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Evaluating signal-to-noise ratios, loudness, and related measures as indicators of airborne sound insulation

H. K. Park and J. S. Bradley^{a)}

National Research Council, Montreal Road, Ottawa K1A 0R6, Canada

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Subjective ratings of the audibility, annoyance, and loudness of music and speech sounds transmitted through 20 different simulated walls were used to identify better single number ratings of airborne sound insulation. The first part of this research considered standard measures such as the sound transmission class the weighted sound reduction index (R_w) and variations of these measures [H. K. Park and J. S. Bradley, *J. Acoust. Soc. Am.* **126**, 208-219 (2009)]. This paper considers a number of other measures including signal-to-noise ratios related to the intelligibility of speech and measures related to the loudness of sounds. An exploration of the importance of the included frequencies showed that the optimum ranges of included frequencies were different for speech and music sounds. Measures related to speech intelligibility were useful indicators of responses to speech sounds but were not as successful for music sounds. A-weighted level differences, signal-to-noise ratios and an A-weighted sound transmission loss measure were good predictors of responses when the included frequencies were optimized for each type of sound. The addition of new spectrum adaptation terms to R_w values were found to be the most practical approach for achieving more accurate predictions of subjective ratings of transmitted speech and music sounds. [DOI: 10.1121/1.3192347]

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I. INTRODUCTION

Airborne sound transmission between spaces is measured using standardized tests¹⁻³ and the results of these tests, when reduced to single number ratings,^{4,5} are intended to be indicative of the perceived disturbance caused by various types of transmitted sounds. A previous part of this research⁶ reviewed earlier evaluations of these measures and presented new results to evaluate their effectiveness as predictors of subjective ratings of the annoyance and loudness of transmitted speech and music sounds. Although the standard sound transmission class,⁴ (STC) and R_w (weighted sound reduction index⁵) ratings were not the best predictors of responses, some variations of them were found to be very successful. In particular, combinations of the R_w measure with new spectrum adaptation terms were found to be good predictors of annoyance and loudness ratings. However, for the most accurate results, different spectrum adaptation terms were needed for each type of sound (i.e., music or speech).

An earlier investigation evaluated speech intelligibility scores of transmitted speech sounds as ratings of the airborne sound insulation of walls.^{7,8} Measures intended to relate to speech intelligibility scores were found to be quite successful predictors of sound insulation, when rated in terms of the intelligibility of the transmitted speech. These measures included the articulation index (AI),⁹ the speech intelligibility index (SII),¹⁰ and the articulation class (AC),¹¹ as well as a

number of related quantities. Measures to indicate the speech privacy of enclosed meeting rooms¹² were also found to be good indicators of the intelligibility of transmitted speech sounds.

Values of the standard sound transmission measures (STC and R_w) are determined from comparisons of plots of measured sound transmission loss (TL) values versus frequency with standard rating contours. In the case of R_w , they may also include spectrum adaptation terms.⁵ However, most of the speech intelligibility rating measures are based on the basic concepts developed by French and Steinberg,¹³ which are incorporated in the AI and SII measures. These include frequency weighted arithmetic summations of the signal-to-noise ratios in decibels, a process that has produced successful indicators of speech intelligibility scores for speech in noise. This same concept is included in the uniformly weighted signal-to-noise ratio measure, SNR_{UNI32} , found to be a good indicator of both the audibility and intelligibility of speech transmitted through walls.¹²

The current paper extends the search for better single number ratings for accurately predicting annoyance, audibility, and loudness ratings of music and speech sounds transmitted through walls. The physical quantities considered were mostly based on existing measures of the intelligibility of speech or the loudness of sounds. Because of their known characteristics relative to intelligibility and loudness, they were expected to be at least reasonably good predictors of ratings of speech and music sounds transmitted through walls. It was hoped that the new analyses would reveal more about the important characteristics of better predictors of subjective ratings of transmitted speech and music sounds.

^{a)}Author to whom correspondence should be addressed. Electronic mail: john.bradley@nrc-cnrc.gc.ca

II. EXPERIMENTAL PROCEDURE

The experimental procedure used in this study was exactly the same as described in the first part of this paper⁴ and is mostly not repeated here. Subjects listened to speech and music sounds in combination with a constant level of noise representative of typical indoor ambient noise. The speech and music sounds were modified to represent transmission through walls with the TL characteristics of 20 different real walls having STC values evenly distributed from STC 34 to STC 58. Subjects heard the test sounds in a sound isolated acoustically dead room. Speech sounds were reproduced by loudspeakers 2 m in front of the listener and simulated ambient noise from a second set of loudspeakers located above the listener.

Subjects rated the annoyance of the sounds on a seven-point scale with labels from *Not at all annoying* to *Extremely annoying*. Similarly loudness ratings were obtained using a scale with labels from *Not at all loud* to *Extremely loud*. The loudness rating scale also included a possible 0 response, which could be selected to indicate that the sounds were inaudible.

Listeners heard three different Harvard sentences¹⁴ and three different music samples through each of the 20 simulated walls for a total of 60 sentences and 60 music samples. The order of the speech and music samples and of the walls was randomized so that subjects heard conditions in one of three different randomized orders. The effective source levels of the music and speech sounds were kept constant throughout the experiment, as was the level of the simulated ambient noise at the position of the listener. The speech and music sounds, heard by the listeners, only varied due to the different sound TL characteristics of the 20 walls. This made it possible to compare signal-to-noise type measures with measures of only the sound attenuation of transmission through the walls.

Results were analyzed by plotting the mean ratings of the 20 walls versus measures of the sound insulation of the walls. Boltzmann equations were fitted to these plots and the associated R^2 values were used as indicators of the goodness of fit. Since there were always 20 data points and the same format of regression equation, the significance is simply related to the R^2 value (i.e., the coefficient of determination). Any R^2 value ≥ 0.193 is statistically significant at $p < 0.05$ and an R^2 value ≥ 0.317 at $p < 0.01$. The Boltzmann equation describes a sigmoidal-shaped relationship and was used because it fits well the form of the responses, which approach asymptotically to the maximum and minimum values of the response scales. There were a number of highly significant results and the calculated R^2 values were used to rank order the better relationships to determine the best predictors of each rating. It was the goal of this work to identify those single number measures that best predict the responses to the transmitted speech and music sounds and to determine the important components of such measures.

FIG. 1. (Color online) Correlation coefficients versus frequency from correlations of mean annoyance and mean loudness ratings of music sounds with 1/3-octave band TL values. The standard deviations (STDev) of the wall TL values are also plotted for comparison and have values indicated by the right hand scale.

III. EFFECTS OF INCLUDED FREQUENCIES

A. More important frequencies for TL data

The first analyses looked at the basic question of the importance of the range of frequencies included in sound insulation measures. Correlations were performed between mean subjective ratings from the annoyance and loudness tests and TL values at each 1/3-octave band frequency for the 20 walls. Figure 1 shows the correlation coefficients for linear relationships between the loudness and annoyance ratings of music sounds and the TL values at each frequency. Similar correlation coefficients for the speech sounds are given in Fig. 2. Although the results for annoyance and loudness ratings are very similar in each graph, there are large differences between the two graphs. That is, the frequencies most important for responses to music sounds are quite different than those most important for speech sounds. The dash-dotted line with cross symbols indicates the standard deviations of the wall TL values, plotted in terms of the right hand axis scale so that they appear to be comparable in magnitude with the correlation coefficients in each graph.

FIG. 2. (Color online) Correlation coefficients versus frequency from correlations of mean annoyance and mean loudness ratings of speech sounds as well as mean speech intelligibility scores (Refs. 7 and 8) with 1/3-octave band TL values. The standard deviations (STDev) of the wall TL values are also plotted for comparison and have values indicated by the right hand scale.

For the responses to music sounds in Fig. 1, there is a strong similarity between the variations in the correlation coefficients and the variations in the standard deviations of TL values with frequency. Since the source music had high levels at all frequencies included in Fig. 1,¹⁵ the correlations are stronger at frequencies where there was more variation in the TL values and hence in the levels of transmitted music sounds. Thus, for music, the low and high frequency TL values best predict the annoyance and loudness ratings of the music sounds.

Figure 2 compares correlation coefficients versus frequency for mean annoyance and loudness ratings of transmitted speech sounds as well as those for speech intelligibility scores from the previous study.^{7,8} As in Fig. 1, the standard deviations of the TL values are also plotted to make possible further comparisons. Compared to Fig. 1, Fig. 2 shows stronger correlation coefficients at mid-frequencies for the annoyance and loudness ratings of speech sounds. The correlation coefficients for these ratings tend to be quite large in magnitude at frequencies from 125 Hz and higher, but with a dip in the values around 1000 Hz. For speech sounds, the more limited bandwidth of the source speech signals limited the range of frequencies at which strong correlations with TL values were obtained.

The correlations with the speech intelligibility scores,^{7,8} from the previous study, have a narrower range of maximum values, which extends from about 250 to 2000 Hz. These differences indicate that annoyance and loudness ratings of speech sounds are influenced by a wider range of frequencies than were speech intelligibility scores.

B. Included frequencies for arithmetic averages of TL values

In the previous study of speech intelligibility ratings of transmitted speech,^{7,8} arithmetic averages of TL values over various frequency ranges were found to be good correlates of speech intelligibility scores. Arithmetic average TL values, $AA(f_1-f_2)$, were calculated over frequency ranges from some lower frequency f_1 to an upper frequency f_2 . The lower frequency, f_1 , was varied from 63 to 2000 Hz and the upper frequency f_2 was varied from 200 to 6300 Hz. All of these arithmetic average TL values were correlated with annoyance ratings of speech and music sounds.

Strong correlations with annoyance ratings of music sounds only occurred when either low or high frequency TL

FIG. 3. (Color online) Mean annoyance ratings of speech and music sounds versus $AA(63-250)$ and best-fit Boltzmann regression lines (music: $R^2 = 0.959$, speech: $R^2 = 0.531$).

values were included and the strongest correlations occurred when only a limited range of lower frequency bands (63–250 Hz) were included.¹⁵ $AA(63-250)$ values were most strongly correlated with annoyance ratings of music sounds and annoyance ratings are plotted versus this measure in Fig. 3. Although annoyance ratings of music sounds were very strongly related to $AA(63-250)$ values ($R^2 = 0.959$), annoyance ratings of speech sounds were not so well related to this measure ($R^2 = 0.531$). (All regression coefficients from fits of Boltzmann equations are summarized in Table VII, for ratings of music sounds, and Table VIII, for ratings of speech sounds. All R^2 values are also included in the related figure titles.)

When the range of included frequencies was extended from 63 to 6300 Hz, $AA(63-6300)$ values were less well related to annoyance ratings of music sounds ($R^2 = 0.788$) but better related to speech sounds ($R^2 = 0.896$). The R^2 values associated with fitting Boltzmann equations to various arithmetic average TL values are compared on Table I.

Correlations of annoyance responses to speech sounds with arithmetic average TL values [$AA(f_1-f_2)$] for the same wide range of combinations of lower frequency, f_1 , and upper included frequency, f_2 , led to better correlations when a broad range of mid- and high frequency TL values was included. A number of combinations yielded quite strong correlation coefficients, but as illustrated in Fig. 4, simply

TABLE I. Summary of R^2 values from Boltzmann equation fits to mean annoyance and mean loudness ratings versus several arithmetic average TL measures [$AA(f_1-f_2)$], calculated over the frequency ranges from f_1 to f_2 . R^2 values equal to or greater than 0.95 are in bold font.

Measure	Annoyance speech	Annoyance music	Loudness speech	Loudness music	Speech intelligibility ^a
AA(100–5000)	0.952	0.625	0.944	0.593	0.751
AA(200–2500)	0.839	0.209	...	...	0.959
AA(200–3150)	0.892	0.290	0.832	0.258	0.948
AA(160–3150)	0.924	0.345	0.871	0.309	0.931
AA(63–250)	0.531	0.959	0.648	0.982	...
AA(63–6300)	0.896	0.788	0.919	0.745	...

^aReferences 7 and 8.

including all 1/3-octave bands from 100 to 5000 Hz [AA(100–5000)] was a successful combination and included all frequencies assessed in standard sound transmission tests. Although this measure predicted annoyance ratings of speech sounds very well, it was not as successful for predicting annoyance ratings of music sounds. The regression line for speech intelligibility scores from the previous study^{7,8} is also included in Fig. 4 for comparison with the annoyance ratings of the speech sounds. The two speech related regression lines have different slopes near their mid-points and speech intelligibility scores vary more rapidly with AA(100–5000) values than do the ratings of annoyance to speech sounds. As a result, there is still reported annoyance when the intelligibility scores are close to 0 because listeners can hear the speech sounds even when they are not intelligible.

Several other arithmetic average TL measures were considered to find a range of frequencies that worked well for ratings of both speech and music sounds. The resulting R^2 values are summarized in Table I. In the previous study,^{7,8} AA(200–2500) was best related to the speech intelligibility scores ($R^2=0.959$). When tested as a predictor of annoyance responses in the current work, this same measure was correlated reasonably well with annoyance to speech responses ($R^2=0.839$) but only weakly related to annoyance to music ratings ($R^2=0.209$). AA(200–3150) values were well related to annoyance to speech sounds ($R^2=0.892$) but were not well related to annoyance ratings of music sounds ($R^2=0.290$). Speech intelligibility scores (from Refs. 7 and 8) were predicted very well by this measure ($R^2=0.948$).

Another arithmetic average measure with a further modified frequency range, AA(160–3150), was found to be a little better compromise for both speech intelligibility scores and annoyance to speech sounds. When Boltzmann equations were fitted to plots of speech intelligibility scores versus AA(160–3150) values, the related R^2 was 0.931 and when annoyance ratings of speech sounds were considered, the associated R^2 was 0.924. However, again annoyance ratings of music sounds were not well related to this measure ($R^2=0.345$).

FIG. 4. (Color online) Mean annoyance ratings of speech and music sounds as well as mean speech intelligibility scores versus AA(100–5000) and best-fit Boltzmann regression lines (music: $R^2=0.625$, speech: $R^2=0.952$, speech intelligibility: $R^2=0.751$).

TABLE II. Summary of R^2 values from Boltzmann equation fits to mean annoyance and mean loudness ratings versus several energy average TL measures [EA(f_1 – f_2)], calculated over the frequency ranges from f_1 to f_2 . R^2 values equal to or greater than 0.95 are in bold font.

Measure	Annoyance speech	Annoyance music	Loudness speech	Loudness music
EA(100–5000)	0.376	0.915	0.587	0.970
EA(80–5000)	0.382	0.922	0.501	0.983
EA(500–5000)	0.931	0.417	0.879	0.365
EA(200–3150)	0.902	0.509	0.910	0.524
EA(500–3150)	0.896	0.343	0.836	0.294

Table I also includes the R^2 values that resulted from fitting Boltzmann equations to mean loudness ratings of speech and music sounds plotted versus arithmetic average TL values. As expected, arithmetic average TL values using frequency ranges that were successful for annoyance ratings were similarly successful for loudness ratings of the same type of sound.

The summary of these results in Table I shows that the optimum frequency range for speech intelligibility scores is different than that for annoyance ratings of speech sounds. However, none of the frequency ranges considered led to very accurate predictions of the ratings of both speech and music sounds.

C. Effects of included frequencies for energy average TL measures

Broadband TL values were also created by energy averaging the measured TL values over various frequency ranges rather than using arithmetic averages of the decibel values. Energy average TL measures, EA(f_1 – f_2), calculated from a lower frequency, f_1 (varied from 63 to 2000 Hz) to an upper frequency, f_2 (between 200 and 6300 Hz) were correlated with annoyance ratings of speech and music sounds. The pattern of higher correlation coefficients was different than those that resulted for arithmetic average TL values.¹⁵ Energy average TL values were strongly related to annoyance ratings of music sounds when a wide range of frequencies was included. An energy average over the frequencies from 80 to 5000 Hz, EA(80–5000), was one of the most successful measures for predicting annoyance and loudness ratings of music sounds (annoyance $R^2=0.922$, loudness $R^2=0.983$).

However, the 80–5000 Hz range was not optimum for predicting annoyance ratings of speech sounds. When energy average TL values were correlated with annoyance ratings of speech sounds, measures that included a broad range of mid- and high frequency TL values were more successful. The EA(500–5000) measure and the EA(200–3150) measure were both good predictors of ratings of speech sounds. However, these measures were not good predictors of ratings of music sounds. None of the energy average TL measures included in the results of Table II were good predictors of ratings of both speech and music sounds.

For both arithmetic average and energy average TL values, the optimum frequency ranges for speech and music sounds were different and more or less mutually exclusive. Whatever worked well for speech sounds was not successful

FIG. 5. (Color online) Mean annoyance ratings of speech and music sounds versus AI values and best-fit Boltzmann regression lines (music: $R^2=0.671$, speech: $R^2=0.843$).

for music sounds and vice versa. This makes it difficult to obtain a single measure that accurately predicts ratings of both types of sounds.

The optimum range of included frequencies for arithmetic average TL measures was more restricted than those for energy average TL values. For example, the AA(63–250) measure that best predicted annoyance ratings of annoyance to music sounds was based on the seven 1/3-octave bands from 63 to 250 Hz. In comparison the EA(80–5000) measure includes 19 1/3-octave bands to predict annoyance ratings of music sounds very accurately. It is probably better to base a successful sound insulation measure on a broader range of frequencies to more completely represent the TL characteristic of walls. Because of this, energy average TL values could be better predictors of ratings of music sounds than are the best arithmetic average values.

IV. EVALUATION OF SPEECH INTELLIGIBILITY AND LOUDNESS RELATED MEASURES

Various existing measures were evaluated as predictors of annoyance and loudness ratings of the transmitted sounds. These included measures that were developed as indicators of speech intelligibility or speech privacy. Others, considered in this section, are usually intended to rate the loudness of sounds.

A. Speech intelligibility related measures

Figure 5 plots mean annoyance ratings versus AI values.⁹ Although AI values are a signal-to-noise ratio measure, the source levels of the test sounds and the simulated ambient noises were held constant in these experiments and subjects heard only the changes that resulted from the varied transmission characteristics of the walls. Thus signal-to-noise ratio measures such as AI were evaluated to look for characteristics of better sound insulation measures. As might be expected, the R^2 values associated with the regression lines in Fig. 5 indicate that AI values were well correlated with annoyance ratings of speech sounds but were not so

TABLE III. Summary of R^2 values from Boltzmann equation fits to mean annoyance and mean loudness ratings versus speech intelligibility and loudness related measures. R^2 values equal to or greater than 0.95 are in bold font.

Measure	Annoyance speech	Annoyance music	Loudness speech	Loudness music
AI	0.843	0.671	0.808	0.618
SII	0.830	0.626	0.790	0.624
AC/10	0.911	0.469	0.857	0.416
SNR _{AI}	0.879	0.680	0.827	0.646
SNR _{SII22}	0.879	0.474	0.798	0.439
SNR _{UNI32}	0.898	0.425	0.913	0.456
SNR(A)	0.800	0.914	0.854	0.963
LR	0.693	0.908	0.793	0.962
LLD	0.690	0.905	0.749	0.947
STA	0.747	0.916	0.826	0.898

well related to ratings of music sounds. Similar R^2 values were obtained from plots of loudness ratings versus AI values and are included in Table III.

The SII is a revised version of the AI measure.¹⁰ Regression fits of loudness and annoyance ratings of speech and music sounds with SII values resulted in very similar R^2 values as were found for AI values and are included in Table III. The R^2 values show that SII values were well correlated with responses to speech sounds but not so well related to responses to music sounds.

The AC (Ref. 11) is a frequency-weighted average attenuation measure that uses the frequency weightings from the AI standard.⁹ Because AC values have the same frequency weightings as AI values, one would expect that the R^2 values associated with plots of annoyance and loudness ratings versus AC values would again show better relationships with responses to speech sounds than to those for music sounds, as shown in Table III.

Studies of ratings of the speech privacy of meeting rooms¹² found frequency-weighted arithmetic summations of signal-to-noise ratios (in decibels) to be good indicators of ratings of transmitted speech sounds. SNR_{UNI32} values were previously found to be a good indicator of both the intelligibility and audibility of transmitted speech sounds.¹² This is a uniformly weighted, arithmetic summation of signal-to-noise ratios over the 1/3-octave band frequencies from 160 to 5000 Hz. In calculating SNR_{UNI32} values, the signal-to-noise ratios in each band are clipped to never fall below –32 dB where they would have no effect on the audibility of the sounds. Annoyance and loudness ratings of speech sounds were strongly related to this measure (see Table III) and the results for annoyance ratings are shown in Fig. 6. Responses to music sounds were again only moderately well related to SNR_{UNI32} values as found for the other speech intelligibility related measures. This is most likely due to the lack of low frequency information in this measure.

Table III also includes R^2 values from plots of SNR_{AI} and SNR_{SII22} values versus annoyance and loudness ratings. SNR_{AI} values are a frequency-weighted arithmetic summation of signal-to-noise ratios over the same frequencies (i.e., 200–5000 Hz) and using the same frequency weightings as

FIG. 6. (Color online) Mean annoyance ratings of speech and music sounds versus SNR_{UNI32} values and best-fit Boltzmann regression lines, [Music: $R^2=0.425$, Speech: $R^2=0.898$].

the AI measure. SNR_{SII22} is a weighted arithmetic summation of signal-to-noise ratios over the 1/3-octave band frequencies from 160 to 5000 Hz using the frequency weightings from the SII measure. In calculating SNR_{SII22} values, the signal-to-noise ratios in each band are clipped to never fall below -22 dB, below which they would have no effect on intelligibility. SNR_{SII22} values were previously found to be a good indicator of the intelligibility of transmitted speech.¹² The results for both SNR_{AI} and SNR_{SII22} values in Table III indicate relatively strong relationships with annoyance and loudness ratings of speech sounds but less strong relationships with ratings of music sounds.

B. Loudness related measures

While there are complex measures for assessing the loudness of sounds, simple A-weighted sound levels are often used as an approximate indicator of the loudness of sounds. Similarly, the signal-to-noise ratios of the A-weighted speech and noise levels [i.e., the difference in the A-weighted levels of the transmitted speech or music and the ambient noise, $SNR(A)$] can be used to rate sound insulation. Previous studies have found $SNR(A)$ values to be a poor indicator of speech intelligibility.^{7,8} However, the results in

FIG. 7. (Color online) Mean annoyance ratings of speech and music sounds versus $SNR(A)$ values and best-fit Boltzmann regression lines (music: $R^2=0.914$, speech: $R^2=0.800$).

Fig. 7, indicate that $SNR(A)$ values are well related to annoyance ratings of speech sounds and even better related to annoyance ratings of music sounds. Plots of loudness ratings of speech and music sounds versus $SNR(A)$ values led to even higher R^2 values (speech: $R^2=0.854$, music: $R^2=0.963$). This suggests that A-weighted ratings may be quite successful indicators of the sound insulation provided against music sounds. This would be in agreement with much earlier results of Vian *et al.*¹⁶ They found A-weighted level differences, limited to the 1/3-octave band frequencies from 125 to 4000 Hz, to be good predictors of the annoyance ratings of transmitted music sounds.

If $SNR(A)$ values are considered to be an approximate measure of loudness, then true loudness measures would be expected to be successful predictors of the subjective ratings. Loudness ratios (LRs) were created from loudness values in sones¹⁷ for the transmitted speech (or music) and noise signals. The R^2 values from fitting Boltzmann regression equations to plots of annoyance and loudness ratings of speech and music sounds versus LR values are included in Table III. Like the $SNR(A)$ values, LR values were moderately good predictors of responses to speech sounds and were very good predictors of responses to music sounds. Although the LR values are less well related to speech sounds than to those of music sounds, they are better related to loudness ratings of the speech and music sounds than to annoyance ratings of these sounds.

As the R^2 values in Table III indicate, plots of annoyance and loudness ratings versus loudness level differences (LLDs) led to slightly lower R^2 values than those for LR values. However, the LLD values were again better predictors of responses to music sounds than those to speech sounds and predicted loudness ratings better than annoyance ratings for both speech and music sounds.

Because A-weighted signal-to-noise ratios were quite successful predictors of subjective ratings, it was of interest to test an A-weighted sound TL measure, STA, as a predictor of annoyance and loudness ratings of the transmitted sounds. STA was defined as follows:¹⁸

$$STA = -10 \log \left\{ \frac{1}{17} \sum_{b=100}^{4k} 10^{(-TL_b + Awt_b)/10} \right\} \text{ dB}, \quad (1)$$

where b is the centre frequency of each 1/3-octave band, TL_b is the sound TL in the 1/3-octave band with center frequency b , and Awt_b is the attenuation of the A-weighting curve at frequency b .

STA values were found to predict annoyance and loudness ratings of speech and music sounds quite well. Although the R^2 values are not quite as high as for some measures included in Table III, STA values are seen to be a relatively good predictor of all responses.

The results of the various regression analyses in this section are summarized in Table III. They generally show a consistent pattern of measures that are either better related to responses to speech sounds or to those for music sounds but are not equally well related to responses to both types of sounds. Measures intended to relate to the intelligibility of speech or other closely related measures (AI, SII, AC,

TABLE IV. Summary of R^2 values from Boltzmann regression equations fitted to plots of audibility ratings versus various sound insulation measures. R^2 values equal to or greater than 0.95 are in bold font. Results for STC, R_w , $R_w + C$, and $R_w + C_{tr(100-3150)}$ from Ref. 4.

Measure	Audibility speech	Audibility music
STC	0.968	0.452
R_w	0.971	0.526
$R_w + C$	0.903	0.757
$R_w + C_{tr}$	0.853	0.920
SNR_{SII22}	0.480	0.356
SNR_{UNI32}	0.650	0.242
$SNR(A)$	0.932	0.946
LR	0.269	0.770
LLD	0.895	0.911
STA	0.874	0.827

SNR_{AI} , SNR_{SII22} , and SNR_{UNI32}) were most strongly related to responses to speech sounds. Loudness related measures [LR values from loudness ratings in sones, and LLD values from loudness level ratings in phons, $SNR(A)$, and STA values] were most strongly related to responses to music sounds. Almost all of this latter group were a little better related to subjective ratings of loudness than to ratings of annoyance.

V. AUDIBILITY OF TRANSMITTED SOUNDS

During the loudness-rating test, subjects could give a score of zero to indicate they could not hear any music or speech sounds. The fraction of subjects scoring greater than 0 was used as a measure of the audibility of the sounds. The first part of this paper⁴ showed that both STC and R_w values were very good predictors of the audibility of speech sounds but were not as successful for the audibility of music sounds. When spectrum adaptation terms [C and $C_{tr(100-3150)}$] were added to R_w values,⁵ the measures became better predictors of the audibility of music sounds but less successful as predictors of the audibility of speech sounds. The R^2 values from the Boltzmann equation best-fit regression lines to plots of audibility ratings versus STC, R_w , $R_w + C$ and $R_w + C_{tr(100-3150)}$ values (from Ref. 4) are repeated in Table IV.

Previous speech privacy studies¹² found the SNR_{UNI32} measure to be successfully related to both audibility and intelligibility ratings of transmitted speech. In the new results, neither SNR_{UNI32} nor SNR_{SII22} values were very good predictors of audibility ratings. However, the R^2 values in Table IV show that SNR_{UNI32} values were better for predicting the audibility of speech sounds than the audibility of music sounds.

Although LLD values were good predictors of the audibility of both speech and music sounds, LR values were less successful (see R^2 summary in Table IV). Surprisingly $SNR(A)$ values were very good predictors of the audibility of both speech and music sounds, as shown in Fig. 8. Because $SNR(A)$ values were found to be very good predictors of audibility ratings, the A-weighted TL measure, STA, was also tested as a predictor of audibility ratings. The R^2 values

FIG. 8. (Color online) Fraction of subjects finding sounds just audible versus $SNR(A)$ values and best-fit Boltzmann regression lines (music: $R^2 = 0.946$, speech: $R^2 = 0.932$).

in Table IV show that STA values predicted the audibility of speech and music sounds a little less well than did the $SNR(A)$ values.

The pattern of relationships between the fraction of subjects finding sounds audible and the various sound insulation ratings summarized in Table IV was different than for the relationships for annoyance and loudness ratings. Because of these differences, the importance of the included frequencies in sound insulation measures for predicting the audibility of sounds was also investigated. As before this was done by calculating arithmetic average TL values, $AA(f_1-f_2)$, and energy average TL values, $EA(f_1-f_2)$, for a range of combinations of lower, f_1 , and upper, f_2 , included frequencies.

The correlations with arithmetic average TL values only showed higher magnitude correlation coefficients for quite limited frequency ranges and were still quite modest in value. For correlations with ratings of the audibility of music sounds, the strongest correlations resulted when only a limited range of low frequency 1/3-octave bands (63–200 Hz) were included and the highest magnitude correlation coefficient was only -0.87 with the $AA(63-200)$ values. For correlations with the audibility ratings of speech sounds, the highest magnitude correlation coefficients occurred when only the highest frequency 1/3-octave bands were included. For the audibility of speech sounds, the highest magnitude correlation coefficient was found for the $AA(1000-6300)$ measure with a value of -0.75 .

When energy average TL values were considered, correlation coefficients with slightly higher magnitude values were obtained. For ratings of the audibility of music sounds, correlations with the $EA(63-6300)$ measure led to a correlation coefficient of -0.89 . For correlations with audibility ratings of speech sounds the $EA(1000-6300)$ measure led to a correlation coefficient of -0.77 .

The correlation coefficients with both types of frequency averaged TL values were disappointing and suggested that these average TL values are not as successful as other approaches considered for predicting the audibility ratings of sounds.

Table IV summarizes the results of the regression analyses of audibility ratings versus sound insulation measures.

TABLE V. Description of the A-weighted level difference measures calculated.

Name	Source spectrum	Included frequencies
$LDA_p(63-6300)$	Pink	63–6300 Hz
$LDA_p(200-6300)$	Pink	200–6300 Hz
$LDA_p(100-4000)$	Pink	100–4000 Hz
$LDA_E(63-6300)$	E597	63–6300 Hz
$LDA_E(200-6300)$	E597	200–6300 Hz
$LDA_E(100-4000)$	E597	100–4000 Hz

While some measures were better predictors of the audibility of speech sounds (STC, R_w , $R_w + C$, and STA), others were better predictors of the audibility of music sounds [$R_w + C_{tr(100-3150)}$, LLD, and SNR(A)]. Only $R_w + C_{tr(100-3150)}$, LLD, and SNR(A) values were reasonably good predictors of the audibility of both speech and music sounds and SNR(A) values best predicted the audibility of both types of sounds.

VI. A-WEIGHTED LEVEL DIFFERENCES FOR RATING SOUND INSULATION

Earlier research by Vian *et al.*,¹⁶ found that annoyance ratings of transmitted music sounds were significantly related to the A-weighted levels of the sounds transmitted through simulated walls if the included frequencies were limited to the range from 125 to 4000 Hz. If a wider frequency range of transmitted sounds from 40 to 10 000 Hz was included, the A-weighted levels were not significantly related to annoyance responses.

For a number of years ASTM had a standard measurement procedure [ASTM E597 (Ref. 19)] for rating the A-weighted level reductions between two spaces. The standard (now withdrawn) was intended to be a simple method for obtaining approximate STC values by measuring A-weighted level differences between room-average levels in adjacent rooms.

Previous analyses in this paper have indicated that some A-weighted ratings can be successful indicators of the annoyance, loudness and audibility of transmitted speech and music sounds. The use of the C-type spectrum adaptation term with R_w values is equivalent to measuring an A-weighted level difference with a pink source spectrum over the frequencies from 100 to 3150 Hz. A-weighted signal-to-noise

ratios, SNR(A), were found to be best related to ratings of the loudness and audibility of transmitted speech and music sounds. An A-weighted sound TL measure, STA, was also reasonably well related to annoyance and loudness ratings of transmitted speech and music sounds. However, our previous studies of the intelligibility of transmitted speech^{7,8,12} showed the STA and SNR(A) measures were not very successful as indicators of the intelligibility of transmitted speech sounds.

Because of the previous interest in A-weighted sound insulation ratings, and because of the success of some A-weighted measures reported earlier in this paper, further considerations of this type of measure are included in this section. The new measures consisted of A-weighted level differences between the A-weighted source and transmitted levels for the simulated walls. These were calculated for two source spectra: (a) an ideal flat pink spectrum and (b) the mean of the range of spectra acceptable in the previous ASTM E597 standard. The ASTM E597 spectrum peaked at 500 Hz and dropped off gradually either side of this band with a more rapid decrease below 125 Hz. For each source spectrum, A-weighted transmitted levels were calculated for three different ranges of included frequencies. The ranges of included frequencies were established from initial tests to determine the most appropriate ranges for responses: (a) to speech sounds (200–6300 Hz), (b) to music sounds (63–6300 Hz), and (c) a range similar to existing standards (100–4000 Hz). Table V lists the symbols used to indicate each of these A-weighted level differences along with the source spectrum and included frequency range used.

The mean values of all available responses were plotted versus each of these measures including annoyance, loudness, and audibility ratings for both speech and music sounds as well as the speech intelligibility scores from the previous study.^{7,8} As in previous analyses, Boltzmann equations were fitted to the data and the associated R^2 values determined. These are included in Table VI along with results for STA and SNR(A) values, which are repeated from earlier sections of this paper to facilitate comparisons.

The results in Table VI show that annoyance and loudness ratings of music sounds were most strongly related to A-weighted noise level differences using a pink noise source with included frequencies from 63 to 6300 Hz. However, for loudness ratings of music sounds, the R^2 value for the rela-

TABLE VI. Summary of R^2 values for Boltzmann regression equations fitted to plots of mean responses versus various A-weighted level differences. R^2 values equal to or greater than 0.95 are in bold font. As described in previous sections, the STA and SNR(A) measures include frequencies from 63–6300 Hz.

Source spectrum	Pink	Pink	Pink	E597	E597	E597	Speech /music	Speech /music
Included frequencies	63–6300	200–6300	100–4000	63–6300	200–6300	100–4000	STA	SNR(A)
Annoyance music	0.978	0.530	0.916	0.801	0.408	0.777	0.915	0.911
Loudness music	0.966	0.511	0.898	0.792	0.398	0.773	0.897	0.968
Audibility music	0.823	0.244	0.753	0.539	0.149	0.507	0.827	0.946
Annoyance speech	0.668	0.977	0.865	0.862	0.954	0.868	0.746	0.756
Loudness speech	0.763	0.960	0.826	0.913	0.930	0.917	0.825	0.859
Audibility speech	0.891	0.753	0.912	0.978	0.669	0.978	0.874	0.932
Intelligibility speech ^a	0.246	0.778	0.294	0.527	0.819	0.515	0.361	0.259

^aSpeech intelligibility results from previous study (Refs. 7 and 8).

FIG. 9. (Color online) Mean annoyance ratings of speech and music sounds versus A -weighted level differences [$LDA_p(63-6300)$] using a pink source spectrum and best-fit Boltzmann regression lines (music: $R^2=0.978$, speech $R^2=0.668$).

tionship with $SNR(A)$ values was slightly higher. $SNR(A)$ values were also very strongly related to ratings of the audibility of music sounds.

For annoyance and loudness ratings of speech sounds, R^2 values were highest for A -weighted level differences over the 200–6300 Hz range with a pink source spectrum. The audibility of speech was better related to A -weighted level differences using an E597 source spectrum for either the 63–6300 Hz range or the 100–4000 Hz range. This may imply that some lower frequency sound helps to make faint speech sounds more audible, even though the low frequency sound does not significantly improve the intelligibility of the speech. The 200–6300 Hz range, which most limited low frequency content, was most helpful for predicting speech intelligibility scores when the E597 source spectrum was used.

Figure 9 plots the relationship between annoyance ratings of speech and music sounds and $LDA_p(63-6300)$ values. As indicated in the title of Fig. 9 and Table VI (which gives a summary of the R^2 values), annoyance to music responses were very well related to $LDA_p(63-6300)$ values. However, annoyance ratings of speech sounds were less well related to this measure.

A plot of annoyance to speech and music sounds versus $LDA_p(200-6300)$ values showed a very good fit for annoyance ratings of speech sounds. However, annoyance ratings of music sounds were less well related to this measure.

The audibility scores for speech sounds were best related to $LDA_E(100-4000)$ and $LDA_E(63-6300)$ values. The latter relationship is shown in Fig. 10. These two relationships had the same R^2 value, which was the highest of any included in Table VI. However, these two measures predicted the audibility of music sounds less well. The audibility of music sounds is best predicted from $SNR(A)$ values as shown previously in Fig. 8 and included in the Table VI summary.

The results in Table VI show that level difference measures that used a pink source spectrum more frequently lead

FIG. 10. (Color online) Fraction of subjects finding sounds just audible versus A -weighted level differences, $LDA_E(63 \text{ to } 6300 \text{ Hz})$, using an E597 source spectrum and best-fit Boltzmann regression lines (music: $R^2=0.539$, speech: $R^2=0.978$).

to the highest R^2 values than did those using the E597 spectrum. As will be seen in Sec. VII of this paper, some of the R^2 values in Table VI are among the highest found in this study.

VII. SUMMARY AND DISCUSSION

In this paper, subjective ratings of the audibility, annoyance, and loudness of speech and music sounds transmitted through 20 different walls were related to a number of potentially useful single number measures of the sound transmission characteristics of the walls. For responses to music sounds, Table VII summarizes the most important regression results including R^2 values and the regression coefficients for the Boltzmann equations⁴ fitted to each sound insulation measure. Table VIII provides a similar summary for relationships with responses to speech sounds. These tables also include the key results of the first part of this research⁴ to facilitate comparisons of the effectiveness of the various measures.

Although a large number of apparently different measures were considered, they can be grouped into a small number of categories according to how they were calculated in this study. This is done in Table IX which shows that there are two main categories of measures: (1) those which were derived only from the 1/3-octave band TL values and (2) those that were derived from the TL values and were also influenced by the source spectrum. Of these two main categories there are five sub-categories describing the calculation method. For measures derived from only TL values, some were obtained using rating contours, some from arithmetic summations of TL values, and others from energy summations of TL values. For the measures including the effect of both TL values and a source spectrum, calculations were either in the form of a signal-to-noise ratio at the receiving point or a level difference between incident and transmitted sounds. Finally, all of the measures were

TABLE VII. Summary of R^2 values and Boltzmann equation regression coefficients (Ref. 6) of the main cases for music sounds in this study. R^2 values equal to or greater than 0.95 are in bold font. An R^2 value ≥ 0.193 is statistically significant at $p < 0.05$ and R^2 values ≥ 0.317 at $p < 0.01$.

Symbol	f_1	f_2	Annoyance			Loudness			Audibility		
			R^2	X_0	dx	R^2	X_0	dx	R^2	X_0	dx
STC	125	4000	0.728	47.916	5.667	0.734	43.417	5.275	0.452	54.742	5.593
R_w	100	3150	0.798	47.507	4.602	0.779	43.744	4.527	0.526	52.979	4.331
STC _{no8}	125	4000	0.670	48.884	5.334	0.654	44.839	5.074	0.378	55.820	5.761
$R_w + C$	100	3150	0.918	44.624	4.371	0.900	40.591	4.638	0.757	48.789	2.910
$R_w + C_{\text{mod}}$	50	5000	0.580	37.605	5.313	0.556	33.735	5.106	0.297	44.594	5.949
$R_w + C_{200-3150}$	200	3150	0.508	33.101	6.110	0.521	28.800	5.378	0.228	41.378	7.177
$R_w + C_{100-3150}$	100	3150	0.950	39.140	5.035	0.960	34.528	5.074	0.920	43.946	2.369
$R_w + C_{150-5000}$	50	5000	0.943	36.812	5.753	0.980	31.574	4.543	0.948	43.143	1.878
$R_w + C_{\text{tr_mod}}$	50	5000	0.983	34.966	4.683	0.991	30.778	4.099	0.889	39.989	2.944
$R_w(63-5000)$	63	5000	0.940	46.060	3.864	0.907	42.633	3.863	0.750	50.226	2.979
$R_w(160-5000)$	160	5000	0.562	49.977	5.808	...	...	...	...	...	...
AA(100-5000)	100	5000	0.625	48.522	4.974	0.593	44.769	5.149	0.330	55.063	5.591
AA(200-3150)	200	3150	0.290	53.277	8.507	0.258	47.710	8.790	...	...	...
AA(63-250)	63	250	0.959	29.904	5.182	0.982	25.284	4.937	0.926	35.121	2.062
AA(63-6300)	63	6300	0.788	46.733	4.157	0.745	43.363	4.298	0.508	51.844	4.159
EA(100-5000)	100	5000	0.915	33.424	5.885	0.970	28.051	5.649	0.866	-38.239	1.714
EA(80-5000)	80	5000	0.922	31.551	6.218	0.983	26.084	5.165	0.933	-39.514	1.636
EA(500-5000)	500	5000	0.417	53.806	6.666	0.365	49.220	6.845	0.174 _{ns}	-63.048	8.134
AI	200	5000	0.671	0.056	0.050	0.618	0.040	0.039	...	...	...
SII	160	8000	0.626	0.081	0.076	0.624	0.057	0.052	...	...	...
AC/10	200	5000	0.469	56.039	6.360	0.416	51.542	6.686	...	...	...
SNR _{AI}	200	5000	0.680	-25.501	4.722	0.646	-27.910	4.711	...	...	...
SNR _{SII22}	160	5000	0.474	-15.474	5.436	0.439	-16.254	4.039	0.356	-21.725	2.511
SNR _{UNB32}	160	5000	0.425	-14.144	5.154	0.456	-15.792	1.636	0.242	-27.335	6.425
SNR(A)	63	6300	0.914	1.323	5.814	0.963	0.416	4.613	0.946	-12.192	1.312
LR	25	12500	0.908	1.190	0.464	0.962	1.027	0.317	0.770	0.2737	0.0521
LLD	25	12500	0.905	-0.4395	7.065	0.947	-1.432	6.062	0.911	-18.843	2.689
STA	100	4000	0.916	46.905	4.355	0.898	42.889	4.622	0.755	51.115	2.935
LDA _p (63-6300)	63	6300	0.978	56.538	4.261	0.966	60.400	4.174	0.823	51.319	2.683
LDA _p (200-6300)	63	6300	0.530	50.642	5.667	0.511	54.668	5.426	0.244	42.573	6.924
LDA _p (100-4000)	63	6300	0.916	55.403	4.359	0.898	59.417	4.623	0.753	51.222	2.942
LDA _E (63-6300)	63	6300	0.801	69.442	4.618	0.792	73.277	4.584	0.539	64.690	4.261
LDA _E (200-6300)	63	6300	0.408	65.035	6.899	0.398	69.701	6.575	0.149 _{ns}	54.287	9.273
LDA _E (100-4000)	63	6300	0.777	69.244	4.808	0.733	73.182	4.730	0.507	63.681	4.476

influenced by the range of 1/3-octave band frequencies included in their calculation.

Some measures that might appear to be quite different actually are very similar. For example, the $R_w + C$ measure can be exactly equivalent to an A-weighted level difference with a pink source spectrum, $\text{LDA}_p(f_1 - f_2)$, if the range of included frequencies, $f_1 - f_2$, is exactly the same. An example of this is seen in the results in Table VII, where the R^2 for the fit of annoyance ratings of speech versus $R_w + C$ values is 0.918 (100–3150 Hz) and for $\text{LDA}_p(100-4000)$ is 0.916. The slightly different range of included frequencies leads to only a very small difference in R^2 values.

From examining the results in Tables VII and VIII, it was not possible to detect a consistent trend for better results to be obtained for one of the two main categories of sound insulation measures. There are some very high R^2 values for each major type of measure as well as for most sub-categories of measures. Other differences such as the range of included frequencies and the combination of the range of included frequencies with the type of calculation seem to

determine which measure is a better predictor of particular responses.

VIII. CONCLUSIONS

In general, loudness and annoyance responses yielded similar information. Although there was a small trend for loudness ratings of music sounds to be more accurately predicted than annoyance ratings, usually little was gained by asking subjects to rate sounds in terms of both concepts. However, audibility ratings usually led to a different pattern of results than those for the annoyance and loudness ratings.

The various measures are strongly influenced by the range of included frequencies and the optimum range of included frequencies is different for predicting ratings of music sounds than for ratings of speech sounds. Because of this some measures are strongly related to ratings of speech sounds and others to ratings of music sounds, but none were highly successful for both types of sounds.

TABLE VIII. Summary of R^2 values and Boltzmann equation regression coefficients (Ref. 6) of the main cases for speech sounds in this study. R^2 values equal to or greater than 0.95 are in bold font. An R^2 value ≥ 0.193 is statistically significant at $p < 0.05$ and R^2 values ≥ 0.317 at $p < 0.01$.

Symbol	f_1	f_2	Annoyance			Loudness			Audibility		
			R^2	X_0	dx	R^2	X_0	Dx	R^2	X_0	dx
STC	125	4000	0.856	43.955	7.018	0.886	39.322	6.906	0.968	54.106	1.731
R_w	100	3150	0.890	43.946	6.176	0.933	39.891	6.013	0.971	53.045	1.551
STC _{no8}	125	4000	0.950	45.271	5.804	0.970	41.299	5.842	0.919	54.915	1.830
$R_w + C$	100	3150	0.741	40.552	7.459	0.821	36.050	6.818	0.903	50.763	1.777
$R_w + C_{\text{mod}}$	50	5000	0.975	34.198	4.994	0.973	30.716	5.142	0.863	42.877	1.720
$R_w + C_{200-3150}$	200	3150	0.901	29.393	5.551	0.912	25.719	5.557	0.701	38.349	2.211
$R_w + C_{\text{tr}100-3150}$	100	3150	0.566	34.370	9.529	0.676	29.197	8.063	0.853	46.252	0.465
$R_w + C_{\text{tr}50-5000}$	50	5000	0.388	32.276	11.912	0.482	26.447	9.560	0.856	44.888	0.090
$R_w + C_{\text{tr_mod}}$	50	5000	0.541	31.084	8.840	0.634	26.422	7.167	0.866	42.593	0.945
$R_w(63-5000)$	63	5000	0.769	42.623	6.361	0.848	38.816	5.701	0.871	52.352	1.493
$R_w(160-5000)$	160	5000	0.972	46.301	5.359	...	...	...	...	...	...
AA(100-5000)	100	5000	0.952	45.154	5.310	0.944	41.358	5.602	0.831	53.764	2.062
AA(200-3150)	200	3150	0.892	48.380	5.471	0.832	44.555	5.793	...	...	...
AA(63-250)	63	250	0.531	25.161	9.811	0.648	19.993	8.016	0.852	36.969	0.180
AA(63-6300)	63	6300	0.896	43.468	4.157	0.919	39.744	5.520	0.937	52.075	1.327
EA(100-5000)	100	5000	0.376	28.085	12.311	0.587	21.976	9.433	0.236	-46.473	8.754
EA(80-5000)	80	5000	0.382	26.489	12.754	0.501	20.393	9.809	0.375	41.223	1.440
EA(500-5000)	500	5000	0.931	49.660	5.008	0.879	46.198	5.156	0.676	-58.787	2.804
AI	200	5000	0.843	0.113	0.085	0.808	0.074	0.049	...	...	...
SII	160	8000	0.830	0.147	0.102	0.790	0.106	0.064	...	...	...
AC/10	200	5000	0.911	52.047	5.469	0.857	48.171	5.832	...	...	...
SNR _{AI}	200	5000	0.879	-21.300	5.731	0.827	-23.309	6.126	...	...	...
SNR _{SII22}	160	5000	0.879	-11.809	4.716	0.798	-13.658	4.046	0.480	-20.994	1.111
SNR _{UNI32}	160	5000	0.898	-10.149	5.154	0.913	-12.307	5.350	0.650	-23.804	2.336
SNR(A)	63	6300	0.800	1.814	6.056	0.854	-0.413	6.079	0.932	-13.538	1.788
LR	25	12500	0.693	0.9739	0.474	0.796	0.770	0.2923	0.269	0.214	0.0153
LLD	25	12500	0.690	-1.784	7.805	0.749	-4.308	8.043	0.895	-22.359	-1.045
STA	100	4000	0.747	42.863	7.400	0.826	38.384	6.769	0.912	52.985	1.757
LDA _p (63-6300)	63	6300	0.668	64.407	7.669	0.763	64.747	6.536	0.891	49.481	1.277
LDA _p (200-6300)	63	6300	0.977	54.139	4.980	0.960	57.674	5.257	0.753	45.355	2.578
LDA _p (100-4000)	63	6300	0.865	59.447	7.393	0.826	63.922	6.770	0.912	49.341	1.792
LDA _E (63-6300)	63	6300	0.862	73.058	6.423	0.913	77.243	6.231	0.978	64.112	1.654
LDA _E (200-6300)	63	6300	0.954	69.058	5.074	0.930	72.616	5.351	0.669	64.112	1.654
LDA _E (100-4000)	63	6300	0.868	72.910	6.467	0.917	77.150	6.306	0.978	63.819	1.621

A compromise approach for achieving better predictions of both speech and music sounds would be to use a measure that is reasonably well related to responses to both speech and music sounds such as $R_w(63-5000)$, AA(63-6300) or

SNR(A) values. However, these compromise approaches would lead to less accurate predictions of some responses with lower R^2 values than the best possible relationships that had R^2 values of 0.97 and higher.

TABLE IX. Lists of sound insulation measures arranged by category and sub-category.

Categories	Depend only on wall TL			Depend on source spectrum and wall TL	
	Rating contour	Arithmetic summation	Energy summation	Signal-to-noise ratios	Level differences
Measures	STC STC _{no8} $R_w(f_1-f_2)$	AA(f_1-f_2) AC	EA(f_1-f_2) STA	SNR _{AI} SNR _{SII22} SNR _{UNI32} AI SII LR LLD SNR(A)	LDA _p (f_1-f_2) LDA _E (f_1-f_2) $R_w + C$ $R_w + C_{\text{tr}}$

More accurate predictions can be obtained, in a manner that is practical to implement, by using R_w with different spectrum adaptation terms for each type of sound. For example, one could use the C_{mod} spectrum adaptation term for speech sounds and the $C_{\text{tr,mod}}$ spectrum adaptation term⁶ for music sounds. This led to very high R^2 values (>0.97) for annoyance and loudness ratings of both speech and music sounds and could be achieved by adding new spectrum weighting terms to the existing ISO procedure.

Various A-weighted measures can provide reasonably accurate predictions of some responses using an easy to implement measure. Choosing an A-weighted level difference measure summed over the frequency range best suited to each type of sound [i.e., $\text{LDA}_p(63\text{--}6300)$ for music sounds and $\text{LDA}_p(200\text{--}6300)$ for speech sounds] would lead to predictions essentially as accurate as the best of the other options. Of course, this would not have the convenience of building on an existing standard procedure. Alternatively, measures such as $\text{LDA}_p(100\text{--}4000)$ and $\text{SNR}(A)$ would be simple but accurate compromise measures for both speech and music sounds.

These results may be limited by the characteristics of the 20 walls that were simulated. They were chosen to include a wide range of construction types and included a wide range of overall sound insulation values. There may be other constructions that might not fit the same pattern of results. In particular, the simulated TL characteristics were based on the results of standard laboratory tests of walls. It is now well established that sound TL in real buildings is typically limited by various flanking paths.^{20,21} These flanking paths often significantly reduce the actual sound TL in a manner that would vary with frequency. Carrying out a similar study based on field measurements of the apparent sound TL characteristics of a wide range of walls might lead to some differences.

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