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Determining Annoyance Thresholds of Tones in Noise

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ABSTRACT

Building services equipment often produces noise signatures with significant tones in them that can lead to complaints in the built environment. Previous studies have investigated prominence levels of assorted tonal frequencies, but it is still unclear what prominence of the tones across varying tonal frequencies can lead to human annoyance. This project seeks to apply two different methods towards defining annoyance thresholds of tones in noise at two tonal frequencies: 125 Hz and 500 Hz. In the first, subjects are asked to perform a task, while exposed to ten minutes of a broadband noise spectrum with a specific level of tonal prominence. They are subsequently asked to rate their annoyance to that noise condition. Five prominence levels of each of the two tones are tested above two different background noise levels, for a total of 20 test trials. In the second methodology, subjects listen to each of the two tonal frequencies at a predetermined level above each of the two background noise levels, and then adjust the level of the tone up or down until it becomes just annoying. The strengths, weaknesses, and results obtained for the annoyance thresholds of tones in noise from each of these methods are compared.

INTRODUCTION

Modern building mechanical systems often produce noise with perceptible tonal components due to rotating parts such as motors, fans, impellers, etc. Such tonal noise can lead to discomfort and subsequent complaints from those in the built environment and surrounding communities. Additionally the current push towards more efficient design of building services equipment often results in the equipment producing louder and more prominent tones, according to HVAC equipment manufacturers. Noise criteria guidelines for designing building mechanical systems can be found in Chapter 48 of the ASHRAE HVAC Applications Handbook (2011); however, these criteria do not apply well if the noise contains prominent tones. (The tables with these guidelines specifically note that it is assumed that no tones are present in the noise.) At this time, sufficient data are not available to provide further guidance on acceptable levels of tones in noise. This paper discusses a recent study aimed at determining the annoyance thresholds of humans with regards to the degree of tonalness in noise.

Previous Research

Tones in noise, and more specifically human perception of tones in noise, have generated much interest over the years as there are many sources (aircraft, industrial machinery, computers and other office equipment) that generate this type of spectra. With the development of jet engines in the 1960's, much research was done relating human annoyance to

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perceptible tones in aircraft noise (Little 1961, Kryter and Pearsons 1965, Little and Mabry 1969). Results from these studies led to the development of a tonal noise correction factor to be added to the metric that had been used to quantify human perception to aircraft noise, Perceived Noise Level (PNL). In the 1980's, Hellman conducted a number of studies on perception to noise containing tones and found that tones in noise do impact ratings of annoyance, loudness and noisiness. She also determined that the frequency of the tone as well as the number of prominent tones affects annoyance (Hellman 1982, 1984, 1985).

Ventilation-like noise spectra that specifically include tones have also been utilized in a number of investigations involving human perception or performance, but in most studies, only six or less signals were compared which is not enough to be able to specify an annoyance threshold. Results indicate that the presence of tones can impact perception or performance (Landström et al. 1991, 1993, 1994; Holmberg et al. 1993; Ryherd and Wang 2010), but none of the investigations could provide guidelines for what the threshold of annoyance for tones in noise should be across a wide range of tonal frequencies. Further work is required to link the degree of tonalness in noise to human annoyance thresholds.

Tonal Metrics

A number of methods for quantifying the prominence of tones in noise have been developed. Annex A in ANSI S1.13-2005 describes two of these metrics: Tone-to-Noise Ratio (TNR) and Prominence Ratio (PR). Tone-to-Noise Ratio is the ratio of the power contained in the tone to the power contained in the critical band centered on the tone but not including the tone, while Prominence Ratio is the ratio of the power contained in the critical band centered on the tone to the average power of the two adjacent critical bands, above and below the critical band containing the tone.

A round robin test was conducted to compare these two metrics (Balant et al. 1999, Hellweg and Nobile 2002); results show 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. How the metrics can be applied to noise with more complex tonal components (e.g. multiple tones in the same critical band, harmonic series of tones, or time-varying tones) is not altogether clear. Some previous work has focused on these more complex cases (Hellman 1985; Hastings et al. 2003, Lee et al. 2004, 2005), particularly on how the tonal additions affect the perceived loudness of the acoustic signal, but none has directly sought to determine the human thresholds of annoyance for tones in noise.

The recent revision of ANSI S1.13 in 2005 includes the work of Hellweg and Nobile (2002), listing the thresholds of tonal prominence for tonal frequencies less than 1000 Hz to range between PR's of 9 dB (at 1000 Hz) and 19 dB (at 100 Hz). Hellweg and Nobile's study, though, was limited in that they extrapolated their findings based on testing only two tonal frequencies (250 Hz and 1000 Hz). Furthermore, their subjective questionnaires focused on the perception of 'prominence' rather than annoyance. The study described in this paper aims to determine thresholds of annoyance to noise containing tones of different frequencies and tonal levels using two different methods; PR is used as the metric for quantifying the degree of tonalness in this study, so that the results may be compared with thresholds of tonal prominence as listed in ANSI S1.13.

METHODOLOGY

Subjects and Test Chamber

Ten subjects (4 female and 6 male) participated in this study. Subjects ranged in age from 25 to 43 with an average age of 31. All subjects underwent a hearing screen to ensure they had hearing thresholds below 25 dB hearing level (HL) from 125 Hz to 8 kHz. Testing was completed in the Acoustic Testing Chamber at the University of Nebraska. The testing chamber is approximately 983 ft^3 (27.8 m^3) and is acoustically isolated from the nearby spaces. Materials in the room include carpeting, gypsum board walls with additional absorptive panels mounted, acoustic bass traps in three corners, and acoustical ceiling tiles. The mid frequency reverberation time is 0.31 seconds, and the lowest achievable ambient background noise level in the space is 37dBA.

Experimental Procedure

Two different methods were used to explore human annoyance due to tonal noise. For Method I (direct assessment with task), subjects were asked to complete Sudoku puzzles while exposed to broadband noise with a tonal component set at a specific level above the noise. They were then asked to complete a subjective rating questionnaire on the noise they had just experienced. For Method II (a magnitude adjustment methodology), subjects were asked to listen to broadband noise with a tonal component and adjust the level of the tone in the signal until it became just annoying. Altogether, the full study consisted of twelve thirty minute sessions including one orientation session, ten sessions of the direct assessment part, and one session of the magnitude adjustment part. All subjects completed the sessions in this order, although the presentation order of signals within each method was randomized across the participants.

For Method I (direct assessment with task), five levels of two tonal frequencies (125 Hz and 500 Hz) were tested above two different background noise levels (40 dBA and 55 dBA, with spectra roughly following RC contours of RC-25 and RC-40 respectively) for a total of 20 test signals. Table 1 shows the prominence ratio values that were used for each tonal frequency and background noise level condition; a bolded PR value indicates the prominence for that tone, as defined by ANSI S1.13. Within one thirty minute test session, a participant was exposed to three different signals for ten minutes each. The first and third signal in each session consisted of broadband noise with a tonal component while the second signal was the same broadband noise without a tone; the background noise level of the signals remained at a constant level throughout a single thirty minute test session. The order of presentation of the background noise levels and particular tonal signals was randomized using a Latin square design. Subjects completed as many Sudoku puzzles as possible while being exposed to each signal for nine minutes, and used the remaining minute to fill out a short 5-question subjective questionnaire before the signal was changed; these steps were repeated twice more during each thirty minute session. Sudoku is a logic-based, number-placement puzzle; this was chosen as the task so that subjects would be mentally engaged in an activity while being exposed to the different signals. The difficulty of the Sudoku puzzles was held constant throughout all ten sessions. The questionnaire that was used is shown in Figure 1; all questions were answered on a 21-point scale.

Table 1. Prominence Ratios of the Signals Used in Method I for the Assorted Tonal Frequency and Background Noise Conditions

Frequency	**125 Hz**		**500 Hz**	
BNL	**40 dBA**	**55 dBA**	**40 dBA**	**55 dBA**
PR	15	13	9	6
	18	15	**12**	9
	21	**18**	15	**12**
	24	21	18	15
	27	24	21	18

For Method II (magnitude adjustment), participants were exposed to a signal that consisted of a tone set at a certain level above broadband noise, and were then asked to adjust the signal by clicking either a plus or minus button on the screen until it became just annoying. Adjusting the signal changed the magnitude of the level of the tone only; however the subjects were not explicitly told what aspect of the signal they were adjusting. The same two frequencies (125 Hz and 500 Hz) and two background noise levels (40 dBA and 55 dBA) were tested for a total of 4 conditions, which were repeated once during the session; so subjects participated in 8 trials total in this test, with the specific presentation order randomized across all subjects.

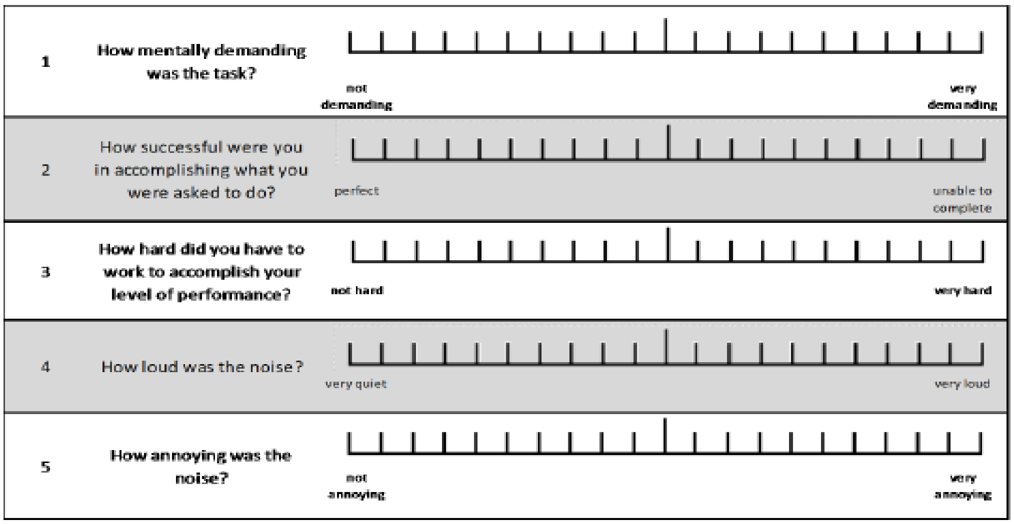

Figure 1 *The subjective questionnaire on a 21-point-scale used in Method I.*

RESULTS

Method I: Direct Assessment with Task

The data for the direct assessment with task portion of this study came from the subjective questionnaires that were filled out after each noise exposure. Repeated measures analysis of variance (ANOVA) was used to determine if there were statistically significant differences in average ratings among the assorted background noise level, tonal frequency, and prominence level conditions. There were no significant differences in ratings for the first three questions on the questionnaire. However, there were significant differences in group means for the ratings on the last two questions of the questionnaire: how loud was the noise and how annoying was the noise. Loudness ratings and annoyance ratings correlated well with each other ($r = 0.836$, $p < 0.01$).

To determine a possible threshold of annoyance, repeated measures ANOVA was used to determine if the annoyance ratings of the background noise signals alone were different from the ratings of the background noise with the tones. Each subject was exposed to the two background noise only signals (40 dBA and 55 dBA) a total of five times each. The annoyance ratings provided during each of these exposures for each background noise level were averaged for each subject to obtain the values that were compared to the annoyance ratings of the noise with the tones. Figure 2 shows average annoyance ratings for the background noise only, as well as for the noise with tones; these are further interpreted in each column of Table 2, where the double asterisk indicates those PR conditions where the average annoyance ratings collected are statistically found to be significantly different than the average annoyance ratings for the background noise only. The lowest PR condition with a double asterisk in each column could be interpreted then as a threshold of annoyance for that noise condition.

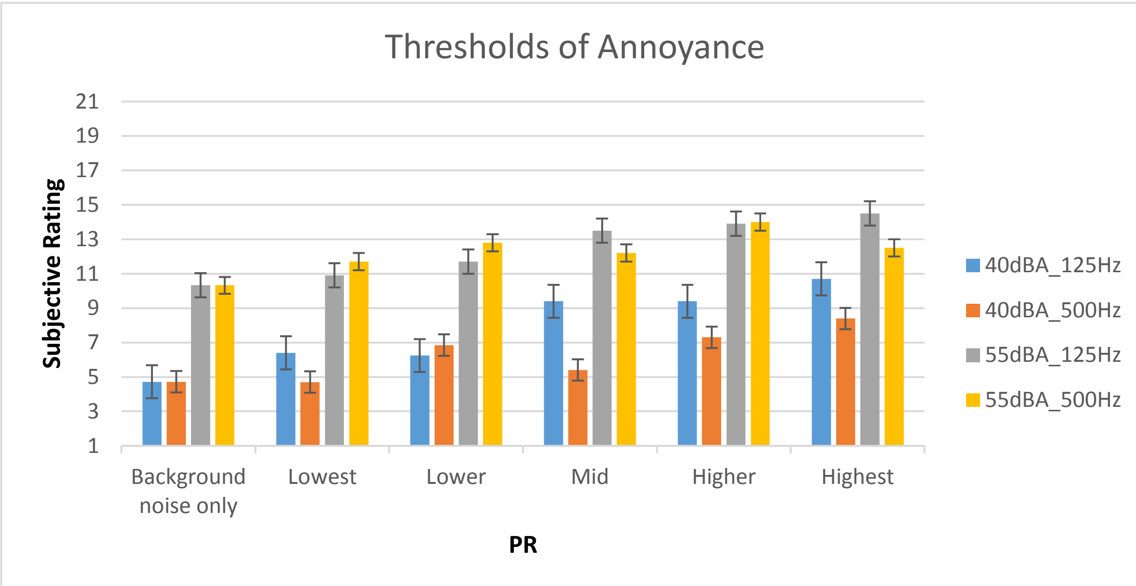

Figure 2 *Comparison of subjective annoyance ratings of the tonal signals to background noise only. The x-axis is related to the level of the tone and the y-axis is the subjective rating from not annoying (1) to very annoying (21). Error bars represent the standard error of the mean.*

Table 2. Results from Comparing Average Annoyance Ratings of Background Noise Only to Noise with Tones

Frequency	**125 Hz**		**500 Hz**	
BNL	**40 dBA**	**55 dBA**	**40 dBA**	**55 dBA**
PR	15	13	9	6
	18	15	**12**	9**
	21**	**18****	15	**12****
	24**	21**	18**	15**
	27**	24**	21**	18**

The data in Figure 2 and Table 2 indicate that for the 125 Hz tone above 40 dBA background noise, there were no differences in the annoyance ratings of the background noise only and the two lowest tone levels (PR=15 and 18). There were significant differences in the ratings of the 40 dBA background noise and the three highest tone levels (PR=21, 24, and 27); so a possible annoyance threshold for 125 Hz tones would be right above the threshold of prominence (PR 18) around a PR of 21 . For the same frequency above the 55 dBA background noise level, though, there were no significant differences found between the annoyance ratings for the background noise only and the two lowest tone levels (PR=13 and 15). There were significant differences between the annoyance ratings for the background noise and the three highest tone levels (PR=18, 21, and 24). Note that in this case, the possible annoyance threshold for the same frequency is lower and closer to the threshold of tonal prominence for this tonal frequency (around PR of 18) than in the previous case, likely due to the increased absolute level of the background noise and tone.

No significant differences were found in the average annoyance ratings for the 40 dBA background noise level and the first three levels of the 500 Hz tone (PR=9, 12, and 15). There were significant differences in the annoyance rating for the background noise only and the two highest tone levels (PR=18 and 21); so a possible annoyance threshold for 500 Hz tones would be above the threshold of prominence (PR 12) around a PR of 18. For the same frequency above the 55 dBA background noise level, there were no significant differences found between the annoyance ratings for the 55 dBA background noise level and the lowest level of the 500 Hz tone (PR=6). However, there were significant differences between the background noise only ratings and the four highest levels of tones (PR=9, 12, 15, and 18). In this case, the possible annoyance threshold for the 500 Hz tone above the louder background noise level is lower and even below the threshold of tonal prominence listed in ANSI S1.13 (around PR of 9) than in the previous case with 40 dBA background noise, again likely due to the increased absolute level of the background noise and tone.

In summary for Method I, if a statistically significant difference between annoyance ratings of the background noise only and the rating of the same noise plus a tone may be considered to be a threshold of annoyance for tones in noise, then the thresholds are found here to be slightly above the thresholds of prominence listed in ANSI S1.13 at lower background noise levels. Annoyance thresholds for a certain tonal frequency appear to be even lower, though, when the same tonal PR is coupled with a louder background noise condition.

Method II: Magnitude Adjustment

For Method II, subjects adjusted the signal until they selected one to be just annoying, or at a threshold of annoyance. Figure 3 shows the signals that were selected as being just annoying for each of the four background noise level and tone combinations. Data from one subject was dropped for this analysis as this subject chose the lowest PR each time. Results from the remaining subjects were fairly consistent with most subjects choosing the same PR, or close to it, both times they were exposed to that particular BNL and tone condition. All selections across the 9 remaining subjects were averaged to determine an average threshold of annoyance for each tonal frequency and background noise level combination; these are marked in Figure 3 and summarized in Table 3. For the 125 Hz tone above the 40 dBA background noise level, the average PR that was determined to be just annoying was 20. For the same tone above the 55 dBA background noise level, the average PR was found to be lower (PR 15), similar to results from Method I although the threshold PR values do not match well for the louder background noise level case. The 500 Hz tone above the 40 dBA background noise level shows an average threshold of annoyance of PR 16. The average PR that was just annoying for the same tone above the louder background noise level was lower in value again, at 11. These results are again similar to those from Method I, although the exact PR threshold values do not match as well for the louder background noise level case.

In summary for Method II, the average PR selected to be just annoying for each background noise level and tonal frequency condition tested was generally below the listed thresholds of prominence in ANSI S1.13 for the louder background noise level and above prominence for the quieter level. This indicates that background noise level does in fact affect perceptions of annoyance, so that a single PR should not be taken as the threshold of annoyance for a certain tonal frequency; both the tonal frequency and the overall background noise level must be accounted for.

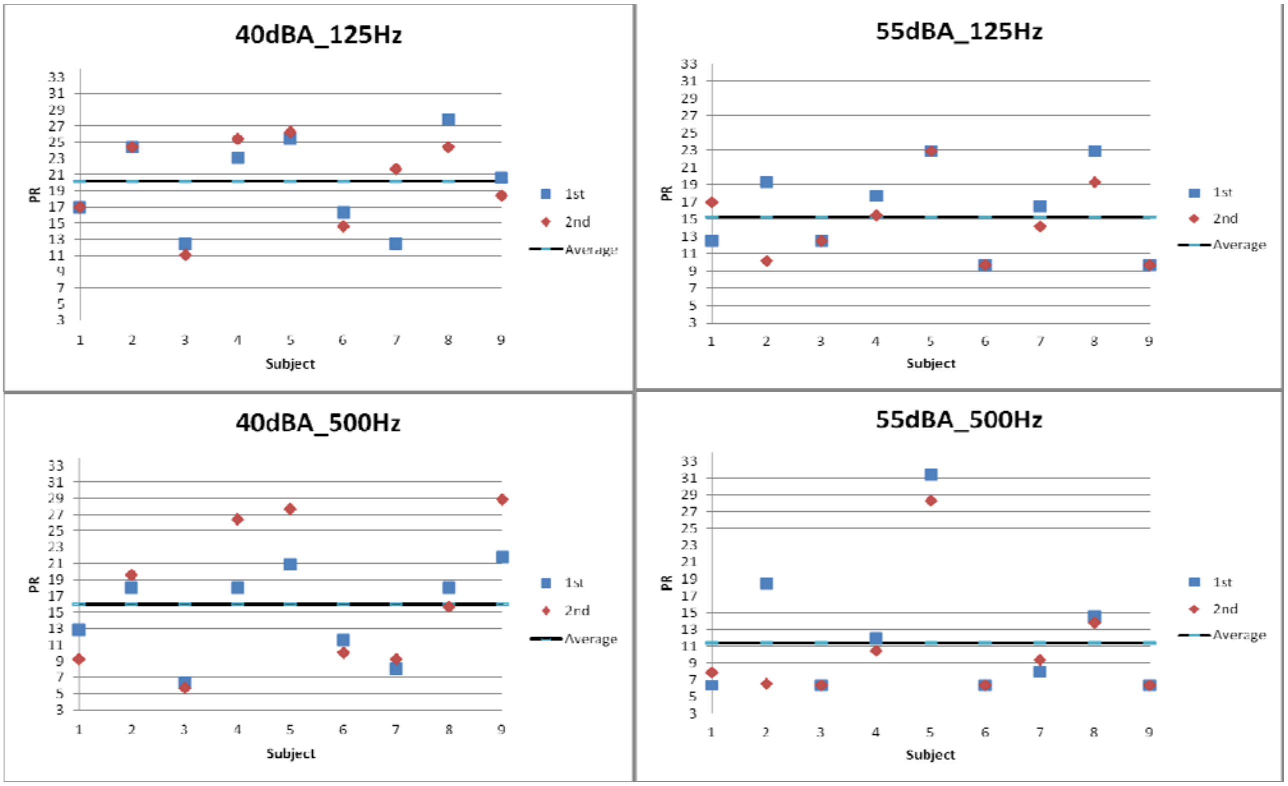

Figure 3 *Data from Method II. Each subject was exposed to each of the four BNL/tone conditions twice; the blue square represents the first exposure to that condition and the red diamond represents the second. The black line is the average PR that was selected as just annoying across all subjects.*

Table 3. The Average PR Selected as Just Annoying using Method II

Frequency	125 Hz		500 Hz	
BNL	**40 dBA**	**55 dBA**	**40 dBA**	**55 dBA**
Avg PR Selected	20	15	16	11

CONCLUSIONS

This study aimed to determine the annoyance thresholds of tones in noise, using two different methods (a direct assessment with task, and a magnitude adjustment methodology) to test combinations of two tonal frequencies (125 Hz and 500 Hz) against two different background noise levels (40 dBA and 55 dBA). PR values that were selected to be just annoying in Method I closely correspond to the PR values that were determined to be thresholds of annoyance in Method II, with slightly greater differences found for the louder background noise cases. Those annoyance thresholds of tones in noise were found to be right around the listed thresholds of prominence. The thresholds of annoyance for the tones in the louder background noise levels were slightly lower than those for the quieter background noise level conditions. These results suggest that background noise level has an effect on perceptions of annoyance and therefore needs to be taken into consideration when trying to predict annoyance. As Method II is much quicker to implement, it may be a better method to use in future tests of more tonal frequencies, background noise levels, and tonal levels. A field-test in an actual office environment would also be very beneficial to validate the findings from lab-based studies. Another idea for future work is to compare other existing tonal metrics besides PR and see how well they correlate with the results obtained here on human perception of annoyance.

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