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Erica Eileen Bowden
University of Nebraska - Lincoln

Lily M. Wang
University of Nebraska - Lincoln, lwang4@unl.edu

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Relating Human Productivity and Annoyance to Indoor Noise Criteria Systems: A Low Frequency Analysis

E.E. Bowden

L.M. Wang, PhD
Member ASHRAE

ABSTRACT

A number of indoor noise criteria systems are used to quantify the background noise in a built environment, including Noise Criteria (NC), Balanced Noise Criteria (NCB), Room Criteria (RC), Room Criteria Mark II (RC Mark II), A-weighted Equivalent Sound Pressure Level (L_{Aeq}), and others. An ongoing debate exists in the acoustical community over which criterion is the most appropriate to use in the variety of ambient noise situations encountered. In an effort to quantitatively support the use of an individual criterion, this project subjectively correlates these various criteria with human task performance and perception. Eleven subjects participated in a pilot study by completing typing and proofreading tasks, as well as subjective ratings of loudness, annoyance, and spectral quality. Results show that there were no significant differences in productivity scores among the 12 noise exposures tested; however, significant relationships were found between indoor noise criteria predictions of level and subjective perception of loudness and annoyance. In this study, RC and RC-Mark II were found to be the most correlated with level perception, although NC, NCB, and L_{Aeq} were also strongly correlated. Additionally, interesting relationships were found between subjective perceptions of rumble or roar and criteria predictions of such. The authors are in the process of extending the pilot study to more subjects, as well as examining the effects of tonal and fluctuating background noise spectra on criteria predictions.

INTRODUCTION

Indoor background noise can dramatically impact occupants by causing annoyance, affecting productivity, hindering speech communication, impacting sleep, and degrading overall occupant comfort and satisfaction. In extreme cases, excessive background noise can even result in hearing damage. Noise is a complex entity, and the effect on occupants can vary depending on factors such as level or loudness, how the sound varies across frequency, and even how it varies across time.

Acoustic specialists have used various criteria over the decades to quantify human perception of the background noise in a room. Most of the descriptors consist of single-number ratings that summarize the background noise level over a range of frequencies. Some provide additional descriptors of quality that evaluate the spectral characteristics of the background noise. Noise Criteria (NC), Balanced Noise Criteria (NCB), Room Criteria (RC), Room Criteria Mark II (RC Mark II), and A-weighted Equivalent Sound Pressure Level (L_{Aeq}) are five criteria systems commonly used by mechanical engineers, architects, and acousticians in the United States. The criteria systems are popular tools in setting appropriate background noise levels in built spaces based on type of occupancy. However, an ongoing debate exists in the acoustical community over which criterion is the most appropriate to use in the variety of background noise situations encountered.

The pool of data linking the use of these various criteria to actual human reaction continues to grow. This study seeks to add to this database by examining the correlations between indoor noise criteria systems and human productivity, loudness, annoyance, and spectral quality.

Previous Research

Many previous studies have sought to evaluate the effects of background noise on humans. Beranek (1956), Keighley (1966, 1970), Hay and Kemp (1972a, 1972b), and Blazier (1981) are among those who have developed criteria systems

Erica E. Bowden is a doctoral student and **Lily M. Wang** is an assistant professor in the Architectural Engineering Program, University of Nebraska, Lincoln.

reflecting occupant response to office noise. Recent years have seen a resurgence of researchers linking subjective perception of ambient noise with measured sound spectra (Tang et al. 1996; Tang 1997; Tang and Wong 1998, 2003; Ayr et al. 2001, 2003). Subjects of these studies were asked to rate their general perception of the background noise with regard to several factors including annoyance, loudness, and satisfaction. Their responses were then related to background noise measurements and criteria systems. Tang and Ayr consistently found L_{Aeq} to be highly correlated with subjective auditory sensation in office surveys. Persson Waye and Rylander (2001), on the other hand, found that L_{Aeq} was not a good predictor of annoyance to long-term noise exposure in residences. This discrepancy indicates that the types of spaces analyzed and the measurement method can affect the performance of criteria predictions.

The effect of low frequency noise in particular has been the focus of much research. In addition to subjective reaction to background noise, productivity was also evaluated in several studies. Kyriakides and Leventhall (1977) investigated performance on central and peripheral vision tasks under three acoustic conditions: audio frequency noise at 70 dBA, an infrasound noise band from 2 Hz to 15 Hz at 115 dBA, and an audio frequency noise band from 40 Hz to 16 kHz at 90 dBA. They found that the peripheral vision task was affected by noise, and the effect of infrasound increased over the 36 minutes spent on the task.

Landström et al. (1991) examined the effects of three different ventilation noise signals on occupant performance, wakefulness, and annoyance. The signals were broadband (40 dBA), 100 Hz tonal broadband (40 dBA), and the same tonal noise masked by means of low frequency pink noise (41 dBA). Length of exposure to each noise signal was 50 minutes, during which subjects performed tasks for the first 40 minutes and rested for the final 10 minutes. Performance on figure identification tasks was found to be lower during the 100 Hz tonal signal than the masked tonal signal.

Holmberg et al. (1993) used five different ventilation noise exposures: gradually falling frequency/level spectral character (35 dBA and 40 dBA), 43 Hz raised filtered broadband noise (40 dBA), 43 Hz tonal broadband noise (40 dBA), and naturally occurring background noise (20 dBA). Subjects were exposed to each noise for 60 minutes, during which time they completed proofreading tasks. Although no significant differences between exposures were obtained on performance tests, the results did indicate that the frequency character should be considered when evaluating the effects of ventilation noise on annoyance sensation and productivity.

In 1997, Persson Waye et al. evaluated the effect on performance and work quality of two ventilation spectra, one of predominately mid-frequency character (NC 35) and the other of predominantly low frequency character (NC 35). Total time spent under each exposure was 60 minutes. The study concluded that the low frequency noise interfered more strongly with performance on three cognitive tasks than the mid-frequency noise. The difference between productivity scores in this study indicates that NC curves do not fully assess the negative impact of low frequency noise on task performance. Furthermore, as in the Leventhall study, there was an indication that the effects of noise developed over time. Persson Waye et al. (2001) extended the study and found that low frequency noise negatively impacts demanding verbal tasks, while the effects on more routine tasks were less clear. Additionally, results indicated that low frequency noise may be more difficult to adapt to.

This study aims to further the research on background noise and work performance with 12 new background noise exposures, all of differing loudness and spectral content. The ability of indoor noise criteria systems to relate to productivity scores, as well as auditory perception of noise, is examined in detail.

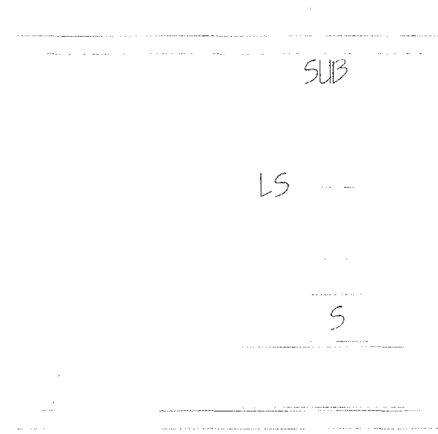

Figure 1 *View of the test chamber, with subject (S), i-ceiling speaker (LS), and subwoofer (SUB) locations.*

METHODOLOGY

Subjects

Eleven subjects (five male and six female) participated in the pilot study. Subjects ranged in age from 19 to 29 with a mean age of 24. All subjects were prescreened for typing ability, auditory ability, and visual function. The subjects were all found to have a minimum typing ability of 20 words per minute using SkillCheck typing test software. Adequate visual function was verified with the Keystone Ophthalmic Telebinocular, which provides a quick measure of phorias, fusion readiness, binocular visual efficiency at far and near, stereopsis, visual acuity, and color vision. Finally, a GSI 17 audiometer was used to verify that all subjects had hearing thresholds below 25 dB hearing level (HL) from 125 Hz to 8 kHz.

Test Chamber

The experiment was performed in a 906 ft^3 (25.7 m^3) test chamber. A view of the floor plan is shown in Figure 1, with test subject and loudspeaker locations noted. The room is

Table 1. Noise Exposure Design Matrix

LEVEL	SPECTRAL QUALITY: Neutral	Rumble	Roar	Hiss
Low	30 dB at 1000 Hz	+5 to 10 dB in 31.5 and 63 Hz octave bands	+10 dB in 125, 250, and 500 Hz octave bands	+10 dB in 2000, 4000, and 8000 Hz octave bands
Mid	40 dB at 1000 Hz			
High	50 dB at 1000 Hz			

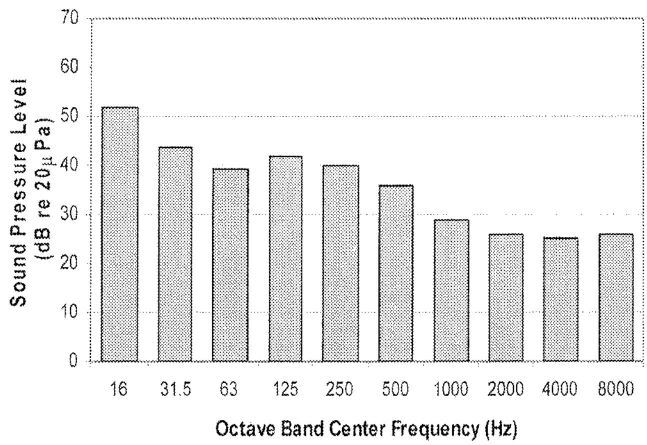

Figure 2 *Frequency character of test chamber background noise levels.*

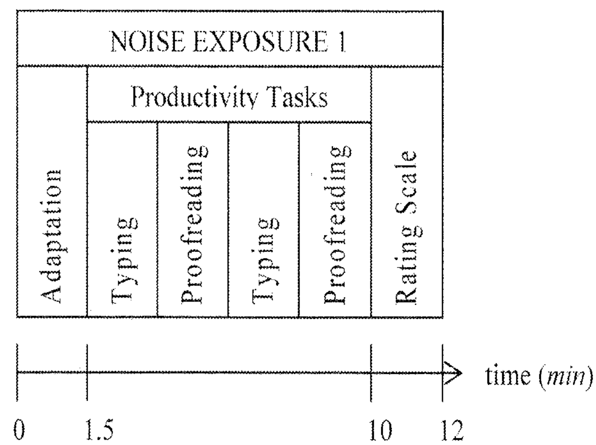

Figure 3 *View of the experimental sequence for a single noise exposure.*

furnished as a typical office with carpeting, gypsum board wall construction, and acoustical ceiling tiles, and it exhibits a reverberation time of 0.25 seconds at 500 Hz. The naturally occurring background noise level in the test chamber is relatively low, as shown in Figure 2. Additionally, the surrounding structure achieves STC 47 to minimize noise intrusion from adjacencies. The spaces immediately surrounding the structure were unoccupied during testing, with the exception of the researcher sitting quietly in an adjacent room. The room was maintained as a comfortable working environment at approximately 68°F (20°C), with overhead fluorescent lighting at an average illuminance of 71 foot-candles (764 lux) at the work plane.

Experimental Procedure

A flowchart of the experimental procedure is shown in Figure 3. Ninety-second adaptation times to the background noise were used at the beginning of each new noise exposure to allow the subject to audiologically adjust to the change in background noise. Subjects were instructed to sit and relax during this period. Productivity tests and a subjective rating portion followed. Each noise exposure trial lasted approximately 12 minutes. To reduce overall fatigue, testing took place over two sessions on two separate days, with each subject scheduled at approximately the same time on both days. Each session lasted approximately one and a half hours, for a total testing time per subject of three hours.

Noise Exposures

Twelve different background noise exposures which simulate ventilation noises that might be encountered in real-world environments were used in this study. Each exposure was controlled to be nonvarying over time and nontonal. The exposures can be generally categorized as having three different levels (low, medium, and high) and four different spectral qualities (neutral, rumbly, roaring, and hissy). A matrix of the noise exposure design is given in Table 1. The neutral signals followed a slope of approximately -5 dB/octave band. Rumbly sounding signals were achieved by raising the levels included of the 31.5 and 63 Hz octave bands by 5 to 10 decibels. Similarly, roaring and hissy sounding signals were achieved by raising the levels by approximately 10 decibels from 125 to 500 Hz and 2000 to 8000 Hz, respectively. Control over the 16 Hz octave band was limited due to subwoofer response and mixing capabilities. Octave band measurements of the mid-level signals are presented in Figures 4 through 7. All

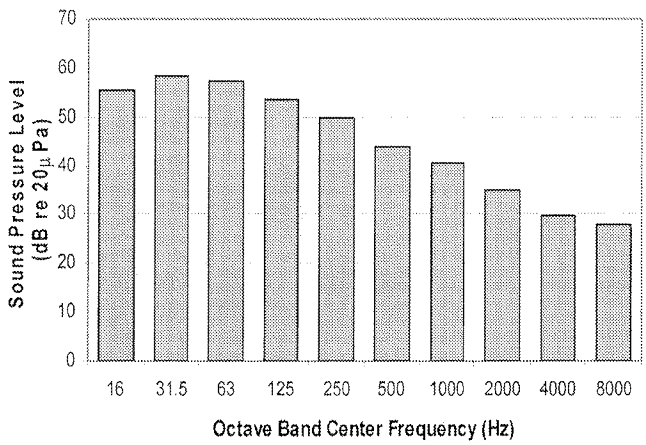

Figure 4 *Frequency character of the mid-level neutral noise exposure.*

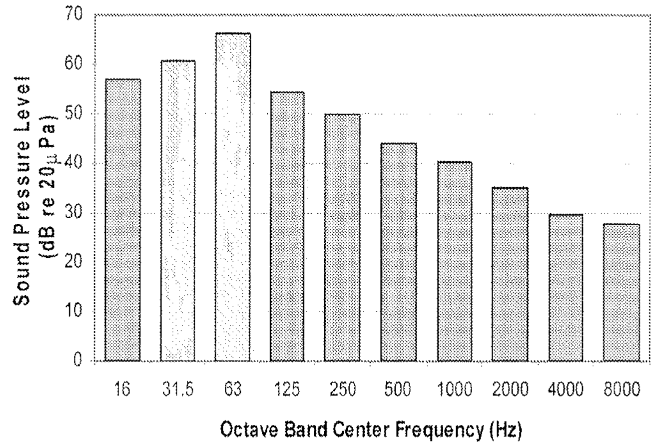

Figure 5 *Frequency character of the mid-level rumbly noise exposure.*

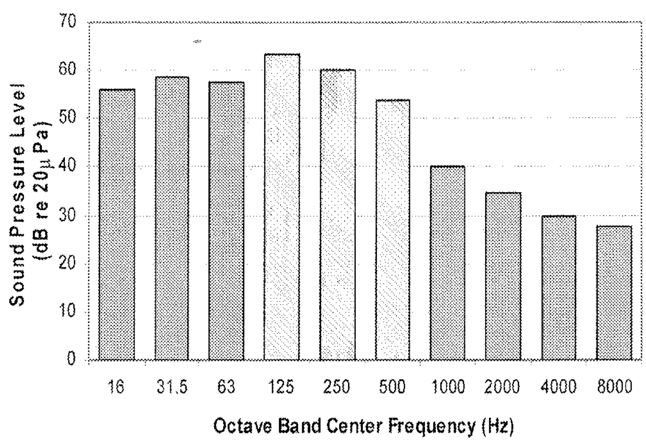

Figure 6 *Frequency character of the mid-level roaring noise exposure.*

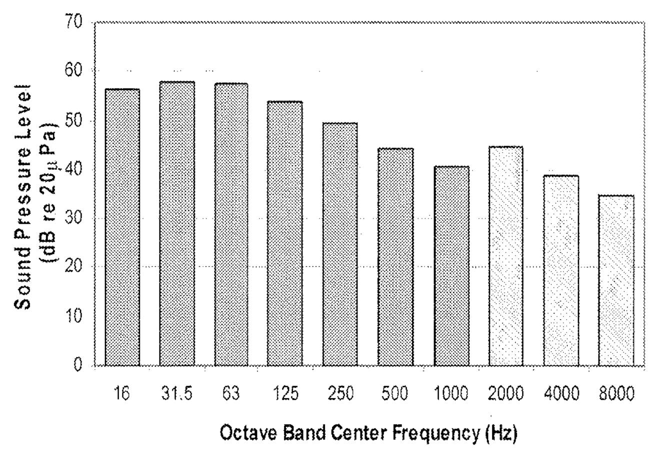

Figure 7 *Frequency character of the mid-level hissy noise exposure.*

measurements were made at the test subject's location using a Larson Davis 824 sound level meter.

Noise exposures were presented over two loudspeakers: an Armstrong i-ceiling™ loudspeaker and a JBL Northridge™ E250P subwoofer. The exposures were presented in random order, and no two subjects heard the same order of presentation. Mixing and amplification of the loudspeakers was achieved with an Armstrong i-ceiling™ D2001 Digital Processor and a D4100 Amplifier. All test signals were generated by filtering white noise into the desired spectra with Cool Edit 2000 software.

The i-ceiling™ loudspeakers are typically used in open office plans for masking systems and look like acoustical lay-in ceiling tiles. The subwoofer was covered in an acoustically transparent fabric to resemble an end table. In a post-study survey, it was found that the majority of subjects were unable to identify the source of the noise and merely commented that it seemed to be coming from above the ceiling somewhere. In this sense, the localization of the noise resembled typical ventilation installations. At the end of the study, subjects were also asked if the background noises reminded them of anything they had heard before. Responses included "air-conditioners," "mechanical noise," "vents," and "the noise in my office," indicating that most of the exposures were generally considered to be similar to office noise they heard before. A few subjects commented that the more hissy-sounding signals were less natural sounding.

Productivity Tests

Productivity was evaluated under each background spectrum via two types of computer-based tests. The test and software were developed in conjunction with the National

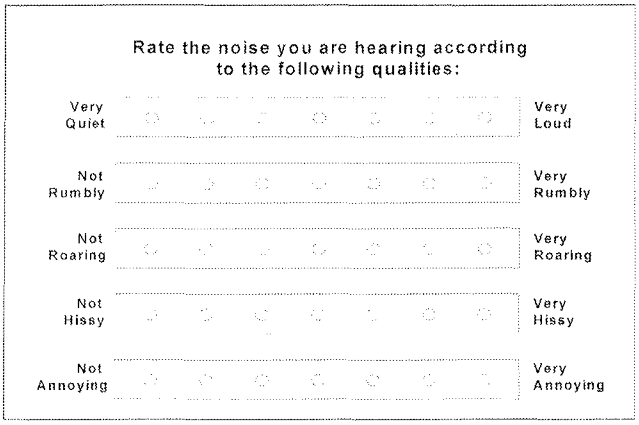

Figure 8 *Scale used for subjective ratings of loudness, annoyance, and spectral quality.*

Research Council of Canada (Scovil et al. 1995a, 1995b). A typing test required the subjects to retype paragraphs presented on the computer monitor. Paragraphs were carefully selected for approximately equal length and difficulty, based on average sentence and word lengths, average characters per word, and readability statistics. Measures of typing speed based on characters per second and average errors in the typing were recorded. In a second test, two columns of 10-digit numbers were presented side by side. The user's task was to mark the rows where the two columns differed as quickly and accurately as possible. Total time taken to complete the task and the percentage of correct identifications were recorded in this test.

Subjective Ratings of Loudness, Annoyance, and Spectral Quality

After each exposure, subjects were asked to rate the background noise in terms of loudness, annoyance, and spectral quality. Estimations were based on a seven-point discrete scale. The form used in testing is shown in Figure 8. Prior to the testing session, subjects completed a training module in which they were exposed to the subjective terms "rumbly," "roaring," and "hissy," as used by several indoor noise criteria systems. The subjects were told that "rumbly" noise contains excessive low frequencies and listened to an audio sample of broadband white noise covering the 16 Hz to 63 Hz octave bands in accordance with the RC Mark II descriptor of rumble (Blazier 1997). Likewise, they were instructed on "roaring" noise being excessive in mid-frequencies and listened to a corresponding audio sample from 125 Hz to 500 Hz. Finally, they were informed that "hissy" noise contained excessive high frequencies and listened to a broadband audio sample from 1 kHz to 8 kHz. No specific instructions were given on the terms *loudness* and *annoyance*, as the researchers were interested in individual subjective interpretation of these terms.

At the beginning of each of the two testing sessions, subjects completed one "control" trial under the mid-neutral noise exposure. This was done to compare the results of the subjective testing on two separate days under the same background noise condition and also to let the subjects warm up for the typing tasks. Ratings of loudness, annoyance, and spectral quality for the control trial were found to be quite consistent for each subject.

DISCUSSION

Indoor Noise Criteria Systems Evaluated

Previous studies have shown that there can be large differences among indoor noise criteria predictions for the same spectrum (Goodfriend 1975; Tocci 2000; Bowden et al. 2002). In this study, the effectiveness of five different criteria systems in predicting human response to background noise was evaluated. The five systems analyzed in this pilot study were: Noise Criteria (NC), Balanced Noise Criteria (NCB), Room Criteria (RC), Room Criteria Mark II (RC Mark II), and A-weighted Equivalent Sound Pressure Level (L_{Aeq}). Other criteria systems will be examined in future research, including Stevens Loudness Level (LL_S) (Stevens 1956), Zwicker Loudness Level (LL_Z) (Zwicker et al. 1957), Noise Rating (NR) (Kosten and van Os 1962), Preferred Noise Criterion (PNC) (Beranek et al. 1971), and Room Noise Criterion (RNC) (Schomer 2000).

The Noise Criteria method was one of the earliest to be widely accepted (Beranek 1957). This system provides a one-number rating, determined by comparing the background sound levels to a set of defined NC curves. The rating is determined through a tangency method, with the NC level given by the curve that lies above all the measured background noise. The NC curves were developed following measurements made in several commercial spaces and include octave bands from 63 Hz to 8000 Hz.

A simple tangency method makes NC a popular choice in part due to ease of use. However, problems with NC can occur because of a lack of specific information on spectral quality. The noise spectrum need not follow the shape of the NC curves, and the existence of a tonal component of excessive level in any one band has the ability to dictate the overall rating.

To provide additional information on the sound coloration, Beranek (1989) developed the Balanced Noise Criterion System (NCB). Like NC, NCB provides a single-number sound level rating, but NCB also gives an indication of the frequency content of the noise with sound quality descriptors. "Rumbly" ratings indicate excessive low frequency content, while extreme high frequency content is described as "hissy." In addition to "rumbly" and "hissy" ratings, NCB provides an assessment of the probability of noise-induced vibration in the low frequencies (16 Hz to 63 Hz).

The NCB system additionally differs from its NC predecessor with the inclusion of the 16 Hz and 31.5 Hz octave bands, and steeper slopes at high frequencies that correspond to lower acceptable levels than found with NC. The NCB sound level rating is not found by a tangency method but is based on the speech interference level (SIL):

$$SIL = \frac{1}{4}(SPL_{500} + SPL_{1000} + SPL_{2000} + SPL_{4000}) \qquad (1)$$

where

SPL_{500} = the sound pressure level in the 500 Hz octave band

A separate family of criteria predictions can be found in the Room Criteria methodologies. The RC methods differ significantly from the Noise Criteria techniques both in development and application. Following an ASHRAE-sponsored survey of office buildings, Blazier determined an acceptable slope for background noise as being approximately –5 dB/octave band (Blazier 1981). The RC curves follow this slope and extend from 16 Hz to 4000 Hz. Use of these curves has been most popular in evaluation of spaces where the mechanical system is the primary noise source.

The original RC method gives a single-number sound level rating, as well as indicators of spectral quality as rumbly, hissy, and vibrational ratings (Blazier 1981). The rating is found by calculation of the mid-frequency average, L_{MF}:

$$L_{MF} = \frac{1}{3}(SPL_{500} + SPL_{1000} + SPL_{2000}) \qquad (2)$$

where

SPL_{500} = the sound pressure level in the 500 Hz octave band

Further refinement of the RC methodology resulted in the development of Room Criteria Mark II (RC Mark II, Blazier 1997). The RC Mark II curves are identical to the RC curves with the exception that the Mark II curves are slightly less lenient in the 16 Hz octave band. The L_{MF} calculation remains the same, but an additional quality descriptor of "roaring" is included for excessive mid-frequency noise. The RC Mark II also includes a Quality Assessment Index (QAI) that provides an estimate of occupant evaluation, ranging from acceptable to objectionable. The QAI is found using spectral deviations between the measured levels and the RC contour levels.

Finally, A-weighted Equivalent Sound Pressure Level is a method used to simulate the unequal sensitivity of the human ear at different frequencies. Measured background noise levels are converted using a frequency weighting network that is based on the equal loudness contours. These contours provide the sound level across frequency necessary to produce the same subjective sensation of overall loudness (ISO 226:1987(E)). The A-weighting network loosely translates into an inversion of the 40 phon contour. The specific weighting network used in this study is taken from ANSI S1.42-2001 and the single number L_{Aeq} found as a decibel average from 16 Hz to 8000 Hz.

As previously stated, many consultants are still not in agreement over which criterion system to use for the various types of background noise situations encountered. This disagreement can even be seen in standards and text. ANSI Standard S12.2-1995 recommends the use of the RC and NCB methodologies to assess background noise. RC Mark II is currently the method of choice in the sound and vibration chapter of the *2003 ASHRAE Handbook—HVAC Applications*. Other standards, such as the recently adopted ANSI S12.60-2002 standard on classroom acoustics, set background noise criteria in L_{Aeq}.

Statistical Analysis

Due to the small subject pool and limited variance in data, a full statistical analysis would not be extremely meaningful for this pilot study. A multivariate analysis of variance is planned for the full study. For the pilot study, Pearson product-moment correlation coefficients (r) were used to assess the relationship between productivity scores, subjective assessment of noise, and criteria predictions. The correlation gives an indication of the relatedness of two variables. Values of the correlation coefficient range from –1 to 1, with the sign indicating the direction of the relationship. A larger absolute value suggests a higher degree of relatedness. The p value is the probability that the observed results have arisen due to chance alone. Note that only relatedness can be interpreted in correlations, not causation.

Productivity Results

Scores on the typing and proofreading tests showed significant correlations with each other, indicating that as speed and accuracy of typing decreased, the time required to complete the proofreading tasks increased ($r = 0.405$, $p < 0.01$). However, no significant correlations were found between the productivity scores and subjective assessment of loudness and annoyance or between productivity scores and criteria predictions of level.

In general, one might hypothesize that louder or more annoying background noise would negatively impact productivity. The lack of a strong correlation in this study could be attributed to a couple key factors. First, the differences in productivity scores for each individual subject across different exposures were extremely small. The small subject pool would exacerbate this issue. It was observed that some subjects exhibited more of the expected trend, while others showed no trend at all. This indicated to the researchers that some subjects were more capable of "tuning out" the background noise while others were more affected by it.

Additionally, the types of tests used may also be a reason for low correlations. Tests that require the subject to use more problem-solving or logical reasoning skills may show more of a trend than the typing and proofreading tests used.

Finally, the trial times of approximately 12 minutes per exposure could be too short to show the effects of fatigue, irritation, and adaptation that might occur for each exposure. As described earlier, other studies correlating productivity with background noise used task testing lasting from 36 to 60 minutes. While it is true that some of these studies found some significant effects of background noise on productivity, this

Table 2. Correlations (r) Between Criteria Level Ratings and Subjective Perception of Loudness and Annoyance

	Subjective Loudness Rating	Subjective Annoyance Rating
NC rating	0.815*	0.711*
NCB level rating	0.839*	0.724*
RC, RC Mark II level rating	0.842*	0.723*
L_{Aeq}	0.815*	0.703*

* p<0.01

does not necessarily prove that 36 to 60 minute tasks would have yielded significant results in the current project. Many other factors, such as the difference between signals used in the studies, number of signals presented, test chamber conditions, adaptation time, etc., could be more of an underlying contributor than the productivity test length. Only a study that controls all factors except length of test would resolve the question of how long productivity tests need to be to yield results that are truly representative of how noise affects performance.

Again it should be noted that with a sample of only 11 subjects the current results may not be indicative of the overall population. When the full study is completed, it is possible a significant effect of background noise on productivity may be found.

Loudness and Annoyance Results

Despite the small subject pool, significant correlations existed between the subjective perception of loudness and annoyance and criteria predictions of level. The correlation values are given in Table 2. Exposures with higher noise level ratings, as given by NC, NCB, RC, RC Mark II, and L_{Aeq}, were perceived as louder and more annoying by the subjects. In this study, RC and RC-Mark II were found to be the most correlated with level perception ($r = 0.842$, $p < 0.01$), although NC, NCB, and L_{Aeq} were also strongly correlated.

Additionally, a significant correlation was found between perception of loudness and annoyance ($r = 0.90$, $p < 0.01$). Note, however, that the relationship between the growth function of loudness and annoyance is relatively complex and beyond the scope of this paper.

Spectral Quality Results—Low Frequencies

Of particular interest to the researchers was subjective assessment of sound quality in the low frequencies. As previously mentioned, NCB, RC, and RC Mark II include descriptors of frequency content. One major difference between these three criteria is that RC Mark II is the only currently widely used system that includes a roaring descriptor for excessive mid-frequency noise (125, 250, 500 Hz octave bands). Both NCB and RC lump the frequencies from 16 Hz to 500 Hz into the rumble range.

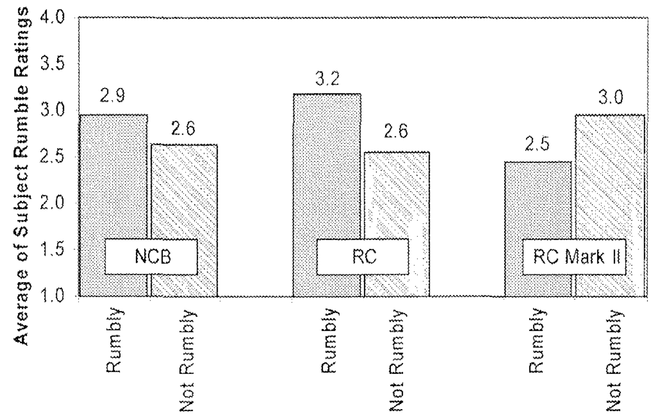

Figure 9 *Average subject ratings of rumble for noise exposures based on rumble predictions by NCB, RC, and RC Mark II.*

Ideally, subjects should perceive a noise to be rumblier when the NCB, RC, and RC Mark II criteria methods rate the noise as rumbly. A test of this trend is shown in Figure 9. For the case of NCB, the 12 exposures were analyzed as two separate groups: those characterized as rumbly by NCB and those characterized as not rumbly. The subjective ratings of rumble for all the exposures in the NCB rumbly group were then averaged, as were the subjective ratings of rumble for all the exposures in the NCB non-rumbly group. Figure 9 shows that subjects gave the NCB rumbly signals an average rating of 2.9 (on the seven-point scale) and the non-rumbly signals an average rating of 2.6. Recall that higher subject ratings indicate higher perceived rumble. So on average, the subjects perceived the NCB rumbly signals as rumblier than the non-rumbly signals, which is the expected trend. A similar analysis was performed for RC and RC-Mark II predictions of rumble. Some difference can be seen between the three methods. Perception of rumble is only slightly higher for the rumbly versus non-rumbly signals when rating with the NCB or RC methods. However, perception of rumble was actually greater for the non-rumbly signals then the rumbly signals using the RC Mark II method. It is possible that the additional quality descriptor of roar is confounding the rumble results for RC Mark II. Indeed, a significant correlation was found between perception of rumble and roar across all 11 subjects and all 12 noise exposures ($r = 0.584$, $p < 0.01$).

Similarly, subjective perception of mid-frequency roar was investigated. Figure 10 shows the average value of roar perception across subjects based on the RC Mark II prediction of roar. Roar was perceived as higher for the exposures that were described as roaring by the RC Mark II method than for those exposures that were described as non-roaring, which is the expected trend.

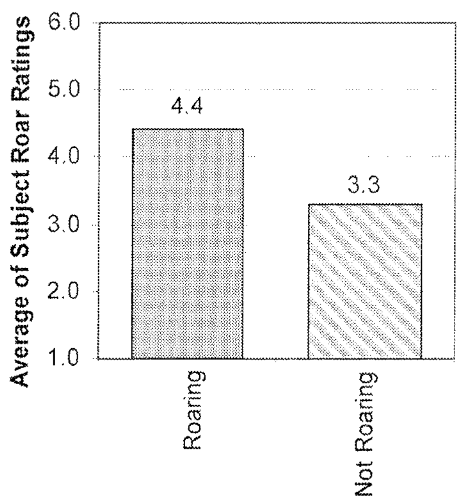

Figure 10 *Average subject ratings of roar for noise exposures based on roar predictions by RC Mark II.*

Interestingly, subjective perception of both rumble and roar were found to be significantly correlated with the level ratings given by all five criteria systems, as shown in Table 3. This indicates that for these noise exposures, as overall level increases, subjective perception of rumble and roar also increases. Additionally, rumble and roar perception was significantly correlated with subjective perception of annoyance and loudness, so as subjects perceived noise to be more roaring or rumbly, they also perceived it to be more annoying and loud. This result adds fuel to the increasingly strong argument that low frequencies can have a significant effect on occupants.

Table 3. Correlations (r) between Criteria Level Ratings, Loudness, Annoyance, and Subjective Perception of Rumble and Roar

	Subjective Rumble Rating	Subjective Roar Rating
NC rating	0.549*	0.542*
NCB level rating	0.512*	0.496*
RC, RC Mark II level rating	0.533*	0.523*
L_{Aeq}	0.553*	0.552*
Subjective Loudness Rating	0.597*	0.551*
Subjective Annoyance Rating	0.619*	0.543*

* $p<0.01$

CONCLUSIONS

A pilot study was conducted to examine the relationships between human productivity, annoyance, and loudness perception with various indoor noise criteria systems. Eleven subjects performed typing and proofreading tasks under 12 noise exposures with differing level and spectral characteristics. Although clear relationships between background noise and productivity were not observed, subjective perceptions of loudness and annoyance were well correlated with NC, NCB, RC, RC Mark II, and L_{Aeq}. Additionally, subjective perception of low frequency noise was found to exhibit the expected trend based on NCB, RC, and RC Mark II predictions of rumble and roar, with the exception of RC Mark II predictions of rumble.

In the next phase of this project, the authors plan to examine the usefulness of an adjusted criterion rating. The current analysis between criteria predictions and productivity, annoyance, and loudness perception is based solely on the level ratings given by the criteria systems. It is anticipated that adjusted ratings might be better related to human performance and perception. To illustrate, consider the following example: two background noise exposures, one of RC 35 neutral and the other of RC 35 rumbly. While the RC level rating remains the same at 35 for both exposures, the rumbly descriptor indicates that the two signals sound quite different. Based on the current results that annoyance increases with increased rumble, it is likely that productivity may be lower for the rumbly signal than for the neutral signal. Applying a penalty to the 35 rating might result in a better correlation between the criteria predictions and the productivity scores.

Additionally, further research will extend the pilot study to more subjects and examine the effects of tonal and fluctuating background noise spectra on criteria predictions. This pilot study provides a good base for future work on how acoustical conditions in offices affect workers and how well current criteria predictions relate to productivity, annoyance, loudness perception, and spectral quality.

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