Assessment of noise-induced annoyance by tones in noise from building mechanical systems

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ABSTRACT

Prominent tones in noise generated by mechanical equipment in buildings can cause complaints from occupants in buildings. The ISO 1996-2 and ANSI S1.13 standards describe methodologies and metrics to quantify tonality perception, but the influence of tones in noise on human annoyance and performance is not fully understood yet. This paper investigates annoyance responses of humans while exposed to background noise with tonal components. Twenty participants completed digit span tasks while exposed to noise signals with differing levels of tones and overall loudness. Subjects were also asked to rate their annoyance after completing tasks under each noise signal. The subjective testing was carried out in the indoor acoustic testing chamber at the University of Nebraska. A dose-response model is investigated to predict the upper limits of acceptability for tonalness using assorted noise metrics.

Keywords: Annoyance, tonality, building mechanical noise I-INCE Classification of Subjects Number(s): 63.2, 63.5

1. INTRODUCTION

Mechanical systems in buildings are adopting more energy-efficient technologies to fulfill current demands towards greater sustainability, but less attention is being directed to the increasingly tonal sound quality of the noise generated by such equipment. Building mechanical equipment often generates prominent tones because most systems include rotating parts like fans and pumps. These tonal noises can cause unpleasant user experiences in spaces and, in turn, lead to increased complaints by building occupants. However, existing noise guidelines for buildings do not typically cover tonal characteristics of noises. This paper aims to investigate effects of tonal background noises on human annoyance perception. Also, this paper examines the relation between associated tonal noise metrics and annoyance. The end goal of the study is to propose upper limits of acceptability for tonality in buildings.

Noise induced annoyance may be defined as “one person’s individual adverse reaction to noise in various way including dissatisfaction, bother, annoyance and disturbance” in ISO/TS 15666 (1). A considerable amount of literature has been published on subjective annoyance perception of tones in noise. More et al. (2) examined the effects of tones in aircraft noise on human annoyance perception and found that subjective loudness and tonality both influenced overall annoyance ratings. Ryherd et al. (3) investigated ventilation-type mechanical noise and showed that current indoor noise criteria were not accurately reflecting subjective annoyance perception because of excluding tonal characteristics of noises for assessment. Besides laboratory studies, Landström et al. (4) explored noise levels in actual working spaces and perceived annoyance by occupants. He found that the relation between noise levels and annoyance was weak, but annoyance ratings were significantly increased when tones were present in noises. None of the previous studies proposed allowable levels of tones in terms of annoyance perception in their studies.

It is generally agreed that annoyance perception may be influenced by noise signal characteristics, the context of measurement, and personal attributes. In this study, the noise signal characteristics that are varied include loudness and tonality. The context remains the same throughout the laboratory

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study, and among the personal attributes that are considered are the participant's noise sensitivity.

2. SUBJECTIVE TESTING

2.1 Noise Signals

A total of 40 tonal signals were generated for use in subjective testing. Five levels of tones at four specific frequencies of 125, 250, 500, 1 kHz were added separately to broadband background noise signals. Two different background noise spectra were used, complying with RC-30 and RC-38 neutral contours. A neutral spectrum was selected to eliminate other subjective spectral impressions other than from the tonal frequencies. The tonal levels were adjusted from barely observed to prominent for each frequency.

2.2 Test Procedure

The subjective tests took place in an indoor acoustic testing chamber at the University of Nebraska. Figure 1 illustrates a schematic plan of the test chamber, which had a volume of approximately 27.8 m^3. The room is acoustically isolated from nearby spaces. Materials in the room include carpet on the floor, gypsum board walls with additional absorptive panels, acoustic bass traps, and acoustical ceiling tiles. The mid-frequency reverberation time is 0.31 seconds, and the lowest ambient background noise level is 32 dBA. Signals were generated through a ceiling-mounted Armstrong i-ceiling speaker and a sub-woofer in a corner. The i-ceiling speaker looks identical to the other ceiling tiles so that participants could not visually identify the location of this sound source. Participants sat on the middle of the chamber during tasks. Twenty participants (9 females, 11 males) were recruited for the test using fliers distributed on the university campus. The average age of all participants was 25 years. Most participants were university students or staff members. All participants took an orientation session including a hearing screen test to confirm that they had hearing thresholds below 25 dB HL from 125 Hz to 8 kHz before completing the main tests.

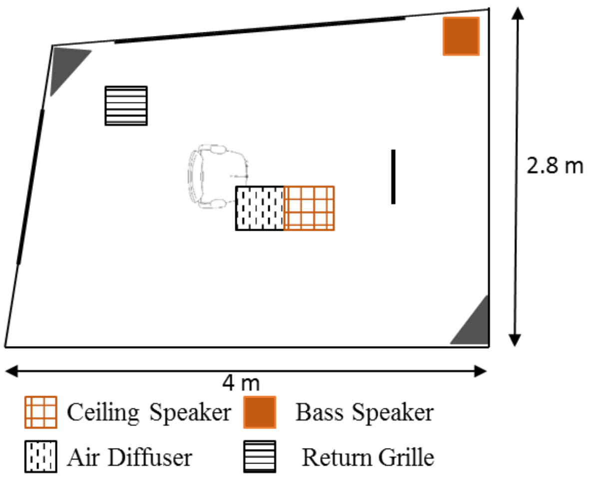
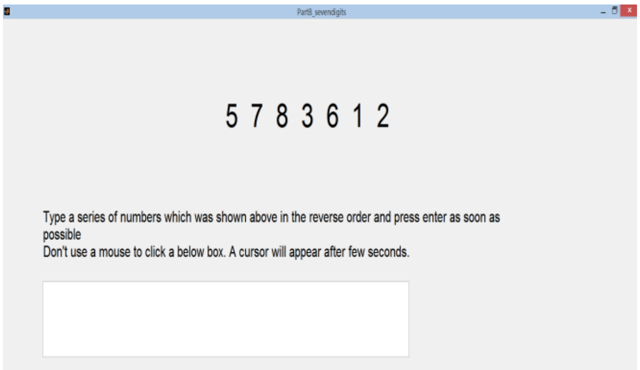


Figure 1 – Schematic plan of Nebraska Acoustic Test Chamber

The main test consisted of five individual sessions, each including ten trials. During each session, participants were asked to perform digit span tasks in which they memorized a series of numbers in the reverse order of presentation while exposed to assorted tonal signals. The digit span task is a measure of working memory commonly used in psychology experiments. For each trial under a particular tonal noise, the length of each digit span task increased from 4 digits up to 8 digits over a duration of approximately 3 minutes. The task was administrated by a custom-coded Matlab GUI program. The program measured accuracy of answers and reaction time of responses. After each trial, the participants were asked to fill out a subjective questionnaire with 2 items: how annoyed they were by the noise, and whether or not they would complain about the noise. The annoyance question was answered on an 11-point scale, and the complaint question was dichotomous choice. Figure 2 shows the computer program display of the digit span task and subjective questionnaire. Trials using only

RC-30 neutral background noise were inserted between trials with tonal noise conditions to eliminate back-to-back comparisons of tonal noise conditions. The order of tonal noise signals was randomized for all participants.

(a)



(b)

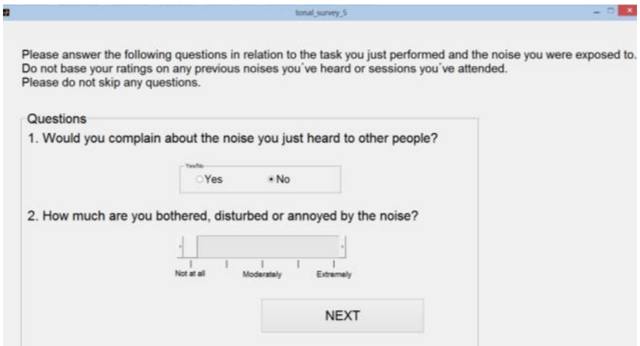


Figure 2 – Subjective test display implemented by MATLAB GUI of (a) digit span task and (b) subjective questionnaire

2.3 Noise Metrics

In this study, a number of metrics are studied that have been developed to quantify the perception of tonality in noises. ANSI S1.13 (5) introduced Tone-to-Noise Ratio [TNR] and Prominence Ratio [PR] to quantify tonality of tones in noise. Similarly, ISO 1996-2 (6) introduced Tonal Audibility [ΔL_{ta}]. A difference between these ISO and ANSI tonality metrics is that prominence of tones is frequency dependent for TNR and PR ratings but not for ΔL_{ta}. Widely used loudness metrics were also investigated in this study because previous studies have indicated that loudness is often the most relevant signal feature related to annoyance perception. Loudness levels were calculated according to ANSI S3.4 (7) [ANSI Loudness] and ISO 532B (8) [ISO Loudness]. A-weighted [dBA] and un-weighted [dB] sound pressure level were also calculated. There are a few noise metrics that take both loudness and tonality into account in an overall rating, primarily by adding penalty values based on tonality to the loudness level. The Joint Nordic Method [dBA+k] is standardized in ISO 1996-2, where penalty k values derived from Tonal Audibility are added to A-weighted sound pressure level. The Tone Corrected Perceived Noise Level [PNLT] was implemented to quantify subjective annoyance to aircraft noise based on one-third octave band sound pressure levels (9). Sound quality indicator [SQI] was similarly implemented by AHRI to rate building mechanical product noise that contains tones (10).

All tonal signals in the investigation were measured using a B&K 4189-A microphone through the PULSE system at the listener’s ear position in the test chamber. The measurement was averaged over a minute for calculation of noise metrics. All noise metrics mentioned above were calculated in MATLAB or a program provided from the associated standards.

3. Results and Discussions

3.1 Noise Metrics Relations with Annoyance

Spearman's nonparametric correlation coefficients were calculated between all noise metrics and participants' annoyance responses. Two subjects' responses were excluded in this analysis because they submitted the same minimum rating across all signals. The results are analyzed in three groups: first with all signals included, and then with each background noise level separately (RC-30 and RC-38) (Table 1). ANSI Loudness level shows the highest correlation coefficients with annoyance ratings across all signals. When separating signals into the two background noise levels, though, tonality metrics show higher correlation with annoyance perception than loudness levels, as may be expected. Among tonality metrics, Tonal Audibility demonstrates better correlation than Tone-to-Noise Ratio and Prominence Ratio. The results of this analysis indicate that loudness is the most important feature of noise to predict annoyance perception, and tonality of noise also should be included for the annoyance model, especially when background noise levels are kept constant. Combined metrics such as the Joint Nordic Method and Tone Corrected Perceived Noise Level and Sound Quality Indicator did not show better performance than loudness metrics, even though they were significantly related with annoyance ratings. The results imply that imposing penalty values to loudness levels may not be the most effective way to quantify overall annoyance of the noise, but rather both tonality and loudness of noises should be considered via separate metrics.

Table 1 – Nonparametric Spearman correlation coefficients table between noise metrics and annoyance perception (**p<0.01, *p< 0.05)

	PR	TNR	ΔL_{ta}	dB	dBA	ANSI Loudness	ISO Loudness	PNLT	dBA+k	SQI
All	.105**	.119**	.157**	.485**	.539**	.570**	.557**	.530**	.532**	.536**
RC-30N	.169**	.212**	.246**	.050	.220**	.246**	.214**	.207**	.241**	.215**
RC-38N	.129*	.179**	.184**	.062	.124*	.178**	.149**	.138*	.133*	.111*

3.2 Dose-Response Model

A dose-response model was developed from the gathered complaint responses to determine thresholds of acceptability for tonality, using a binary logistic regression model with ANSI Loudness Level and Tonal Audibility metrics. The logistic regression equation is given by:

$$\%\ \text{Complain} = \frac{1}{1 + e^{20.354 - 0.294[ANSI\ Loudness\ Level] - 0.04[\Delta \text{Lta}]}} \qquad (1)$$

in which % complain is the percentage of possibility that complaints would be lodged against a particular tonal noise condition. Table 2 presents coefficient values, bootstrap confidence intervals of two prediction variables. The two noise metrics were used because they showed best correlations with annoyance perceptions. Both predictors significantly improve the model fit to complaint responses based on chi-square statistics. The model yielded a chi-square (χ^2) of 189.00, which is highly significant, $p < .001$. The accuracy of prediction by the model for observed responses was 76.4%. Figure 3 illustrates the logistic regression line with actual responses.

Table 2 – Coefficients of the logistic regression model predicting whether a participant would complain

	b	95% BCa bootstrap confidence intervals	
Constant	-20.354	-24.694	-17.398
ANSI Loudness Level (phon)	.294	.248	.357
ΔL_{ta} (dB)	.040	.000	.081

Note. Model $\chi^2(2)=189.00$, $p<0.001$

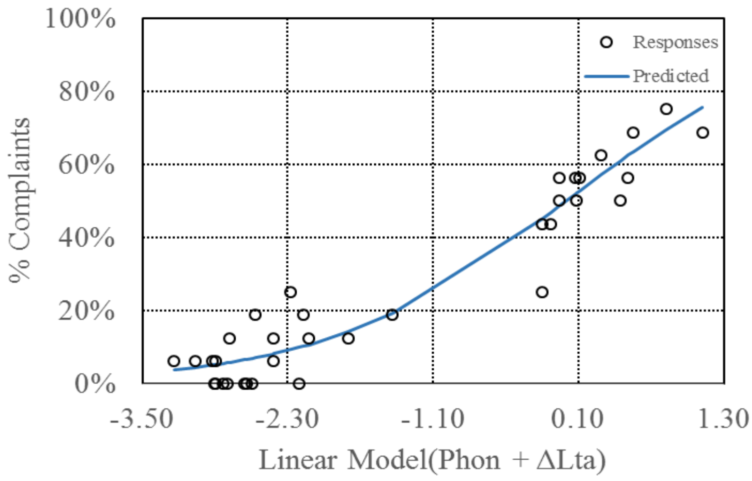


Figure 3 – Dose response model of % of persons lodging complaints with a linear model of ANSI loudness level and Tonal Audibility

3.3 Thresholds of Tonal Components in Noise

To suggest allowable tonality in background noise, the points at which 40%, 50% or 60% of possibility of complaints were set to determine maximum Tonal Audibility. From the logistic regression model introduced above, allowable Tonal Audibility is plotted in Figure 4 according to given background noise loudness levels in phons. The lines in the graph demonstrate that the thresholds of acceptable tonality decrease as overall background noise level increases. The results mean that low levels of tonal components can significantly increase annoyance rating when the overall noise signal is loud.

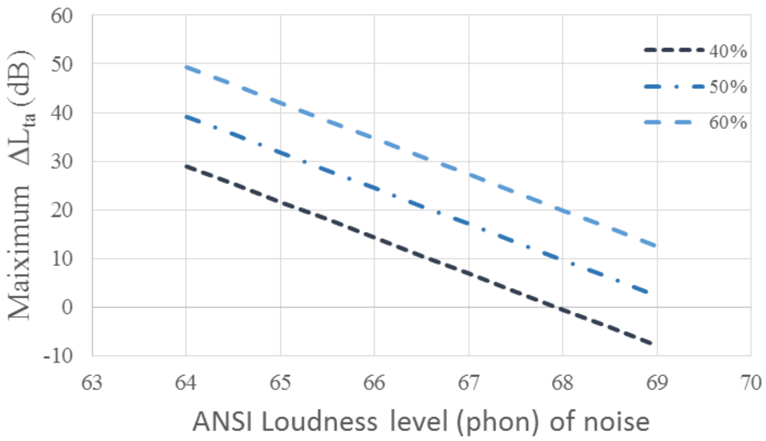


Figure 4 - Maximum allowable Tonal Audibility criteria for given loudness levels

4. CONCLUSIONS

This paper has investigated the relation between tonal noise metrics and human annoyance perception. Subjective testing in a controlled laboratory results has been conducted with assorted tonal noise signals. The results show that loudness and tonality both have a significant influence on noise-induced annoyance. Furthermore, ANSI Loudness Level and Tonal Audibility are the most reliable metrics to reflect human annoyance perception among the investigated noise metrics. A dose-response model using these two metrics was developed in this paper to predict the % of persons lodging complaints when tonality and loudness are both considered. Suggested threshold values of Tonal Audibility are presented for given background noise levels. The results show that maximum allowable tonal components decrease when background noise level is high.

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