a cursor along the line. Adjectival descriptions of “not at all annoying”, “moderately annoying” and “extremely annoying” were placed at the leftmost, center, and rightmost gradations, respectively. These verbal anchor points are recommended to represent equal subjective intervals between tick marks⁸. Software constraints were applied to prevent responses to the left of “not at all annoying” or to the right of “extremely annoying”. When subjects were satisfied with their evaluation, they pressed down on the top of the rotary dial to record their evaluation. The location of the cursor was converted to a numeric score between 0 (not at all annoying) and 4 (extremely annoying) for analysis. After completing the test, subjects were asked for written feedback on the overall test, such as suggestions for improvement. A post-test audiogram was administered, and subjects were compensated \$50 plus transportation costs for their participation.

III. RESULTS

Three questions are posed in this research. First, does changing the vibration exposure affect annoyance ratings of sonic booms when heard indoors? Second, when vibration is present, does an annoyance model that combines a vibration descriptor with an acoustic descriptor perform better than a model with only an acoustic descriptor? Third, what is the approximate magnitude of the vibration penalty for the range of sounds and vibrations in this study?

A. Annoyance analysis using a binary vibration descriptor

The first question is whether the difference in vibration exposure between vibration conditions affects the annoyance ratings. For each chair, annoyance ratings from the 30 subjects were averaged across all subjects and all sounds ($N = 30 \times 45 = 1350$). The average ratings from the isolated chair (vibration below threshold) and the non-isolated chair (vibration above threshold) are shown in Fig. 8(a) along with the standard error of the mean. There is no significant difference in mean annoyance between the non-isolated (estimated mean=1.49, estimated std. dev. =1.21, $N=1350$) and the isolated (estimated mean=1.49, estimated std. dev. =1.19, $N=1350$) chairs; $t(2698)=0.0857$, $p < 0.47$. Under the assumption that condition order has no effect on subjects, one would conclude that vibration exposure does not affect annoyance. However, that conclusion is erroneous. Below, it will be shown that condition order can have an important effect on test subjects performing the same task under different conditions.

A difference in average annoyance ratings emerges when subjects are grouped by the order in which they sat in the chairs, suggesting that subjects were influenced by their experience in the first chair while rating annoyance in the second chair. Group I sat in the non-isolated chair first and switched midway through the test session to the isolated chair while Group II did the opposite. As shown in Fig 8(b), Group I's annoyance ratings were, on average, higher in both chairs than Group II's. There is no reason to suspect an inherent difference between groups because the subjects were assigned to groups randomly. One theory for the observed behavior is that subjects developed a strategy for rating annoyance while in the first chair and then transferred that strategy when rating signals in the second chair. The work of Poulton and his colleagues supports this theory¹¹. Poulton and coauthors coined the term asymmetric transfer bias to describe the bias observed when people do the same task sequentially under different conditions. Evidence of asymmetric transfer bias appears to be present in this data.

One technique to salvage data contaminated by asymmetric transfer bias is to compare only the first condition results for each group and discard second condition results¹¹. Following this approach, the data was reanalyzed using only the data from the first isolation condition that each subject experienced (Group I first chair and Group II first chair), indicated by the two circular data points in Fig. 8b. A significant difference is found between estimated mean annoyance in the non-isolated (estimated mean=1.67, estimated std. dev. =1.29, $N=675$) and the isolated (estimated mean=1.30, estimated std. dev. =1.08, $N=675$) chairs; $t(1348)=5.82$, $p < 0.0001$. Group I subjects (non-isolated chair first) rated signals as more annoying than Group II subjects (isolated chair first). Because the acoustic levels at the two chairs are comparable and slightly lower in the non-isolated chair, the increase in estimated mean annoyance from Group I in the non-isolated chair cannot be ascribed to acoustical differences.

A plausible hypothesis is that greater chair comfort led subjects to rate signals as less annoying, since the compliance differed between the two chairs. While the chair-floor interface for the non-isolated chair was completely rigid, the more compliant interface of the isolated chair allowed for chair movement in response to motion or adjustments in seated position. As a result, it is possible that subjects found this chair less rigid and more comfortable. However, chair compliance is confounded with vibration condition, so this hypothesis cannot be tested. A subsequent investigation using only isolated chairs, not described in this manuscript, showed vibration penalties similar to those reported later in Section III(D). Therefore, chair comfort as a source of annoyance differences will not be examined further in this manuscript.

It has been shown that subjects in the non-isolated chair rate signals more annoying on average than subjects in the isolated chair when comparing first chair conditions only. These results appear to contradict research results reported by Kryter³. Those results showed no apparent difference in annoyance ratings between subjects who were and were not seated on vibration isolators. Subjects from that study also switched chairs midway through the test session, but in the analysis the responses were not grouped by chair-type and by chair order. If responses had not been separated into subgroups in the present analysis, no difference would have been found, as illustrated in Fig. 8(a). Without access to the raw data from that

study, it is not possible to check for differences in the average responses between the two isolation conditions in the first half of the test only, and whether asymmetric transfer bias affected the results.

The difference in results between the current study and Kryter's study may also stem from the differences in excitation signals. Kryter's signals were N-waves from traditional supersonic aircraft. By contrast, in the present study, a mixture of traditional N-wave and shaped sonic booms were used along with other transient signals with different spectral content. Shaped sonic booms have much less high frequency energy than traditional N-wave sonic booms (Fig 1(b)), but the low frequency energy is more comparable. For this reason, it is possible that vibrations play a larger role in indoor annoyance from shaped sonic booms than from traditional N-wave sonic booms.

B. Correlation of annoyance with acoustics metrics

Because sonic boom acoustic level is considered a primary annoyance descriptor, an analysis of the annoyance data was conducted to determine which acoustic metrics best describe sonic boom annoyance. Although people spend the majority of their time indoors¹², aircraft certification measurements are generally made outdoors. Therefore, a future certification metric for supersonic aircraft should adequately describe indoor annoyance based on an outdoor measurement. For this reason, the analysis described in this section considers outdoor loudness descriptors for both the isolated and non-isolated chairs, both separately and together. In subsequent sections, a vibration descriptor is added to the annoyance model.

Twelve acoustics metrics, which are listed in the first column of Table II, were calculated for each of the signals using measurements from the exterior facade of array #1 discussed in section II.F. The metrics include Perceived Level (PL),^{9,17} which is commonly used to quantify sonic boom exposure. Additional metrics include Sound Exposure Level²⁰ (XSEL) where X indicates the frequency weighting function¹⁸, maximum weighted sound pressure level using either slow or fast exponential averaging (e.g., LASmax means maximum A-weighted sound level using slow exponential averaging)¹⁹, and Perceived Noise Level (PNL)²⁰. These metrics were previously found to correlate highly with annoyance ratings across several laboratory sonic boom studies in three different facilities, including both outdoor and indoor listening environments¹³. The multi-predictor metric Indoor Sonic Boom Annoyance Predictor (*ISBAP*) was derived from a previous NASA sonic boom study^{14,15} and includes both Perceived Level (PL)⁸ and A- and C-weighted Sound Exposure Levels, as shown in Eq. (1). The second term based on Sound Exposure Levels is sometimes referred to as "heaviness". Heaviness has accounted for the effects of low-frequency energy in a sound beyond what is predicted by loudness metrics¹⁶.

$$ISBAP = PL + 0.4201(CSEL - ASEL)^1 \quad (1)$$

Based on the correlation analyses, PL results in one of the highest coefficients of determination (R^2) for either or both chairs. The metrics *ISBAP*, ESEL, and DSEL also have high coefficients of determination. As shown in Table II, *ISBAP* does not account for more annoyance variation than *PL*. In other words, the addition of heaviness does not improve the

PL metric's descriptive capability for this dataset. A-weighted metrics and PNL did not perform as well, and C-weighted metrics performed poorly. In some cases the descriptive capability of a metric is marginally better for the non-isolated chair. The rank order of the metrics, however, is very similar between chairs. Based on these results, *PL* will be used as the acoustic descriptor when assessing models that include both acoustic and vibration descriptor.

The mean annoyance rating for each sound is plotted against *PL* in Fig. 9. Because the exterior measurements are used, each value on the x-axis corresponds to two ratings on the y-axis, one for the isolated and one for the non-isolated chair. The figure shows best fit lines to the data corresponding to fitted linear models of *Mean Annoyance* based on *PL* for the isolated chair data, the non-isolated chair data, and both chairs combined. The coefficients of determination for *PL* and other models are given in Table II.

C. Annoyance models containing both Perceived Level and vibration descriptors

In this section annoyance models are examined that include both Perceived Level and vibration descriptors. Table III includes five annoyance models. As shown in models 3, 4, and 5, vibration descriptors increase descriptive power beyond *PL* significantly. When *Chair Type*, the binary vibration descriptor, is added to a model containing *PL*, the coefficient of determination increases from 0.776 to 0.837. The coefficient of determination increases to 0.865 when peak w_k -weighted vibration, the continuous vibration descriptor, is added to a model containing *PL*. Thus, quantifying vibration as a continuous variable instead of a binary variable contributes only a small increase in descriptive power from 0.837 to 0.865. Note that the descriptive power of the continuous vibration variable might be underestimated because an average vibration value is used for all subjects, instead of the vibration value experienced by each subject individually.

As a rule, regression coefficient estimates can be unstable if predictors are correlated. To assess collinearity among predictors the Variance Inflation Factor (VIF)²¹ is calculated for each predictor in each model. For all models in Table III the VIF is less than 3, indicating that collinearity among predictors is unlikely. Furthermore, the interaction effects in models 4 and 5 are both non-significant.

D. Vibration penalty

Certain indoor secondary factors are known to increase annoyance. These factors include contact-induced rattle sounds. The influence of secondary factors is often quantified in terms of a correction term, or penalty. The penalty is the increase in acoustic level of a sound without secondary factors that makes it subjectively equivalent to the sound with secondary factors.

The multiple regression equation for model 4 in Table III can be rearranged to extract a vibration penalty. The full equation for predicting Mean Annoyance based on *PL* and *Chair Type* is given in Equation 2. Following the same approach as described in the footnote 1 for the *ISBAP* metric, the *Chair Type* term can be rewritten to appear as a correction to the *PL* metric. When *Chair Type* changes from 0 (non-isolated) to 1 (isolated), the effect is the same as reducing *PL* by 4.8 dB.

$$MA = -5.483 + 0.0785PL - 0.377 \text{ Chair Type} \quad (2)$$

$$MA = -5.483 + 0.0785 (PL - 4.803 \text{ Chair Type}) \quad (3)$$

The algebraic manipulation in Equations 2 and 3 can also be interpreted geometrically, as follows. When *Chair Type* = 0 (non-isolated), the models yield a best fit line through the non-isolated data. When *Chair Type* = 1 (isolated), the model yields a parallel line through the isolated data with a lesser y-intercept. In contrast to the best-fit lines drawn in Fig. 9, the lines predicted by Eq. (2) are parallel because the interaction term between descriptors was not significant. The horizontal distance between the two parallel lines described by Eq. (2) is 4.8 dB.

For this dataset, the presence of vibrations made impulsive signals, on average, as annoying as if the sound level were increased by 4.8 dB with no vibration. Because the interior sounds were higher, on average, by 1.45 dB at the isolated chair, this estimated vibration penalty may be conservative. In fact, when model 4 in Table II is developed using sound metrics derived from interior measurements at the two chairs, which takes into account the acoustic level differences at the two chairs, the vibration penalty increases to 5.6 dB (not shown).

To put this vibration penalty in context, sonic boom rattle penalties from the literature have been identified on the order of 3 -- 9 dB²² and 5 dB²³ for sonic booms, and from 6 -- 13 dB for blast noise²⁴. Thus, the vibration penalty estimated here is within the range of rattle penalties previously identified.

IV. CONCLUSIONS

This study suggests that perceptible whole-body vibrations increase indoor annoyance caused by shaped sonic booms and other environmental sounds. The mean difference in annoyance ratings from a chair with and a chair without vibration isolation is statistically significant ($p < 0.0001$). The effect of vibrations on annoyance was quantified in two ways. First, a linear regression model's descriptive capability increased from $R^2 = 0.776$ to 0.837 and 0.865, respectively, when a binary vibration indicator or continuous vibration quantifier was added. Second, a vibration penalty was calculated from the regression model to quantify the annoyance increment. The vibration penalty is 4.8 dB. This means that the presence of perceptible vibration is equivalent to increasing Perceived Level by 4.8 dB.

Previously, the influence of perceptible whole-body vibration exposure was discounted, possibly due to experimental methods that did not account for asymmetric transfer bias or to spectral differences between traditional N-wave and shaped sonic booms. The current findings complement other laboratory results that demonstrate the role of vibration in indoor annoyance caused by railways as well as passenger discomfort in aircraft cabins. While

¹As detailed in Ref. 15, a multiple linear regression analysis was conducted to describe mean indoor annoyance using the acoustic metrics Perceived Level and Heaviness calculated for exterior acoustic measurements. The resulting model was $Mean\ Annoyance = -6.8270 + 0.0864*PL + 0.0363*(CSEL - ASEL)$. All terms were normalized by the coefficient estimated for *PL* (0.0864), and the result shown in Eq. (1) is a hybrid metric with units of dB.

future research should explore whether this penalty is more widely applicable beyond these waveforms and this laboratory, these data provide evidence that ultimate public acceptability of shaped sonic booms may be related to perceptible whole-body vibration exposure, in addition to acoustic exposure.

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Figure 1.

Ground level predicted F-5¹ N-wave sonic boom compared to a shaped sonic boom from a future supersonic aircraft (duration is approximately 80 ms); a) time histories and b) one-third-octave band sound pressure levels.

Figure 2.
Plan view of the Interior Effects Room at NASA Langley Research Center.

Figure 3.
Pneumatic elastomeric isolators (indicated by arrows) attached to all four chair legs of the isolated chair.

Figure 4.
Legs of the non-isolated chair.

Figure 5.

Acceleration in the occupied non-isolated and isolated chairs (ambient measured without test signals); a) sample modeled acceleration time history with a seated 94.8 kg person after w_k -weighting, b) modeled peak w_k -weighted acceleration of all 45 signals.

Figure 6.

Perceived Levels of the signals measured inside the facility were slightly higher, on average, at the isolated chair than at the non-isolated chair.

Figure 7.
Categorical line scale presented to subjects.

Figure 8.

A comparison of mean annoyance ratings for both vibration conditions. Error bars indicate the standard error of the mean. (a) Ratings by chair (1350 observations per data point; 30 subjects times 45 signals), (b) Ratings by chair order (675 observations per data point; 15 subjects times 45 signals).

Figure 9.
Mean annoyance ratings for each chair as a function of Perceived Level.

Table I:

Facility response characteristics, where * indicates frequencies below the Schroeder frequency of the room (approximately 190 Hz) and – indicates frequencies where valid estimates of the listed quantities could not be obtained.

Center Frequency, Hz	Measured Deviation from Desired Exterior Level [dB]		Exterior-to-Interior Noise Reduction [dB]	Test Space Reverberation Time [T60, s]
	Array #1	Array #2		
6.3*	--	-1.90	23.1	--
8*	--	-1.60	22.2	--
10*	--	-0.75	20.7	--
12.5*	-0.35	0.50	18.9	--
16*	0.51	-1.63	23.7	--
20*	1.31	0.39	17.4	--
25*	0.12	1.53	9.4	--
31.5*	0.72	0.25	9.6	--
40*	0.30	0.02	12.1	0.80
50*	-0.21	0.45	20.4	0.47
63*	-0.40	0.54	19.9	0.55
80*	0.89	0.86	15.9	0.59
100*	-0.18	-0.13	21.7	0.50
125*	0.39	-0.94	18.0	0.43
160*	0.36	1.14	17.0	0.25
200	-1.15	-0.18	22.1	0.34
250	-0.34	-0.81	19.3	0.45
315	0.02	0.14	19.9	0.51
400	0.76	0.21	22.0	0.53
500	0.50	0.28	26.4	0.58
630	0.09	-0.10	34.1	0.58
800	-0.33	-0.71	33.2	0.58
1000	0.00	-0.89	36.0	0.60
1250	-0.57	-0.74	39.7	0.61
1600	-0.43	-0.46	40.6	0.61
2000	0.44	-0.05	42.0	0.56
2500	-0.84	-0.49	46.5	0.50
3150	-1.02	-0.53	50.0	0.49
4000	0.09	-1.01	55.3	0.50

Table II:

Coefficients of determination for the isolated, non-isolated, and combined chair groupings for twelve acoustic metrics computed using exterior measurements. All correlations are significant ($p < 0.001$).

Metric	R^2		
	Isolated	Non-isolated	Combined
<i>PL</i>	0.82	0.85	0.78
<i>ISBAP</i>	0.81	0.84	0.78
<i>ESEL</i>	0.83	0.83	0.78
<i>DSEL</i>	0.81	0.81	0.76
<i>ASEL</i>	0.77	0.78	0.73
<i>L_{ASmax}</i>	0.76	0.78	0.72
<i>BSEL</i>	0.77	0.77	0.72
<i>PNL</i>	0.73	0.76	0.70
<i>L_{AFmax}</i>	0.73	0.74	0.69
<i>L_{CFmax}</i>	0.59	0.60	0.56
<i>CSEL</i>	0.59	0.59	0.56
<i>L_{CSmax}</i>	0.59	0.59	0.55

Table III:

Coefficients of determination for several models of Mean Annoyance (MA). All descriptors are significant with $p < 0.0001$. Mean annoyance data from both chairs are used.

Model	Outcome	First Descriptor	Second Descriptor	R^2
1	MA	$Chair\ Type$	--	0.060
2	MA	$w_{k,peak}$	--	0.199
3	MA	PL	--	0.776
4	MA	PL	$Chair\ Type$	0.837
5	MA	PL	$w_{k,peak}$	0.865