FINDING CONNECTIONS AMONG INDOOR NOISE CRITERIA, HUMAN PERCEPTION, AND WORKER PERFORMANCE

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Clickity-clickity-clickity-CLACKity … clickity-clickity-clickity-CLACKity … what is creating that background noise in your office, in your home, or in the movie theater? It may be hard to pinpoint, but certainly it can cause you different kinds of distress. It may make you annoyed, disturb the flow of conversation, interrupt your sleep, cause fatigue, and even impact how productive you are. Some of the most pervasive sources of background noise are the modern heating, ventilating, and air-conditioning (HVAC) systems that keep us at comfortable temperatures indoors. These systems range broadly from the window unit in your apartment to a chiller supplying chilled water to cool a gymnasium in the summer.

"We consistently find that performance significantly decreases as participants perceive the noise to be louder or more spectrally imbalanced..."

Today's buildings contain an assortment of HVAC equipment, each contributing its unique flavor to the indoor auditory environment, or soundscape. Add to this the fact that other characteristics of a space influence the background noise, such as the amount of absorption in the room, the geometrical configuration, and the acoustical isolation properties of the building materials—the result is that no two rooms have exactly the same background spectrum. So with all of this variety, how can we characterize background noise in the modern built environment? Furthermore, how can we rate acceptability of these background soundscapes?

Introduction to indoor noise criteria systems

Several acousticians have considered these questions over the past 50 years, resulting in empirically developed indoor noise criteria systems. These systems are commonly used today by building engineers and designers to quantify the background noise in rooms, and are also incorporated into manufacturers' data, design guides, and standards. Some of the more popular criteria include Noise Criteria[1] (NC), Balanced Noise Criteria[2] (NCB), Room Criteria[3] (RC), Room Criteria Mark II[4] (RC Mark II), and A-weighted Equivalent Sound Pressure Level[5] (L_{Aeq}). Each of these criteria provides a single number rating that describes the overall level, or loudness, of the sound. This rating is generally found by comparing the measured background noise levels in a space against a set of sound level versus frequency curves. NCB, RC, and RC Mark II also include spectral quality descriptors; terms such as rumbly, roaring, and hissy are used to describe background noise with excessive low-, mid-, and high-frequency energy, respectively. If the low-frequency energy is very high, the space may also be described as causing noise-induced vibration.

Despite the popularity of these criteria systems, there is still dissatisfaction in the architectural acoustics community concerning their appropriate use in describing the wide variety of background noise situations we encounter. Previous studies have shown that there can be significant differences among indoor noise criteria ratings of the same spectrum.[6-8] For example, one may characterize a particular room as sounding hissy, while another says that the same room sounds not hissy, but rumbly. Which method should you trust then?

One might turn to industry experts to determine which criteria system is best to use. However, from a review of several sources, you would quickly see that there is no consensus that a particular criterion generally performs better than the others:

- ANSI Standard S12.2-1995 recommends the use of NCB and RC, although this standard is currently under revision and may replace these with other criteria.[9]
- ANSI Standard S12.60-2002 on classroom acoustics sets background noise criteria in L_{Aeq}.[10]
- The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) *HVAC Applications Handbook* recommends use of RC Mark II in general, but provides guidelines on how other criteria may be used for design versus diagnosis.[11]
- Manufacturers' data on diffuser noise usually provide NC ratings.
- Noise Rating (NR) is commonly used in Europe, but not in the United States.[12]
- Preferences among acoustical consultants vary greatly!

Additional concerns exist over these criteria systems because they may not characterize all of the qualities of background noise that affect occupants. Besides overall loudness, background noise may have different effects based on (a) its distribution across frequency (spectral quality), (b) whether or not the noise contains tones, and (c) whether or not the noise changes over time. The majority of the criteria systems account for loudness and spectral quality, but few specifically account for tonality or time-varying fluctuations.

Can we just ignore these other two factors? Many acoustical consultants believe we cannot, since tones and time-varying fluctuations are both frequently produced by modern HVAC systems. Motors, fans, and compressors are just a few examples of equipment that can produce audible discrete tones. Noise that fluctuates over time can occur rapidly, as in a rattling air diffuser, or more slowly, such as with the cycling of a variable air volume (VAV) system that adjusts to changing occupancy.

How does indoor noise affect occupant perception and performance?

Many sources list the range of indoor noise criteria ratings that are appropriate for some space usage; for example, an auditorium should maintain a lower noise criteria than the lobby that serves it. But questions have arisen about how well these criteria systems are related to actual occupant perception of the noise. Building owners are also very interested in whether or not meeting a particular noise criteria may be linked to worker performance. Unfortunately, the range of research in this field is not yet broad enough to provide definitive answers to these questions.

Recent studies linking subjective perception of ambient noise with measured sound spectra have demonstrated conflicting results. In these studies, people were asked to rate their general perception of the background noise, and their responses were then related to background noise measurements and criteria systems. Tang[13-15] and Ayr[16-17] consistently found L_{Aeq} to be highly correlated with subjective auditory sensation in office surveys. Persson-Waye and Rylander, on the other hand, found that L_{Aeq} was not a good predictor of annoyance to long-term noise exposure in residences.[18]

Much work has been done on how high levels of noise affect productivity,[19] but the pool of research examining how typical office background noise affects worker performance is more limited. Some researchers have focused on the effects of low frequency noise on task performance.[20-24] Among the main conclusions from these studies are that productivity can be affected by background noise, the impact can potentially change over time, and that the frequency character should be considered. While previous work has been instrumental in proving that a relationship exists between indoor noise and productivity, few studies have tried to determine whether or not the commonly used indoor noise criteria can represent this relationship for a variety of background noise conditions.

Research at the University of Nebraska "Indoor Environment Lab"

We are conducting an extensive study at the University of Nebraska to draw more connections between indoor noise criteria and the effects of HVAC noise on occupant perception and productivity.[25] Human test subjects have been exposed to a wide range of background noise conditions that are typical of existing indoor background noise from HVAC systems. Noise conditions at various levels and spectral quality are used, as well as some with tones and time-varying fluctuations. The test subjects complete performance tests and perception questionnaires under each noise condition, and their scores are then related to criteria ratings of the noise, including NC, NCB, RC, RC Mark II and L_{Aeq}. Our analysis seeks to determine how well the indoor noise criteria systems match human perception and productivity and also to find links between the latter two.

An "Indoor Environment Lab" was specially constructed at the University of Nebraska to conduct this type of research. As shown in Fig. 1, this lab resembles a typical office with

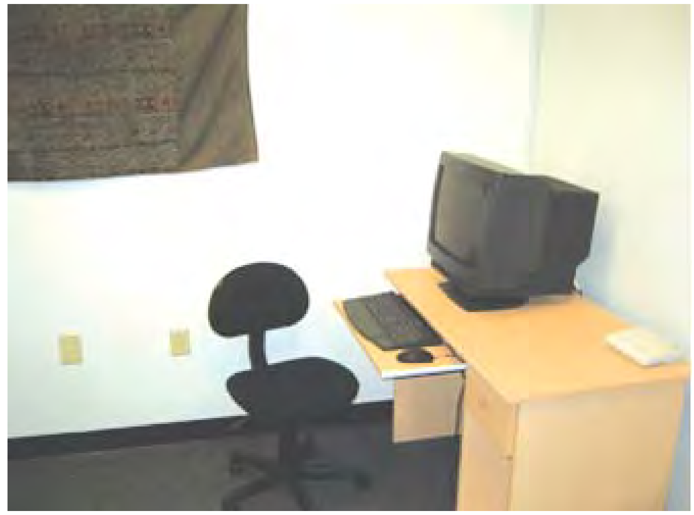

Fig. 1. View of a work station in the University of Nebraska Indoor Environment Lab.

carpeting, gypsum board wall construction, and acoustical ceiling tiles. The lab is designed to be acoustically isolated from adjacent spaces, and thus has very low naturally occurring background noise levels. The room is both thermally and acoustically controlled. For our research on indoor noise criteria, the temperature in the room is kept at a relatively constant level, so that the only factor changing is the noise. In the future, the lab may be used for studies on the interaction between the lighting, thermal and acoustical environments.

The variety of background noise conditions are presented over two loudspeakers that are disguised so that neither is easily identifiable. An overhead panel loudspeaker resembles a ceiling tile and a subwoofer in the corner is fashioned to look like an end-table. The overhead loudspeaker primarily supplies mid- to high-frequency energy, while the subwoofer provides the low-frequency components.

So far, the effects of 18 different noise conditions have been examined over several phases of testing. The noises mimic ventilation sound that might be encountered in real-world buildings, and span a range of sound levels (from roughly 37 to 57 dBA), spectral qualities (neutral, rumbly, roaring

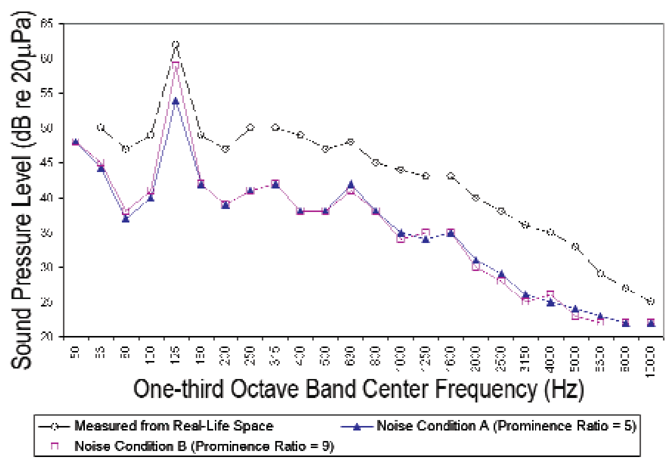

Fig. 2. Two of the tonal noise exposures used in the study. The dashed line shows the levels of the background noise measured from the real-life space. Noise conditions A and B are the laboratory-reproduced spectra with two different tonal prominence ratios.

and hissy), and characteristics (broadband, with tones, and with time-fluctuating components). Many of the conditions are based on recordings made in real spaces. We have calibrated these recordings so that the sound being reproduced in the lab very nearly matches what was measured in the real-life spaces. Some examples of the sources heard in these noise conditions are an apartment heat-pump, a research laboratory fume hood, twin exhaust fans above a library, and a screw compressor above an office. Figure 2 shows sample spectra of two noise conditions that exhibit a low frequency tone at 120 Hz. The two are essentially identical except for the prominence of the tone; the tone in noise condition A has a higher prominence ratio than in condition B.[26]

Under each noise exposure, test subjects complete a variety of performance tasks, including typing, math, grammatical reasoning, and proofreading. These computer-administered tests are carefully developed to be equally difficult across all trials. Prior to the testing, all participants are prescreened to ensure that they meet a required level of auditory and visual function and a minimum typing ability of 20 words per minute.

Participants also complete perception questionnaires under each noise exposure. These questionnaires ask them to rate their general impressions of various qualities of the testing room, including the noise, temperature, lighting, and work station comfort. (Recall that only the background noise is manipulated, though.) Additional questions specifically ask them to rate the noise with regard to loudness, annoyance, distraction, tonality, fluctuations over time, and rumble, roar, and hiss characteristics.

The testing takes place over multiple testing days to reduce fatigue. When each participant is finished with all of his/her testing sessions, he/she completes a post-study survey. They are asked if the noises remind them of anything they have heard before. The majority of subjects have responded that the noises sound like HVAC noise, with comments such as, "the noise in my office," or "air-conditioning." When prompted to identify where they think the noises are coming from, most have responded that they are coming from above the ceiling somewhere. Several thought the noise was coming from the air diffuser located adjacent to the overhead panel loudspeaker. This indicates to us that we are realistically mimicking the content and localization of HVAC noise.

After much statistical analysis…

In all, around 650 hours of subjective testing have been completed. First, we will focus on the results to date connecting indoor noise criteria to human perception. Statistically significant relationships exist between the criteria level ratings and subjective perception. That means that background noise conditions with higher criteria level ratings are perceived to be louder, more annoying, more rumbly, more roaring, and more hissy ($p<0.01$). Examples of such relationships are shown in Fig. 3; as the RC level rating increased, perceptions of loudness (Fig. 3a) and annoyance (Fig. 3b) also increased ($p<0.01$). Similar graphs have been obtained for the other four criteria methods. These relationships are certainly what we would expect.

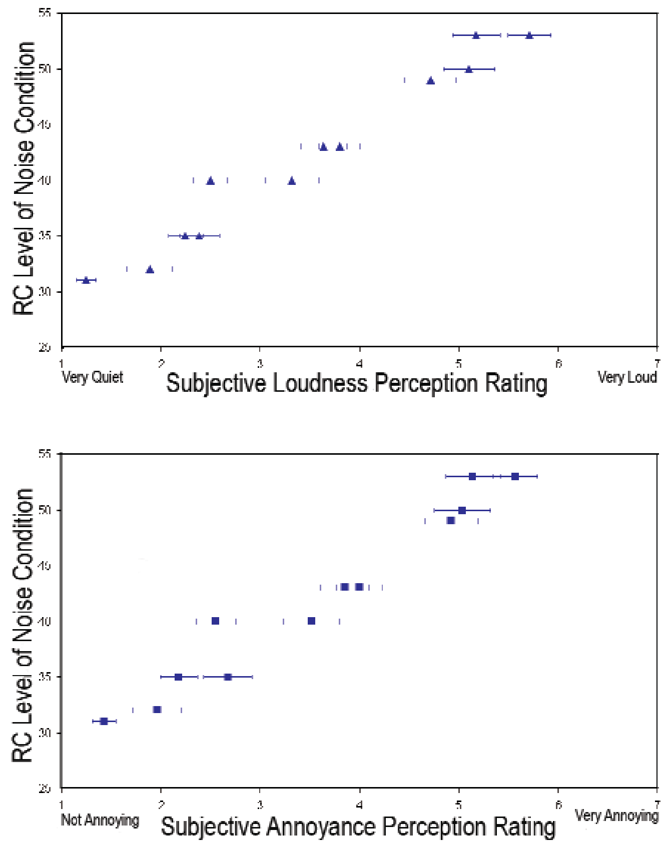

Fig. 3. Subjective perceptions of (a) loudness and (b) annoyance increase as Room Criteria (RC) level rating of noise conditions increases. The subjective rating values are averaged across 30 test subjects and displayed with standard error bars. Similar relationships were found for the other indoor noise criteria tested.

Next, let us examine the results about spectral quality, as given by the criteria systems and as rated by the test subjects. Only three of the criteria systems studied so far (NCB, RC, and RC Mark II) include descriptors of frequency content. One major difference between these three is that RC Mark II is the only one that includes a roaring descriptor for excessive mid-frequency noise, covering the 125, 250, 500 Hz octave bands. Both NCB and RC lump the frequencies from 16 Hz to 500 Hz into the rumble range.

Ideally, participants should perceive noise conditions rated as "rumbly" by the criteria systems to be more rumbly than conditions rated "not-rumbly." We tested this hypothesis by splitting the noise conditions into groups, depending on their rumble, roar, and hiss ratings given by each criterion. A statistical analysis was then run to see if the perception ratings were higher for (a) the rumbly versus not-rumbly groups, (b) the roaring versus not-roaring groups, and (c) the hissy versus not-hissy groups. Results are mixed. RC spectral ratings match perception in terms of rumble ($p<0.01$); however, RC spectral ratings are not clearly found to match hiss perception. RC Mark II ratings match perception with regard to roar and hiss ($p<0.01$), but not with rumble. And no significant relations are found between NCB spectral ratings and perception, although a general trend is appropriately followed.

Our conclusion is that the spectral ratings given by the criteria do not fully match subjective perception. We are now taking a closer look at the various criteria to determine if adjustments to their methodologies may improve the results. For example, part of the reason for the RC Mark II results may be due to the fact that this criterion currently only allows for a rumble, roar, or hiss characterization of any one noise condition, and not for a combination. That is, you may obtain an RC Mark II "40-Roaring" rating, or an RC Mark II "40-Rumbly" rating, but not an RC Mark II "40-Roaring-and-Rumbly" one. We are currently working with a subcommittee of ASHRAE's Technical Committee 2.6 on Sound and Vibration regarding possible adjustments to the RC Mark II method.

Now we will turn our attention to the connections between criteria and the performance test results. So far, we have found no significant relationships between the indoor noise criteria predictions of level and task performance results. What exactly does this tell us? It might indicate that these five criteria simply do not relate to task performance. This may not be entirely surprising, as the criteria were developed based on perception surveys, not on productivity.

We have also investigated how performance changes when participants perceive the noise to be different, regardless of what the criteria indicate. To examine this, we have compared performance test results to perception questionnaire results. We consistently find that performance significantly decreases as participants perceive the noise to be louder or more spectrally imbalanced ($p<0.01$); this is demonstrated in Fig. 4 which shows subjective rating of hiss versus typing speed. Our on-going work involves running more subjective tests and analyzing the growing data bank to determine how specific relationships depend on the characteristics of the noise conditions. We already see that negative perception of background noise can significantly decrease productivity, but it would be interesting to know which perceived traits (rumbly? roaring? hissy? tonal? time-fluctuating?) may impact performance more than others.

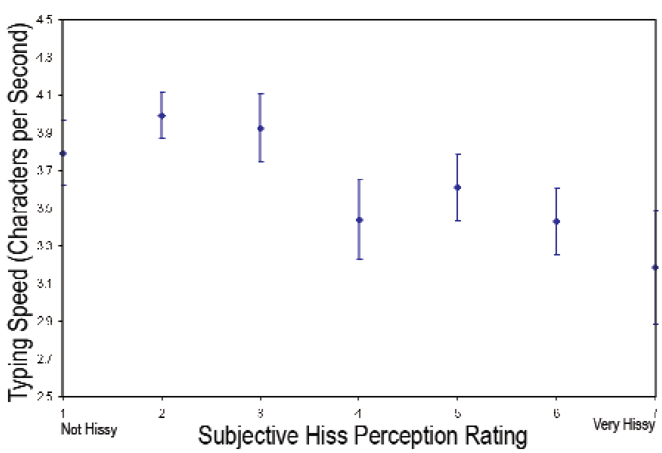

Fig. 4. Typing performance decreases as the subjects perceive there to be more hiss in the noise condition. The typing speeds in characters per second are averaged data compiled from 30 test subjects and displayed with standard error bars. Similar relationships with performance were found when subjects had negative perceptions of the noise in terms of loudness, annoyance and the other spectral qualities.

Summary

Our overall goal is to determine how closely widely-used indoor criteria systems relate to task performance and psychoacoustic perception of HVAC sound. We are finding that perception of background noise can significantly impact productivity, but that these performance effects are not fully represented by NC, NCB, RC, RC Mark II, or L_{Aeq}. Additionally, our results show that indoor noise criteria predictions of spectral imbalance, such as excessive rumble, roar, or hiss, may not always agree with subjective perception. We continue to investigate how these criteria and our own testing methodology may be altered to produce clearer results, and we hope to expand our analyses to include a number of more recently proposed indoor noise criteria measures in the near future.**AT**

Acknowledgments

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