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AB-10-018 (RP-1322)

The Effects of Noise from Building Mechanical Systems with Tonal Components on Human Performance and Perception

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This paper is based on findings resulting from ASHRAE Research Project RP-1322.

ABSTRACT

This study investigated the effects of noise from building mechanical systems with tonal components on human task performance and perception. Six different noise conditions based on in-situ measurements were reproduced in an office-like setting; all were set to approximately the same sound level (47 dBA) but could have one particular tonal frequency (120 Hz, 235 Hz, or 595 Hz) at one of two tonal prominence ratios (5 or 9). Thirty participants were asked to complete typing, grammatical reasoning, and math tasks plus subjective questionnaires, while being exposed for approximately 1 hour to each noise condition. Results show that the noise conditions that had tonal prominence ratios of 9 were generally perceived to be more annoying than those of 5, although statistically significant differences in task performance were not found. Other findings are (1) that higher annoyance/distraction responses were significantly correlated with reduced typing task performance; (2) that the noise characteristics most closely correlated to higher annoyance/distraction responses in this study were higher ratings of loudness followed by roar, rumble, and tones; and (3) that perception of more low frequency rumble in particular was significantly linked to reduced performance on both the routine and cognitively demanding tasks.

INTRODUCTION

Modern mechanical systems in buildings for heating, ventilation and air-conditioning can produce noise with perceptible tonal components, often due to rotating parts, such as fans, motors, impellers, etc. The tonal aspects of the back-

ground noise may then result in increased occupant discomfort and reduced worker performance, but these effects have not been systematically investigated across a range of controlled conditions that represents what can be found in existing spaces. Additionally, methods of rating the acceptability of indoor noise characteristics, such as Noise Criteria (NC), Room Criteria (RC), and others listed in the ASHRAE Applications Handbook (2007) do not clearly account for tonal noise components or necessarily reflect their effects on human performance and perception. The goal of this research study has been to determine how a variety of building mechanical system noise conditions with varying degrees of tonal components affect human performance and perception in a typical office setting. The performance and perception results have been subsequently correlated with a number of indoor noise criteria ratings to evaluate the limitations of current criteria methods and suggest improvements, if applicable.

Many researchers have investigated effects of noise on human perception and performance; a number of early studies focused on the consequences of very high noise levels (e.g. greater than 70 dBA) (Kryter 1985, Jones and Broadbent 1998). Beginning in the 1950s, much work focused on defining acceptable noise conditions found more commonly in office buildings (Beranek 1956, Keighley 1966, 1970, Hay and Kemp 1972, Blazier 1981, Beranek 1989, Blazier 1997). This resulted in the development of a number of indoor noise criteria, including Noise Criteria (NC), Balanced Noise Criteria (NCB), Room Criteria (RC), Room Criteria Mark II (RC-Mark II), which are described in Ch. 47 of the ASHRAE Applications Handbook (2007). More recently, Tang and colleagues have surveyed occupants in built offices (Tang et al. 1996, Tang 1997, Tang and Wong 1998) and in

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residential apartments (Tang and Wong 2004), and statistically correlated participant responses to the measured noise conditions as quantified by a variety of noise criteria and indices. Ayr and colleagues have also conducted such occupant surveys in offices (Ayr et al. 2001, Ayr et al. 2003). Both of these groups have concluded that among the indices tested, the A-weighted equivalent sound pressure level (L_{Aeq}) consistently correlates most strongly with subjective responses of loudness, annoyance and dissatisfaction.

In addition to sound level, though, spectral qualities of the noise are considered important. As found by Persson and colleagues in lab studies (1985, 1988), noise conditions with more low frequency content resulted in greater annoyance than those with higher frequency content with the same L_{Aeq} . Results from a subsequent investigation in the field also suggested that the dominance of low-frequency content in residential noise conditions was better related to long-term annoyance perception than L_{Aeq} (Persson Waye and Rylander 2001). The loudness level of the signal is an important link to annoyance, but when comparing signals of equal loudness or perhaps over long-term exposures, spectral qualities such as rumble become more significant. Some of the indoor noise criteria listed above, including NCB, RC, and RC Mark II, include such spectral quality descriptors (e.g. "R" for rumble or excessive low frequency content, and "H" for hiss or excessive high frequency content).

A number of investigations have specifically focused on the effects of noise with excessive low frequency content on task performance, as reviewed by Leventhall et al. (2003). Some of these have utilized ventilation-type spectra while testing different tasks, such as vision tasks (Kyriakides and Leventhall 1977), figure identification tasks (Landström et al. 1991), proofreading tasks (Holmberg et al. 1993), and other cognitively demanding tasks like grammatical proofreading and verbal reasoning (Persson Waye et al. 1997, 2001). There is evidence that background noise with rumble can affect task performance negatively in certain cases, but these previous studies often compared only two or three noise conditions at a time, making it difficult to make broader quantitative recommendations.

The topic of noise with tones, particularly in terms of how the addition of tones impacts perception of loudness or annoyance, has also generated much interest over the years, as aircraft, industrial machinery, and other office equipment can generate such spectra (Kryter and Pearsons 1965, Hellman 1982, 1984). A number of methods for quantifying the prominence of the tone in the noise or its 'tonalness' have been developed, including Tone-to-Noise Ratio (ANSI S1.13-2005), Prominence Ratio (ANSI S1.13-2005), and Aures' Tonalness metric (1985). In Annex C of ISO Standard 1996-2 (2007), Tone-to-Noise Ratios are further linked to decibel adjustments that can be applied to measured A-weighted equivalent sound pressure levels for use in environmental noise assessment. Of particular note is a round robin test conducted to compare the two metrics discussed in ANSI S1.13, Tone-to-Noise Ratio and Prominence Ratio (Balant et al. 1999, Hellweg et al. 2002). They found that

for broadband noise with a single prominent tone, the two metrics correlate well with each other and also with the degree of tonalness perception, but further issues need to be clarified regarding more complex tones (e.g. multiple tones in the same critical band, harmonic series of tones, or time-varying tones). Some work has been directed towards dealing with these more complex cases (Hellman 1985; Hastings et al. 2003, Lee et al. 2004, 2005).

Ventilation-like noise spectra that specifically include tones have been utilized in a few investigations involving perception or performance. Landström et al. used two noise signals with tones at 100 Hz, one of which was additionally masked by other low frequency pink noise; they found that performance on figure identification tasks was significantly lower when participants were exposed to the unmasked tone as compared to the masked tone (1991). One of Holmberg et al.'s five noise signals had a superimposed tone at 43 Hz, but in this study no statistically significant differences were found in the proofreading task performance across the signals (1993). To study acceptable levels of tones while performing tasks, Landström et al. asked test subjects to adjust the levels of a 100 Hz tone, a 1000 Hz tone, or broadband noise centered around one of these two frequencies to acceptable levels while working on various tasks, and found that much lower levels of the high frequency tone were tolerable (1993). In a subsequent investigation, Landström et al. asked subjects to adjust the frequency of a tone in ventilation noise between 35 Hz to 500 Hz until it was considered to be the least or most annoying. Results showed that participants found 58 Hz to be least annoying and 380 Hz to be most annoying (1994).

What differentiates the work reported herein from previous research is that a wider range of realistic tonal spectra from building mechanical systems are tested systematically, including three different tonal frequencies and two different tonal prominence ratios. Specifically, the effects of that tonal noise on human task performance using three types of tasks (typing, grammatical reasoning and math tests) and perception in a typical office setting are quantified. These results may then be related to commonly used indoor noise criteria, suggested within the ASHRAE Applications Handbook, in an effort to improve those methods.

METHODOLOGY

The protocol described in this section for this phase of research is similar to one used for a subsequent phase of testing, presented in an accompanying paper (Wang and Novak 2010). As the authors believe that readers may not necessarily access both papers, some of the same methodology is discussed in both manuscripts.

Thirty test subjects (15 males and 15 females) from the University of Nebraska community were recruited to participate in this study, ranging in age from 19 to 44 with a mean of 25 years. All participants first underwent a series of pre-test screens to gauge the subject's vision, hearing, and typing skills. The minimum requirements to participate in the study

were as follows: normal vision as verified by a Keystone Ophthalmic Telebinocular, hearing thresholds below 25 dB hearing level in octave bands from 125 Hz to 8 kHz, and a minimum typing speed of 20 wpm.

Testing was conducted in a 906 ft³ (25.7 m³) indoor environmental test chamber at the University of Nebraska, outfitted as a typical office with two desks, carpet, gypsum board walls, and acoustical ceiling tile. The test chamber's envelope has a high sound transmission class of STC 47, and its interior acoustic condition demonstrates low background noise level of RC 26(H) (or an equivalent A-weighted sound level of 35 dBA) and a low reverberation time of 0.25 sec at 500 Hz. During all tests, the test chamber was thermally controlled to maintain a temperature of 68°F (20°C). Overhead fluorescent lighting provided an constant average illuminance of 71 foot-candles (764 lux) at the work plane. The sound in the test chamber was the only environmental characteristic that changed between test sessions, with the signals being presented in an inconspicuous manner over two loudspeakers: (i) an Armstrong i-ceiling loudspeaker which has the same appearance as the other ceiling tiles in the room, and (ii) a JBL Northridge E250P subwoofer, disguised to resemble an endtable in the corner of the room. The test administrator and various equipment (e.g. the hard drive to the test computers and other audio gear) were located in a control room, adjacent to the chamber.

Each subject was exposed to the same six noise conditions, each for a period of 55 minutes at a time. This length of exposure time was selected due to the results from a previous phase of the ASHRAE 1322-RP project (Ryherd and Wang 2007). Participants were asked to come for their six listening sessions at approximately the same timeslot on different days. For each session, the test subjects spent the first 25 minutes adapting to the noise condition and completing a test on paper, developed from material taken from the verbal portion of the Graduate Record Examination (GRE). Unbeknownst to the subject, this material was not to be marked but was simply to keep the subject mentally alert during the adaptation period.

The next 15 minutes consisted first of three skill tests, administered on a computer using SkillCheck software: typing, grammatical reasoning, and math. The typing test was allotted five minutes, and involved typing a passage from a piece of paper with the mouse disabled. The reasoning task was allotted two minutes, and included 20 questions in which subjects indicated whether a statement regarding a presented sequence of letters was true or false. The math test was allotted seven minutes, and included 11 problems involving the four basic functions with integers, fractions, and decimals, presented either mathematically or as a word problem. Participants were provided with pencil and paper but no calculator. Results for the typing test were output as an adjusted typing speed, accounting not only for the subject's typing speed but also the number of errors made. Results for the reasoning and math tasks were output as a percent correct, with questions that were not answered within the time limit considered incorrect.

Further details on the development of the test material may be found in Ryherd and Wang (2007).

The skill tests were followed by a subjective questionnaire that asked the participant to rate his/her perception on discrete seven-point scales of various indoor environmental qualities of the space, where 1 generally represented a low rating and 7 represented a high rating. Eight questions focused on perceptions related to the acoustic condition: loudness, rumble, roar, hiss, tones, changes over time, annoyance, and distraction. The remaining five focused on other conditions of the working environment, including lighting, thermal comfort and indoor air quality; as these conditions were kept constant and were not the focus of this investigation, the data are not presented further in this paper. The last 15 minutes repeated this sequence once more: typing, reasoning, and math tests, followed by the questionnaire. In total then there were 360 observations (= 30 subjects x 6 noise conditions x 2 test/questionnaire sequences).

Six versions of the paper-based task and 12 versions of the typing, reasoning, and math tasks were utilized. Each subject completed all versions of the tasks with the order of presentation randomized for each subject. Two subjects participated in each test session whenever possible, but they were instructed not to discuss or interact with each other during the testing. The order of presentation for the noise conditions remained flexible to accommodate subjects' schedules. For example, if two participants happened to be available for the same timeslot and both still needed to complete a particular noise condition, then that was the noise condition they would be exposed to during that session. In this sense, the order of presentation was randomized by availability. Care was taken by the researchers to avoid scheduling the sessions in any sort of systematic order.

Prior to testing, the subjects completed a powerpoint tutorial that described the test procedures and introduced them to the subjective terms "rumbly", "roaring", "hissy", and "tonal". The "rumbly" noise characteristic was described as containing excessive low frequencies, and a corresponding audio sample of broadband white noise band-limited from 16 Hz to 63 Hz octave bands at a level of 54 dBA was presented over headphones. The "roaring" noise characteristic was described as being excessive in mid-frequencies, and a corresponding audio sample band-limited from 125 Hz to 500 Hz at 59 dBA was presented. The "hissy" noise characteristic was described as containing excessive high frequencies, and a corresponding broadband audio sample band-limited from 1 kHz to 8 kHz at 63 dBA was presented. The "tonal" training signal consisted of broadband noise at an overall L_{Aeq} level of 60 dBA with a tone at 500 Hz of PR = 16. No other training was provided concerning the remaining descriptors on the questionnaire.

Noise Conditions

The six different noise conditions used had varying degrees of tonal components. Signal T1 was a non-tonal

broadband signal generated in Cool Edit 2000 software with a -5 dB/octave band slope, intersecting 40 dB (re 20 μ Pa) at the 1000 Hz octave band. Signals T2 through T6 were based on in-situ recordings made in existing spaces that exhibited tones from mechanical systems, adjusted within Cool Edit 2000 so that the tones had either a prominence ratio (PR) of 5 or 9. The metric used for tonalness in this investigation, PR is a ratio of the power of the critical band centered on a tone compared to the mean power of the two adjacent critical bands, so it quantifies the degree of tonalness based on relative loudness differences, rather than based on whether the tone is masked within its critical band as the Tone-to-Noise Ratio does (ANSI 2005a). The 1995 version of the ANSI S1.13 standard listed that a tone is considered prominent, or clearly audible, when the PR is greater than 7; consequently the noise conditions in

this study were selected to fall both below and above the prominence limit at PR = 5 and PR = 9.

Signals T2 and T3 were based on a recording of an apartment heat pump with a 120 Hz tone; signals T4 and T5 were based on a recording of a laboratory fume hood with a 235 Hz tone; and signal T6 was based on a recording of a screw compressor with a 595 Hz tone. Table 1 lists the six noise conditions along with their corresponding indoor noise criteria ratings. The loudness in sones was calculated per ANSI Standard S3.4 (2005). Procedures for calculating the other criteria are described in the ASHRAE Applications Handbook (2007).

Figure 1 shows the one-third octave spectra measured for signals T2 through T6 in the test chamber. To minimize the effect that different signal levels would have on human performance and perception and attempt to isolate any effect due to different degrees of tonalness, the sound levels of all six signals

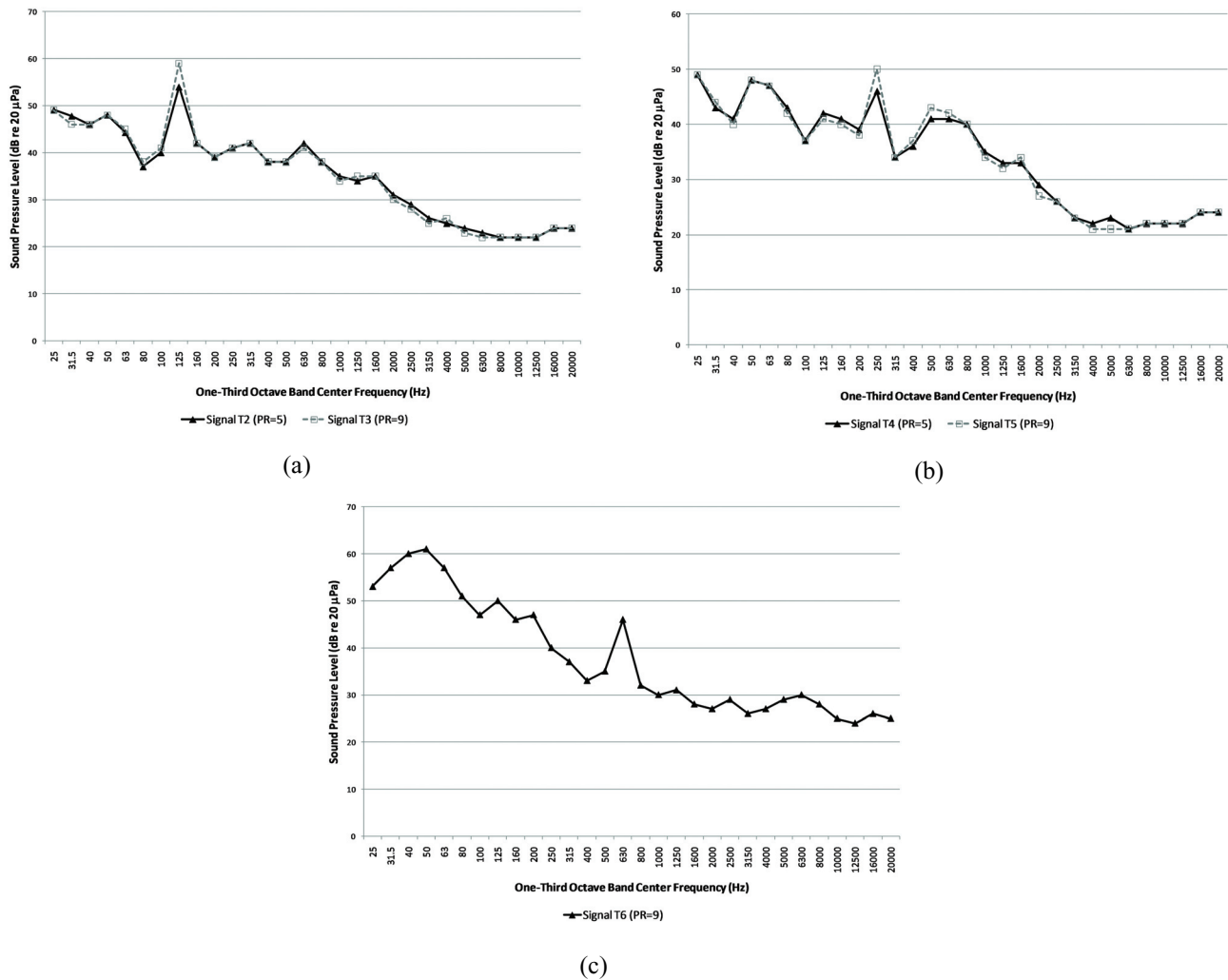


Figure 1 One-third octave band spectra measured in the test chamber for (a) signals T2 and T3, (b) signals T4 and T5, and (c) signal T6, based on in-situ recordings from an apartment heat pump, laboratory heat pump, and screw compressor, respectively.

were adjusted so that they each produced a L_{Aeq} of approximately 47 dBA in the test chamber. The one-third octave band levels of each signal were compiled as an average of measurements using a Larson Davis 824B sound level meter on multiple days at both work stations. Above the Schroeder frequency of the room (around 196 Hz), the sound field surrounding each subject was relatively uniform (within 3 dB), and the overall levels at two work stations did not vary by more than 3 dBA on average. Note that equalizing the levels of all signals meant that they exhibited small changes in indoor noise criteria ratings across noise conditions as shown in Table 1.

RESULTS

Various statistical analyses have been used to evaluate the results. The independent variables were the six different noise conditions. The dependent variables were the task performance scores for three types of tasks (verbal, grammatical reasoning, and math) and the subjective ratings for the eight questions regarding acoustics. The statistical results from applying Pearson's Product Moment Correlations and repeated measures analysis of variance (ANOVA) with Bonferroni post hoc tests on the task performance scores and the subjective questionnaire responses are first presented.

Then these two groups of dependent variables are related through a further statistical method, linear mixed models, to investigate significant correlations between performance and perception. All of the statistical analyses were conducted in SPSS software. For more details on the statistical methods used, refer to Field and Hole (2003).

Some of the results of this study have previously been presented in Ryherd and Wang (2008). The current paper provides additional details, analyses, and results, including the following: analysis of an additional noise metric (loudness in sones), descriptive statistics for all dependent variables, correlations between the subjective perception ratings and responses, and relationships between criteria spectral quality ratings and subjective perception.

Task Performance Results

The descriptive statistics for the task performance results across all the test subjects and noise conditions are presented in Table 2. The reasoning test suffered from a restricted range; that is, the subjects scored quite high on that task, indicating that the task was not sufficiently difficult.

Table 1. Noise Conditions and their Corresponding Indoor Noise Criteria Ratings

Noise Condition Label and Description	NC	NCB	RC	RC-Mark II	L_{Aeq} (dBA)	Loudness (sones)
T1: Mid-level neutral	40	38 (N)	40 (N)	40 (HF), marginal	47	8.8
T2: 120 Hz tonal noise PR = 5	40	38 (N)	41 (N)	41 (HF), marginal	47	7.5
T3: 120 Hz tonal noise PR = 9	44	38 (R)	41 (N)	41 (HF), marginal	48	7.5
T4: 235 Hz tonal noise PR = 5	41	37 (H)	40 (N)	40 (HF), objectionable	46	7.0
T5: 235 Hz tonal noise PR = 9	42	37 (R,H)	41 (N)	41 (HF), objectionable	47	7.1
T6: 595 Hz tonal noise PR = 9	43	37 (R,H)	39 (H)	39 (N), acceptable	47	8.2

N = Neutral, R = Rumbly, H = Hissy, V = Vibrational, LF = excessive low frequency, MF = excessive mid frequency (roaring in character), and HF = excessive high frequency

Table 2. Descriptive Statistics for Task Performance Results, Averaged Across all Subjects and Noise Conditions

	Mean	Standard Deviation
Typing	47.4 wpm	15.4 wpm
Grammatical Reasoning	90.7% correct	14.2%
Math	76.4% correct	20.7%

A repeated measures analysis of variance (ANOVA) was conducted to determine if there was any significant effect of noise condition on task performance. Results indicate that noise conditions did not have a significant main effect on any of the three tasks. Figure 2 shows sample results of the typing task for each noise condition, averaged across all subjects; standard error of the mean bars are shown. Similar results were found for the other two tasks, leaving the conclusion that the sound signals with higher prominence ratios used in this study (T3, T5, T6) do not consistently result in significantly different task performance than the others.

Subjective Perception Results

The descriptive statistics for the subjective questionnaire responses to questions on acoustic conditions are presented in

Figure 3, averaged across all the test subjects and noise conditions. Six of these questions are linked to subjective *ratings* of the noise signal characteristics (loudness, rumble, roar, hiss, tones, and changes in time), while the remaining two are linked to subjective *responses* due to the noise (annoyance and distraction). Comparison of the descriptive statistics shows that the ratings for loudness, roar, and hiss have similar means and standard deviations. Similarly the evaluations for rumble, tones, and changes in time have similar means and standard deviations, as do the responses on annoyance and distraction.

Pearson Product Moment Correlation analysis was run among these dependent variables on subjective perception, resulting in correlation coefficients as listed in Table 3. Many of

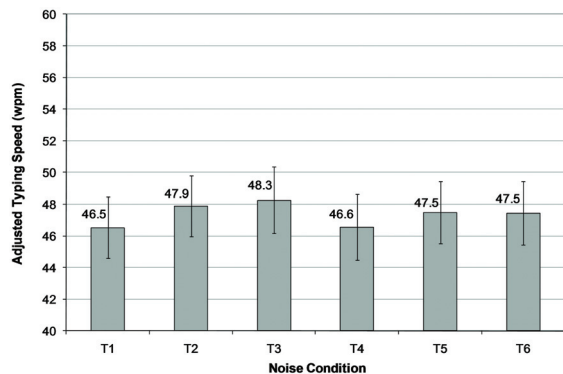


Figure 2 The adjusted typing speed in words per minute for each noise condition, averaged across all subjects. The bars represent the standard error of the means.

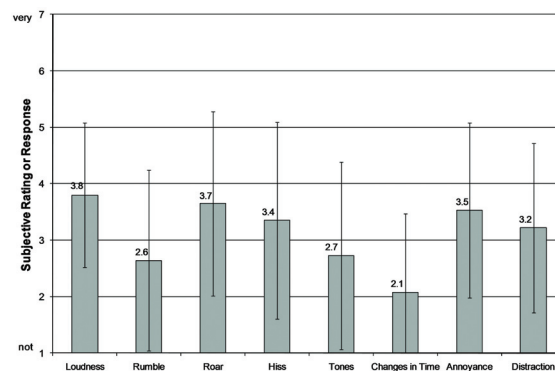


Figure 3 The descriptive statistics for the subjective questionnaire responses to questions on acoustic conditions, averaged across all test subjects and noise conditions. The bars represent standard deviation.

Table 3. Correlations Between the Subjective Perception Dependent Variables

	Loudness	Rumble	Roar	Hiss	Tones	Changes in Time	Annoyance	Distraction
Loudness	-	0.54**	0.57**	0.40**	0.51**	0.27**	0.77**	0.71**
Rumble		-	0.41**	0.41**	0.42**	0.24**	0.48**	0.44**
Roar			-	0.09	0.37**	0.26**	0.54**	0.44**
Hiss				-	0.37**	0.26**	0.40**	0.44**
Tones					-	0.55**	0.50**	0.47**
Changes in Time						-	0.32**	0.29**
Annoyance							-	0.86**

** indicates significance at $p < 0.01$ level

the variables were found to be significantly correlated at the $p < 0.01$ level.

The two subjective responses on annoyance and distraction had the highest correlation coefficient of 0.86. This indicates that when participants gave higher responses on annoyance, they commonly gave higher responses on distraction as well. The next highest correlations were found between the rating of loudness and both responses of annoyance (0.77) and distraction (0.71). Even though the loudness levels of the signals used in this investigation did not vary greatly, this result indicates that of the noise characteristics evaluated, loudness perception is still the most highly linked to annoyance and distraction responses.

The noise characteristic ratings that were next highly correlated to annoyance in terms of correlation coefficients were roar (0.54), tones (0.50), and rumble ratings (0.48). These characteristics were slightly less correlated to distraction responses, though: tones (0.47), roar (0.44), and rumble (0.44). The rating for changes in time showed the lowest correlation coefficients to annoyance (0.32) and distraction (0.29), as might be expected, since the signals in this phase of the ASHRAE 1322-RP research did not evidence a large degree of fluctuation. These results confirm that loudness perception is often the noise characteristic most significantly linked to annoyance/distraction, but also show that the next characteristics connected to annoyance/distraction perception in this study are the perceived amount of roar, rumble, and tones in the noise.

Next a repeated measures ANOVA was conducted to determine if there was any significant effect of noise condition on the questionnaire responses. Results show that there was a main effect of noise condition on loudness ratings ($F=3.40$, $p < 0.05$); participants did give different ratings on loudness

perception between the six signals. Bonferroni post hoc tests were run to highlight statistically significant differences between the six noise conditions, and show that signal T1 was rated as louder than signals T2 and T4, both of which have tones with $PR=5$ ($p < 0.05$). As Figure 4 indicates, the neutral and $PR=9$ noise conditions (T1, T3, T5, T6) also seem to be perceived as louder than the other two with $PR=5$. These perceptual ratings match well with the actual sound values for each signal, listed previously in Table 1.

ANOVA analysis also indicates that there was a main effect of noise condition on tonal ratings ($F=4.84$, $p < 0.01$); participants did perceive different degrees of tones in the six signals. Bonferroni post hoc tests show statistically significant differences as follows: (1) signal T3 was rated to be significantly more tonal than T4, and (2) signal T5 was rated to be significantly more tonal than T4 and T1. Figure 5 plots these results and shows that, as might be expected, noise conditions with $PR=9$ (T3, T5, T6) were generally perceived as more tonal than the other signals. However, signals T3 and T2 (both with 120 Hz tones but with different PR) were not found to be statistically different in tonal ratings, whereas T5 and T4 (both 235 Hz tones but with different PR) were; this lends further support to Hellweg Jr. and Nobile's results that lower frequencies should require a higher PR to be considered prominent (2002). The latest version of the ANSI S1.13 standard now reflects this (2005a).

The previous ANOVA results confirmed that subjects perceived differences in loudness and tones between the six test signals. ANOVA main effects of noise condition on annoyance ($F=2.57$, $p < 0.05$) and distraction ($F=2.32$, $p < 0.05$) responses were also found, indicating that the participants did respond with different degrees of annoyance and distraction to the six noise conditions. The post hoc tests demonstrate that

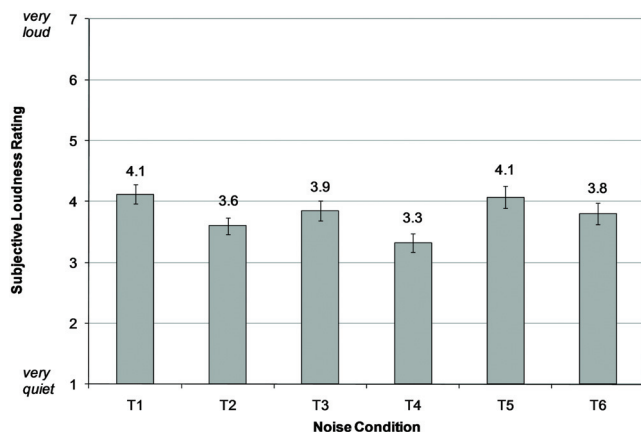


Figure 4 Subjective loudness ratings of the various noise conditions, averaged across all subjects. The bars represent the standard error of the means.

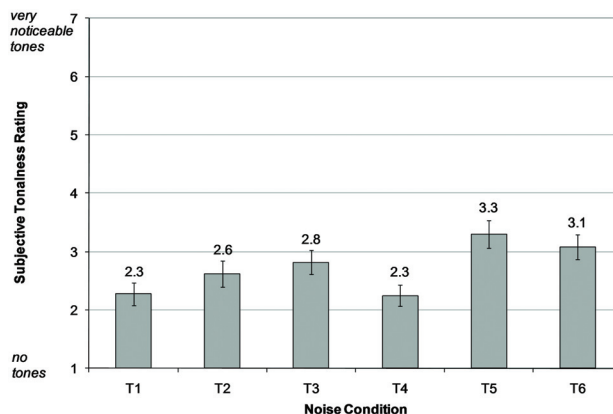


Figure 5 Subjective tonality ratings of the various noise conditions, averaged across all subjects. The bars represent the standard error of the means.

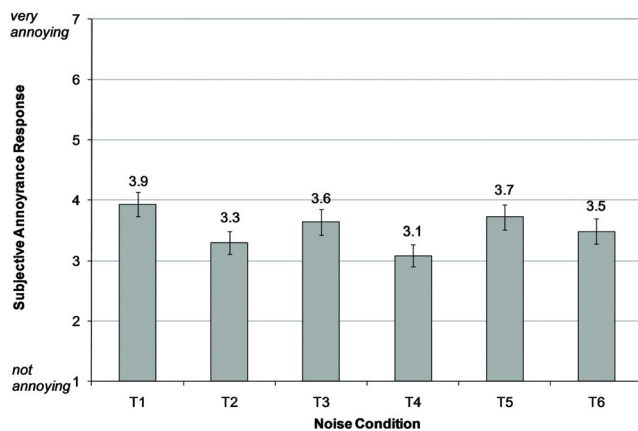


Figure 6 Subjective annoyance responses to the various noise conditions, averaged across all subjects. The bars represent the standard error of the means.

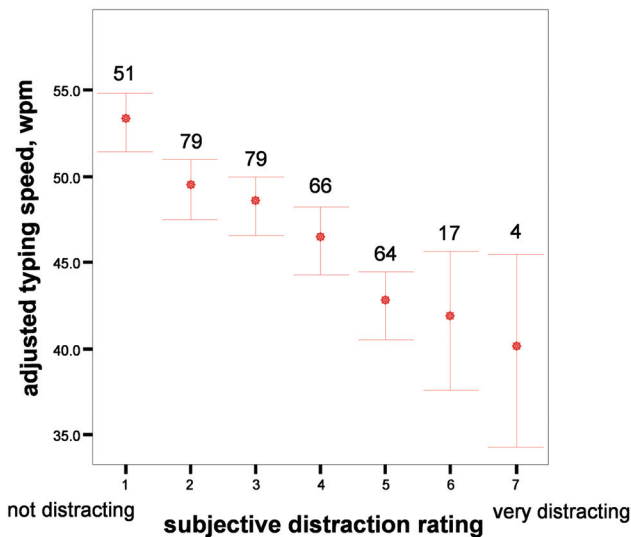


Figure 7 The average adjusted typing speed in words per minute at each subjective distraction response value. The bars represent standard error of the means. Numbers above the bars represent the number of observations out of 360 in which a participant gave this response to a noise condition.

only signal T1 was significantly found to be more annoying than signal T4, but the trend as shown in Figure 6 is that signals with the higher PR of 9 in this study were perceived as more annoying than the ones with PR of 5. The plot for distraction responses is similar. The fact that the tonal signals were not found to be more annoying or distracting than the 'neutral' T1 condition may be linked more to perception of loudness rather than tonalness. As Table 1 indicates, the signal T1 had the highest sone rating, which may have influenced the annoyance responses it generated, more so than its lack of tones.

Relationships between Task Performance and Subjective Perception

Previous research by the authors has indicated that task performance scores are often significantly linked to subjective perception ratings, even if they do not change in a statistically significant fashion with regards to noise conditions (Bowden and Wang 2005, Ryherd and Wang 2007). Such a relationship was statistically tested using a linear mixed model in SPSS. Results show that there are significant relationships between performance and perception. Typing scores decreased as subjects perceived the noise to be more rumbling ($F=13.52$, $p<0.01$), roaring ($F=5.21$, $p<0.05$), or changing in time ($F=3.81$, $p<0.05$) in character, and when they felt more annoyed ($F=14.19$, $p<0.01$) or distracted ($F=18.75$, $p<0.01$) by the sound. Figures 7 and 8 show examples of the typing scores in relation to distraction responses and rumble ratings. The average adjusted typing speed decreased from 53 wpm to 40 wpm (or 24%) with higher distraction responses, and less regularly from 52 wpm to a low of 34 wpm with higher rumble ratings. (Note that the number above each standard error of the mean bar in Figures 7-10 indicates the number out of 360 observations that some participant assigned that rating.)

Math and reasoning task performances, however, actually significantly improved with higher ratings of hiss or roar and only seemed to decrease somewhat with rumble ratings. Figure 9 shows the average math scores increasing from a low of 71% to a high of 85% with higher hiss ratings ($F=8.91$, $p<0.01$), while Figure 10 indicates average reasoning scores decreasing from 93% to a low of 84% with higher rumble ratings ($F=4.81$, $p<0.05$). The fact that a difference is found here between typing performance and math/reasoning performance is not unexpected, as the authors and others have previously found that the type of task can affect results since different neural processes occur in accomplishing the tasks (Hughes and Jones 2001, Landström 2004, Ryherd and Wang 2007); the typing task requires less cognitive thought than math/reasoning tasks. Low frequency rumble seems to be the only noise characteristic that generally produces lower scores for typing and math/reasoning performance, corroborating what has been found by other researchers (Leventhall et al. 2003). With other noise characteristics such as roar and hiss, it could be that subjects feel annoyed or distracted so performance on a routine task like typing degrades, but the increased annoyance or distraction may compel subjects to focus more

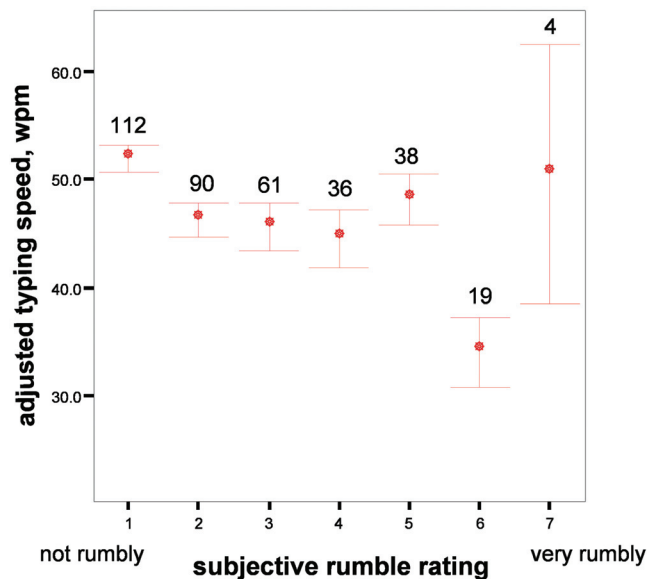


Figure 8 The average adjusted typing speed in words per minute at each subjective rumble rating value. The bars represent standard error of the means. Numbers above the bars represent the number of observations out of 360 in which a participant gave this rating to a noise condition.

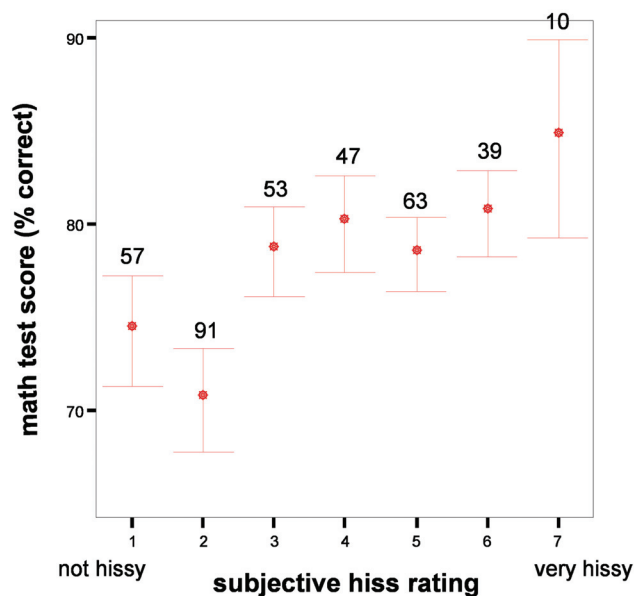


Figure 9 The average math score in percent correct at each subjective hiss rating value. The bars represent standard error of the means. Numbers above the bars represent that number of observations out of 360 in which a participant gave this rating to a noise condition.

when working on cognitive tasks like math/reasoning, resulting in better performance scores.

Relationships between Indoor Noise Criteria Ratings and Task Performance or Subjective Perception

Although the indoor noise criteria ratings listed in Table 1 do not vary widely across the six signals tested in this phase, one research question that this project sought to answer was: how well do indoor noise criteria ratings relate to task performance or subjective perception results? Linear mixed models were used to investigate these relationships.

None of the indoor noise criteria levels in Table 1 were found to be significantly related to task performance scores. However, some of the subjective perception ratings were captured by the objective indoor noise criteria. Both L_{Aeq} ($F=4.96, p<0.05$) and sones ($F=4.92, p<0.05$) were confirmed to be significantly related to loudness perception. That these two descriptors are most linked to differences in loudness perception from the list in Table 1 is not unexpected, even in this study where the levels of the noise conditions did not vary greatly. In terms of detecting tones, the NC method was the only one to be significantly related to subjective perception of tones ($F=7.46, p<0.01$). This result is logical, because NC is a tangency method so that a prominent tone in a particular

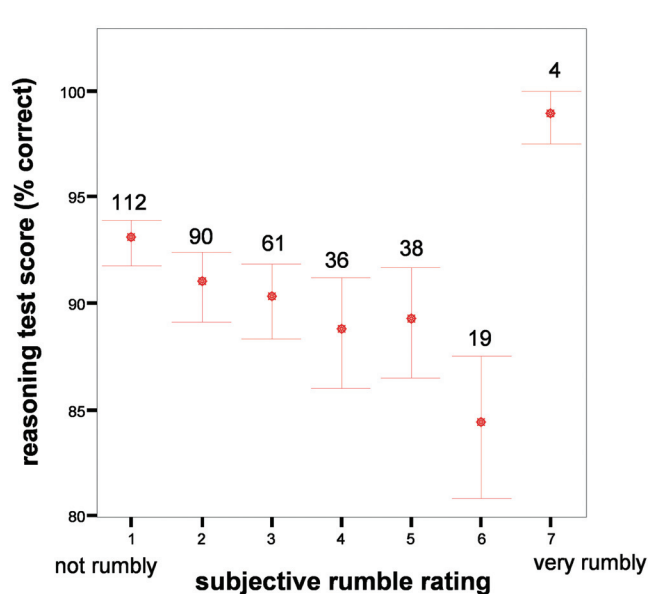


Figure 10 The average reasoning score in percent correct at each subjective rumble rating value. The bars represent standard error of the means. Numbers above the bars represent the number of observations out of 360 in which a participant gave this rating to a noise condition.

octave band would raise the NC value by raising the tangency point.

No significant relations were found between the spectral ratings provided by certain criteria (NCB, RC, and RC Mark II) and the subjective ratings of rumble, roar or hiss. However, Figures 11 and 12 show plots of the six noise conditions and their average subjective rumble and hiss ratings, respectively, averaged across all subjects. In examining Figure 11, NCB rated signals T3, T5 and T6 as rumbly, which does seem to reasonably follow the subjective ratings. RC and RC Mark II, however, rated none of these six as rumbly. In examining Figure 12, NCB rated signals T4, T5, and T6 as being hissy, which only matches perception of T6. Meanwhile, RC rated only signal T6 as hissy, while RC Mark II rated all others as having excessive high frequency. From this analysis, it appears that the RC Mark II spectral rating system does not do well with matching subjective perception, while the spectral ratings of the NCB and RC methodologies may be reasonably linked to perception.

DISCUSSION AND SUMMARY

The results of this project can help to answer two central questions, regarding noise characteristics of building mechanical systems, subjective perception, and task performance. The first is: which noise characteristics are linked to higher annoyance and distraction responses? Among the noise characteristics surveyed, it was found that loudness perception is most closely linked to annoyance/distraction, followed by the perception of roar, rumble and tones in the noise. (Recall that annoyance and distraction responses were highly correlated in this study.) Consequently, in designing commercial office buildings, the degree of loudness, roar, rumble and tones in the background noise should be minimized to optimize worker

comfort. Particularly with regards to tones, certain signals with tones of PR=9 were generally perceived in this project as more annoying than those of PR=5, but more research should be conducted to investigate a wider range of tonal prominence ratios across different frequencies.

The second question is: which noise characteristics are linked to lower task performance scores? While none of the typing or math/reasoning scores were found in this study to be statistically related to the degree of tonalness in the noise conditions, there was indication that signals perceived to be more rumbly generally produced lower performance on typing and math/reasoning tasks. This finding further supports the fact that the degree of low frequency rumble should be minimized in background noise conditions of offices, not only for occupant comfort but also for improved performance. Furthermore, statistically significant relationships were found between higher annoyance/distraction responses and lower typing performance, so reducing occupant annoyance/distraction by reducing the other perceived characteristics of loudness, roar, and tones, may have additional benefits on performance.

In general, the currently used indoor noise criteria listed in Table 1 do not significantly relate to task performance scores. Subjectively, some of the criteria do well in rating loudness perception, and only one (NC) seems to respond to increasing tonal prominence, but spectral quality ratings of rumble, roar, hiss are not as consistent. Results from this phase of research have been considered with those from a subsequent phase of ASHRAE 1322-RP, involving building mechanical system noise with time-varying fluctuations, to assist in determining what components make up an 'ideal' indoor noise criteria method – one that matches human perception and links to human performance for a broad range of mechanical system

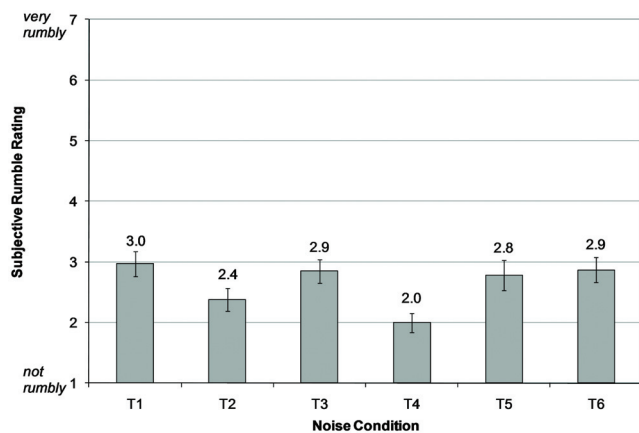


Figure 11 Subjective rumble ratings of the various noise conditions, averaged across all subjects. The bars represent the standard error of the means.

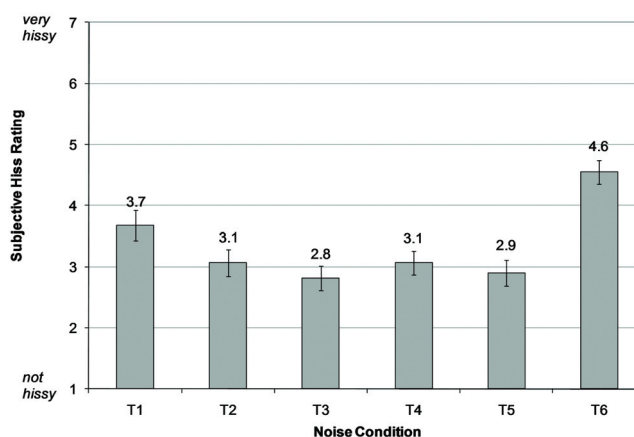


Figure 12 Subjective hiss ratings of the various noise conditions, averaged across all subjects. The bars represent the standard error of the means.

noise conditions in buildings. Readers are referred to the other manuscript for further detailed discussion.

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