Evaluating aural comfort in tropical high-rise environment

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ABSTRACT

This study endeavours the evaluation of daytime 'Acoustic Comfort' among the high-rise apartment dwellers in tropical Singapore. Based on a holistic evaluation framework that is founded on Stallen's (1999) theory of noise annoyance and the profound theory of Evaluation Response Model (ERM), a multinomial logistic regression model for aural comfort is developed. The comfort model has been established based on extensive noise survey and objective evaluation of the aural environment of the subjects. Aural comfort is found related to the noise exposure level, the subjective perceptions of noisiness within the apartments and the level of subjective disturbances due to dominant noise sources that includes road traffic noise and train noise. The validation of the model has been done through a psychoacoustical investigation in laboratory environment. Absolute evaluation, mixed evaluation and paired-comparison evaluation techniques have been used for subjective evaluation of the binaurally recorded objective sound levels in laboratory environment. The analysis shows that 'moderate' favourable subjective perception is observed in semantic space for road traffic sound at a level of 55 dB(A), at a mean loudness of 10 sone and at a five percentile roughness of 28 centi-asper. For train noise, a 'moderate' favourable subjective perceptions is observed in semantic space at a level of 56 dB(A), at a five percentile loudness of 10 sone, at a five percentile sharpness of 1.35 acum and at a mean roughness of 26 centi-asper.

INTRODUCTION

Among the different types of environmental stressors that city dwellers are exposed to, noise is probably the most spectacular, the most often mentioned and the one on which the most complaints are concentrated (Moser, 1992). In a modern city, noise is increasingly found as a key quality of life issue (Atkinson 2007). In this paper, the term 'acoustic comfort' is defined as the condition of mind which articulate satisfaction (or dissatisfaction) with the surrounding aural environment. Being a qualitative evaluation of the aural environment, acoustic comfort does not depend on the physical noise level alone, rather it depends on the inter-relations among the factors that contribute to people's satisfaction in his/hers surrounding aural environment. A host of physiological, psychological, behavioral and contextual factors shape a person's engagement, experience and enjoyment of environmental conditions in building (Raymond, 2008).

An extensive research has been carried out in the past on noise annoyance perception which is generally the unfavourable evaluation of an aural environment. Researchers found that a little has been studied on the positive evaluation of an aural environment - specially acoustic comfort in urban perspective. Marquis-Favre et al. (2005) noted that one often speaks about annoyance (the negative perception of noise) and less about the positive perception of noise as a comfort. Marquis observed that the combination of different types of noises, a relatively unstudied subject which requires more investigations. In the multidimensional context of a complex environment, it must be underlined the importance of other sensorial aspects which could figure in a more general methodology. In past researches, the evaluation of indoor aural environment has been limited to evaluation of noise exposure levels (several descriptors such as $\mathrm{L_{DEN}}, \mathrm{L_{Aeq}}$ etc) and several social, demographical and psychological aspects in a disintegrated manner rather than in a holistic approach. Among the acoustical factors investigated L_{Aeq}, L_{DNL}, L_{DN} and L_N have been found to have better correlations with noise annoyance in isolation. A very influential attempt that included many studies was Schultz's synthesis (Schultz, 1978). Schultz discussed 24 noise annoyance surveys carried out in several countries. These investigations concerned aircraft, road traffic, and railway noise. In an attempt to make the investigations comparable, Schultz used the available data to estimate a common noise measure and a common annoyance measure, namely, DNL and the percentage of respondents who could be considered to be highly annoyed. Fidell et al.(1991) extended the original compilation of Schultz and arrived at substantially the same curve (Miedema and Vos 1998). The indoor aural environment has not been related simultaneously and examined for different psychoacoustical quantities in these studies that might be responsible for acoustic comfort. Research on soundscape demonstrates that aural comfort in urban areas are not only dependent on the level of the sound but it also quantifies the qualitative aspects of the sound and its perceptual dimensions. This missing link, which was not connected to the evaluation of indoor aural environment in earlier research, has been addressed in this research study. This research study focuses on the evaluation of aural comfort among the high rise dwellers in densely urbanized environment in Singapore and investigates the key factors involved in acoustic comfort among the dwellers.

Generally, there are two sets of factors investigated for noise annoyance evaluation: a) Sound-related factors - physical characteristics of sound (type of noise, noise level, duration of exposure, frequency spectrum), time of the day when exposure occurs and previous experience with noise source. b) Person-related factors including physiological, psychological and social factors that affect the perception of noise and impair activities (communication, concentration, sleep, recreation or rest) (Ouis, 2001). Defining noise annoyance with such factors and evaluation approach individually do not demonstrate evaluation of sound environment at dwellings holistically. Guski (1999) concluded that approximately one third of the variation in noise annoyance can be explained by acoustical factors (e.g. sound level, peak level, sound spectrum and number of noise events) and a second third by non-acoustical factors. The last third can either be attributed to measurement errors, the presence of yet unknown factors which influence noise annoyance or stochastic variation related to idiosyncrasies of individuals. Past studies that investigated relevant non-acoustical factors, however, have some major shortcomings. Firstly, the research can be characterized as highly inductive, which generally means that it lacks a sound theoretical basis. Many of the models which are tested by using path analysis are exploratory. As a result they do not adequately represent the processes of noise annoyance (Taylor, 1984). Secondly, the lack of elementary understanding related to the topic of noise annoyance can result in misspecification of the statistical model and hence even lead to false inferences related to the effect sizes of relevant variables. Thirdly, most of the models developed for noise annoyance are based on empirical evidence related to previously found correlations between noise annoyance and other variables. Since these associations between noise annoyance and non-acoustical factors were found in an exploratory manner, these models are based on implicit theory rather than on a predefined theory of noise annoyance (Maarten et. al., 2008). Beside the investigation on non-acoustical factors, a numerous numbers of research were carried out to establish the noise annoyance relationship with several sound-related factors. However, there is no one-on-one relationship established between noise exposure and noise annoyance (Maarten et. al., 2008).

RESEARCH FRAMEWORK

Stallen (1999) developed a theoretical framework for describing the process of noise annoyance based on the psychological stress theory of Lazarus (1966). As Maarten (2008) noted, this is the only theory that gives an explanation for noise annoyance. According to Maarten (2008), Stallen (1999) argued that if the perceived threat (i.e., noise) is larger than the perceived resources to face the threat (i.e., perceived control and coping capacity), psychological stress (i.e., noise annoyance) will arise. In addition, even though the perceived disturbance may be very high, no noise annoyance will arise if there are sufficient coping resources. Lastly, since the process of coping is in a constant flux, the theoretical framework includes multiple reciprocal relationships between variables. Based on the noise annoyance model by Stallen (1999), it is assumed that acoustic comfort is dependent on the perceived disturbance and behavioural responses (perceived control) towards the perceived disturbance. It is also assumed that a decrease in perceived disturbance shall increase level of acoustic comfort. Acoustic comfort is conceptualized as long term evaluation of an indoor acoustic environment.

To investigate acoustic comfort among high-rise dwellers in the tropics, for the development of a comfort model, a conceptual framework is proposed as illustrated in Figure 2. The proposed conceptual evaluation framework is an integration of objective and subjective evaluation of acoustic comfort. Objective evaluation is based on the quantitative evaluation of noise exposure and the relevant acoustical factors. Subjective evaluation is based on the Evaluative Response Model (ERM) proposed by Eagly and Chaiken (1993) as shown in Figure 1.

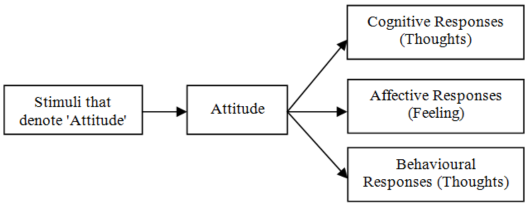

Figure 1. Eagly and Chaiken's (1993) model of attitude

Eagly and Chaiken identified three response types that form the cornerstone of the ERM. These response types are (a) cognitive, (b) affective and (c) behavioural. These three main response types are similar to the tripartite model of attitudes and also referred to as the structural approach to attitudes (Lyons, 1998). Eagly and Chaiken suggested that each one of these response types can be defined as follows. Eagly and Chaiken suggested that cognitive response reflects the thoughts and ideas people have about the attitude object (i.e. noise), which are often conceptualized as beliefs but more often referred to as knowledge, opinions, information and inferences about an attitude object. Affective response refers to emotions, feelings and moods that are experienced with regard to the evaluation of the attitude object and are thus a way of responding to the attitude object. Behavioural response refers to the intentions to act or to the overt action associated with the attitude objects.

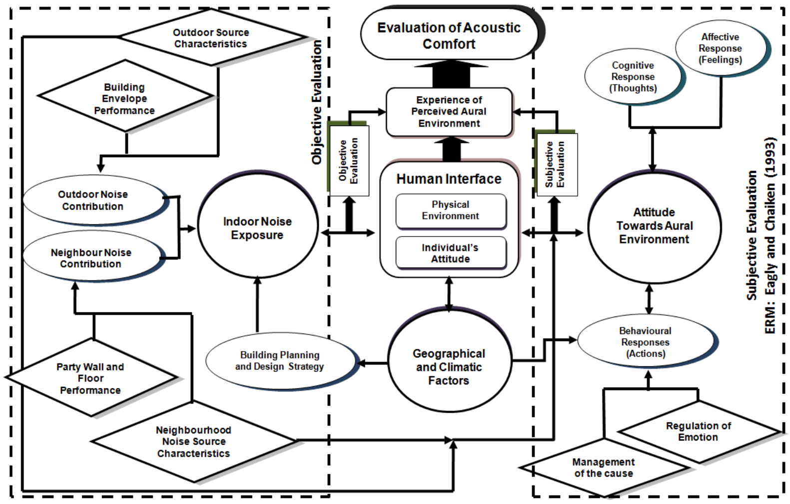

Figure 2. Proposed acoustic comfort evaluation framework

According to the proposed conceptual acoustic evaluation framework (Figure 2), human interface, which is built up on relevant physical environmental conditions and individual's attitude, is subjected to noise from outdoor and immediate neighbours. The physical environment influence the noise exposure at dwellings which in turn depends on the type and characteristics of noise sources, their proximity to dwellings, level of noise exposure, acoustical performances of the building components, the geographical and the climatic requirements for building design. Therefore, the evaluation of aural comfort in dwelling is not limited to the individual's attitude towards noise environment, it also requires the evaluation of the physical environment related to noise exposure at indoor which in a way or other influence the acoustic comfort of an individual at dwelling. A comprehensive evaluation of the aural comfort thus necessitates an integrated evaluation approach which is founded on an objective evaluation of the physical environment and subjective evaluation of the individual's attitude towards the objective noise exposure that influence acoustic comfort among the dwellers in the tropics.

RESEARCH METHODOLOGY

Objective Evaluation: According to the proposed framework for the evaluation of acoustic comfort, the objective evaluation of acoustic comfort requires characterization of various environmental and community noise sources, establish apartments' noise exposure levels due to outdoor noise sources and evaluation of sound transmission loss performances of different types of facades. All these are required to establish the indoor noise exposure levels of the apartments which shall be used in evaluating subjective comfort responses of the respondents during noise survey.

As there were no established model for road traffic noise, Mass Rapid Transit (MRT) train noise and different community noise sources (e.g. waste disposal truck, children playground, food centre etc) in Singapore for prediction of the noise exposure levels of high-rise apartments subjected to these sources, CadnaA software was used to model these noise sources and predict the noise exposure levels of buildings at different elevation. The predicted data were verified with measured noise levels data on the same buildings. With the validation of the predicted results, CadnaA software was used to simulate facade noise exposure levels for different source to buildings distances. A number of charts were established for quick estimation of the noise exposure levels of buildings subjected to different source to building distances. This part of the study is not include in this paper and can be found in the published papers by Lee et. al. (2008, 2009). Measurements for noise isolation of different types of facades were also carried out and it was found that with 'one window opened' conditions, the mean NIC rating of the facades is 11 dB (Alam et al, 2009). Considering the natural ventilation requirements in the high-rise residential buildings in Singapore, the indoor noise exposure level is computed considering that there is only one window open for natural ventilation in the room subjected to the particular noise source. The established charts for prediction of noise exposure for buildings subjected to different noise sources are used along with the mean facade noise isolation rating to compute the indoor noise exposure levels of the apartments surveyed to evaluate subjective responses about acoustic comfort.

Subjective Evaluation: For evaluation of acoustic comfort among the high-rise dwellers, in accordance to the proposed acoustic comfort evaluation framework, a noise survey using stratified sampling technique was conceived. The stratification criteria included different noise exposure levels of buildings subjected to different category of road traffic and different distances from MRT train tracks. A total of 604 households (302 households near different categories of roads and another 302 households at different distances from MRT tracks (at different sites) were surveyed at 20 different locations in Singapore. Both major environmental and neighbour noise were investigated. Indoor noise exposure levels of the individual apartments surveyed were computed from the established charts for predicted noise exposure levels of the apartments and the measured mean sound insulation performance of facades. The computed indoor noise exposure levels of the apartments were then correlated with the subjective responses of the respondents with respect to environmental and neighbour noise.

Psychoacoustics Evaluation (Laboratory): The research methodology for the Psychoacoustics evaluation in the laboratory is shown in Figure 3 below.

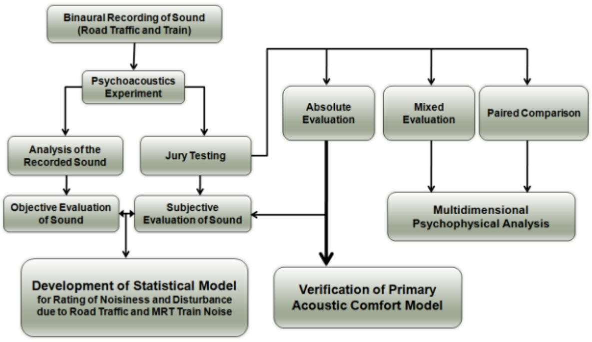

Figure 3. Research method for subjective experimental test

For psychoacoustical evaluation of different types of road traffic and MRT train sounds, binaural recording of the sounds were carried out at the locations where noise survey in stratified sampling was conducted. These include ten locations near different categories of roads (expressway, major arterial, minor arterial, primary access and local road) and another ten locations at different distance (30m, 40m, 50m, 60m and 70m) from MRT track to residential buildings. Recording of these sounds were generally carried out in front of the open window of the apartments (generally on the 10th floor of the building), facing the respective noise source. This is to ensure that the psychoacoustical evaluations are made for those stimuli which are experienced by the residents during their living in high-rise naturally ventilated buildings. Binaural recording of the sounds were carried out using the Binaural Recording System from 01-dB Metravib which uses a binaural headset to record the sound through dBSonic software.

After recording of the sounds, each stimulus was equalized for a duration of 6 seconds and an amplitude of A-weighted equivalent noise level of 75 dB. After equalization, each of these sounds were referred as the 'Reference Level' (also called as 'Ref + 0 dB') for each respective class of road and MRT train noise. Afterwards, the equivalent noise level of each stimulus was changed to four different levels such as +3 dB, 0 dB, -3 dB and -6 dB relative to the reference level (L_{Aeq}). As a result, a total of 40 binaural road traffic sounds were generated for psychoacoustic evaluation. Similarly, for MRT train noise, another 40 binaural MRT train sounds were generated by dBSonic for the psychoacoustic evaluations. Beside the overall noise level, there were total six key psychoacoustical indicators that have been examined for acoustic comfort. These include Loudness, Sharpness, Fluctuating Strength, Roughness, Tonality and Prominence.

A total of 50 subjects were selected for the laboratory experiment. However 36 subjects completed all the experiments with valid data. There were total 80 stimuli (40 road sound signal and 40 train sound signal) for evaluation. Each stimulus was of 6 seconds length. It is important to note, studies showed that the duration of listening session (length of stimuli) does not influence the ratings of noise annoyance ratings if the evaluation question refer to the home situation (Poulsen, 1990). As a result, shorter session length with the evaluation question relating to home environment reduces the experimental time significantly. Each subject is expected to evaluate a maximum of 10 sessions per day which generally takes about 30 minutes. The experimental lasted for a month, starting from 18th October 2010 to 11th November 2010. A maximum of 13 subjects were scheduled per day (during the weekdays only) starting from 10am in each 30 minutes interval.

The study of acoustic comfort requires a conducive environment to carry out the psychoacoustic research experiment. Based on the experimental design, criteria for such environment include a signal-to-noise ratio of 10 dB, thermal, visual and spatial comfort. Due to the lack of funding to establish such a conducive environment, the 'Staff Lounge' (which is generally used for the resting of the academic staff of the school) of the School of Design and Environment was considered suitable for the study, since it meets all the required criteria.

Prior to the psychoacoustic research investigations, an ethical approval was received from the National University of Singapore Institutional Review Board (NUS-IRB) to conduct the study (Approval number: NUS 1118).

DATA ANALYSIS

The analysis of data from the noise survey (refer to Table 1) demonstrates that the rating of the overall acoustic comfort in the apartment is strongly and significantly correlated to the three factors namely: rating of overall noisiness of the apartment, rating of disturbance by Road traffic noise and the rating of disturbance by MRT train noise. A factor analysis was then carried out on all these factors in SPSS. From the Principal Component Analysis (PCA), five components were extracted. From the rotated component matrix it is noted that the most important factors related to the first component (explains 16.4% of the variance) are rating of disturbance by neighbour noise and personal activities disturbed by neighbour noise The second component (explains 14.9% of the variance) include the factors like rating of the noisiness of the apartment, noise sensitivity, consideration of noise as an important aspect in the living environment and rating of disturbance due to road traffic noise. The third component (explains 14.5% of the variance) include the factors like rating of disturbance by MRT train noise and the computed indoor noise exposure level. Regulation of emotion like listening to music and watching TV belongs to fourth component (explains 14.2% of the variance) in the factor analysis while factors related to the management of the cause of stress (reduce noise annoyance to achieve acoustic comfort) like closing door and windows belong to the fifth component (explains 14% of the variance) in the factor analysis. All the five components extracted from PCA cumulatively explained 74% of the total variance in all of the variables.

Table 1. Correlations between overall acoustic comfort and other factors

Factors	Correlation Coefficient	Level of Significance
Rating of overall noisiness of the apartment	.673	0.01
Sensitivity to noise	.178	0.01
Consideration of noise as an important aspect in living environment	.175	0.01
Disturbance by neighbour noise	.129	0.01
Personal activities disturbed by neighbour noise	.134	0.01
Rating of disturbance by road traffic noise	.414	0.01
Rating of disturbance by MRT train noise	.244	0.01
Likeliness of closing window	.174	0.01
Likeliness of closing door	.150	0.01
Likeliness of playing music	.165	0.01
Likeliness of watching TV/Video	.139	0.01
Calculated indoor noise exposure level, Lday (dBA)	.154	0.01

DEVELOPMENT OF PRIMARY ACOUSTIC COMFORT MODEL

Since the dependent variable - acoustic comfort, used in the noise survey is a nominal or ordered category scale with five distinct category (i.e. very comfortable, comfortable, neither, uncomfortable, very uncomfortable), it is inappropriate to use a simple linear/multiple regression model for its specification. Therefore, Multinomial Logistic Regression (MNL) is considered appropriate for the development of a 'primary acoustic comfort' model. The reason we call it a 'primary' model since it is the fundamental model that integrate respondents' experience which further require to integrate with different acoustical quantities through a psychoacoustical experimentation.

Table 2: Likelihood ratio test result

Effect	Model Fitting Criteria	Likelihood Ratio Tests		
	-2 Log Likelihood	Chi-Square	df	Sig.
Indoor noise exposure level	1.447E3	578.395	4	.000
Rating of noisiness of the apartment	1.175E3	307.086	4	.000
Rating of disturbance due to Road Traffic noise	896.085	27.677	4	.000
Rating of disturbance due to MRT Train noise	924.523	56.115	4	.000
The chi-square statistic is the difference in -2 log-likelihoods between the final model and a reduced model. The reduced model is formed by omitting an effect from the final model. The null hypothesis is that all parameters of that effect are 0.				

The likelihood ratio test result shows that among the twelve factors used for the model development, only four factors are significant is developing relationship with the dependent variable, acoustic comfort. These factors are: 1) Indoor Noise Exposure Level, 2) Rating of the Noisiness of the apartment, 3) Rating of Disturbance due to Road Traffic Noise and 4) Rating of Disturbance due to MRT Train Noise. As a result, the model needs to refine and the regression needs to carry out with the these four factors. The likelihood ratio test results (refer to Table 2) of the second regression shows that all the four factors are in significant relation with acoustic comfort in the multinomial regression model. The Cox and Snell Pseudo R-square values computed from SPSS was 0.817 whereas the Nagelkerke Pseudo R-square values was computed as 0.851 which demonstrate the good fit of the model. The final form of the primary acoustic comfort model is shown in Equation (1).

$$\widehat{\Pr}(y_i = Very\ Comfortable)$$

$$= \frac{\exp\left(0.608x_{1i} - 8.377x_{2i} - 1.244x_{3i} - 1.299x_{4i}\right)}{\begin{array}{c}1 + [\exp\left(0.608x_{1i} - 8.377x_{2i} - 1.244x_{3i} - 1.299x_{4i}\right) + \exp\left(0.592x_{1i} - 6.819x_{2i} - 1.215x_{3i} - 1.205x_{4i}\right) \\ + \exp\left(0.478x_{1i} - 5.351x_{2i} - 0.814x_{3i} - 0.879x_{4i}\right) + \exp\left(0.258x_{1i} - 2.463x_{2i} - 0.466x_{3i} - 0.519x_{4i}\right)]\end{array}}$$

$$\widehat{\Pr}(y_i = Comfortable)$$

$$= \frac{\exp\left(0.592x_{1i} - 6.819x_{2i} - 1.215x_{3i} - 1.205x_{4i}\right)}{\begin{array}{c}1 + [\exp\left(0.608x_{1i} - 8.377x_{2i} - 1.244x_{3i} - 1.299x_{4i}\right) + \exp\left(0.592x_{1i} - 6.819x_{2i} - 1.215x_{3i} - 1.205x_{4i}\right) \\ + \exp\left(0.478x_{1i} - 5.351x_{2i} - 0.814x_{3i} - 0.879x_{4i}\right) + \exp\left(0.258x_{1i} - 2.463x_{2i} - 0.466x_{3i} - 0.519x_{4i}\right)]\end{array}}$$

$$\widehat{\Pr}(y_i = Neither\ Comfortable\ nor\ Uncomfortable)$$

$$= \frac{\exp\left(0.478x_{1i} - 5.351x_{2i} - 0.814x_{3i} - 0.879x_{4i}\right)}{\begin{array}{c}1 + [\exp\left(0.608x_{1i} - 8.377x_{2i} - 1.244x_{3i} - 1.299x_{4i}\right) + \exp\left(0.592x_{1i} - 6.819x_{2i} - 1.215x_{3i} - 1.205x_{4i}\right) \\ + \exp\left(0.478x_{1i} - 5.351x_{2i} - 0.814x_{3i} - 0.879x_{4i}\right) + \exp\left(0.258x_{1i} - 2.463x_{2i} - 0.466x_{3i} - 0.519x_{4i}\right)]\end{array}}$$

$$\widehat{\Pr}(y_i = Uncomfortable)$$

$$= \frac{\exp\left(0.258x_{1i} - 2.463x_{2i} - 0.466x_{3i} - 0.519x_{4i}\right)}{\begin{array}{c}1 + [\exp\left(0.608x_{1i} - 8.377x_{2i} - 1.244x_{3i} - 1.299x_{4i}\right) + \exp\left(0.592x_{1i} - 6.819x_{2i} - 1.215x_{3i} - 1.205x_{4i}\right) \\ + \exp\left(0.478x_{1i} - 5.351x_{2i} - 0.814x_{3i} - 0.879x_{4i}\right) + \exp\left(0.258x_{1i} - 2.463x_{2i} - 0.466x_{3i} - 0.519x_{4i}\right)]\end{array}}$$

$$\widehat{\Pr}(y_i = Very\ Uncomfortable)$$

$$\begin{aligned} &= 1 - \widehat{\Pr}(y_i = Very\ Comfortable) \\ &\quad - \widehat{\Pr}(y_i = Comfortable) \\ &\quad - \widehat{\Pr}(y_i = Neither\ Comfortable\ nor\ Unconfortable) \\ &\quad - \widehat{\Pr}(y_i = Uncomfortable) \end{aligned} \tag{1}$$

Where,

y_i is the rating of overall acoustic comfort for the *i-th* subject

x_{1i} is the indoor noise exposure level for the *i-th* subject

x_{2i} is the rating of noisiness of the apartment for the *i-th* subject

x_{3i} is the rating of disturbance due to road traffic noise for the *i-th* subject

x_{4i} is the rating of disturbance due to MRT train noise for the *i-th* subject

The developed 'primary acoustic comfort model' has clearly demonstrated that beside the indoor noise exposure level, acoustic comfort is dependent on the subjective rating of 'noisiness of the apartment' and 'noise disturbance' due Road traffic and MRT train noise. The relationships of these variables with the overall daytime acoustic comfort are found statistically significant. As a result, once the indoor noise level of a dwelling is evaluated and subjective perceptions of the noise level (road traffic and/or train) are established in terms of the above two factors, the developed primary model shall be able to predict the probable comfort level of the dweller.

VALIDATION OF THE MODEL

Primary acoustic comfort model (Equation (1)) is validated for noise exposure due to road traffic and MRT train noise. During the experiments in absolute evaluation approach, subjects were asked how would they rate the 'acoustic comfort', 'noisiness of the apartment' and the 'noise disturbance' due to road traffic and MRT train noise they listened considering their home environment during the day. The acoustic comfort ratings by all the 36 subjects (completed all the experiments) for all 80 different stimuli in the experiments are then used to validate the primary acoustic comfort model. The predicted acoustic comfort ratings are computed (using Equation 2) by taking into account of the subjective responses on the 'noisiness of the apartment' and 'noise disturbance' due to road traffic and train noise from the experiment.

Since perception of acoustic comfort is subjective in nature, the predicted and experimental comfort ratings are analysed for cumulative percentage of respondents. Besides, since the first variable of the primary acoustic comfort model is the A-weighted noise exposure level, both predicted and experimental comfort ratings are plotted against the A-weighted noise exposure level. It is noted that acoustic comfort rating 1 refers to the 'very comfortable', rating 2 refers to 'comfortable', rating 3 refers to 'neither', rating 4 refers to 'uncomfortable' and rating 5 refers to 'very uncomfortable'. A polynomial regression of the subjective ratings and the noise exposure levels generates a best fit curve with a higher regression coefficient.

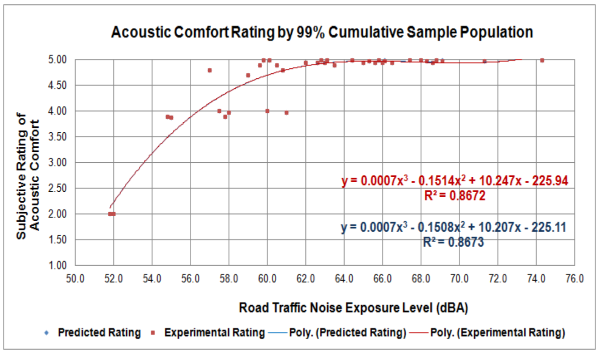

Figure 4: Comparison of predicted & experimental comfort ratings for different road traffic noise levels

It is noted from Figure 4 that for 99% of the cumulative respondents, the predicted acoustic comfort ratings are in very good agreement with the experimental comfort ratings for different road traffic noise exposure levels. A paired sample t-test in SPSS shows that the mean difference for the pair is small (0.001). The standard deviation of the mean difference is 0.004 while the standard error of the mean is 0.0007. Beside, the test statistics shows that the correlation between the predicted and experimental results are strong and significant (correlation coefficient is 1, p<0.001).

Similar to road traffic noise, it is observed that for 99% of the cumulative respondents, the predicted acoustic comfort ratings are in very good agreement with the experimental comfort ratings for different train noise exposure levels. A paired sample t-test shows that the mean difference for the pair is small (0.009). The standard deviation of the mean difference is 0.053 while the standard error of the mean is 0.008. The paired sample t-test in SPSS showed a significantly strong (correlation coefficient is 0.999, $p<0.001$) correlation between the predicted and experimental results.

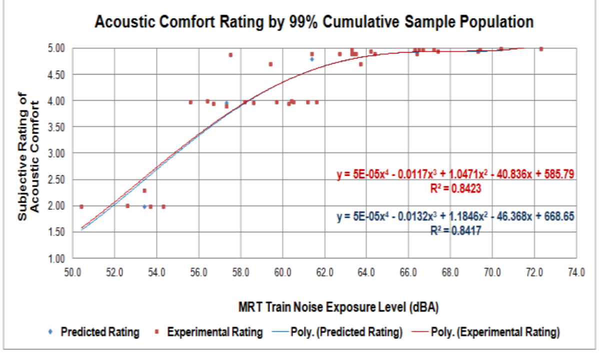

Figure 5: Comparison of predicted & experimental comfort ratings for different train noise levels

The above analysis confirms that the predicted acoustic comfort ratings from 'primary acoustic comfort model' are in strong agreement and significantly related to the experimental comfort ratings for different Road and MRT Train Noise exposure.

It is interesting to note from Figure 4 and Figure 5 that elevated train (MRT) noise is less likely to be found 'very uncomfortable' (approximately by 6 dB) than road traffic noise. The finding here is in good agreement with previous findings by Mohler (1998) and others. Paired comparison studies were also carried as part of this research investigation to detail the relationship between subjective perceptions of noise due to these sources which are beyond the scope of this paper.

RELATION BETWEEN ACOUSTIC COMFORT AND PSYCHOACOUSTICAL PARAMETERS

Two variables of the primary acoustic comfort model - 'rating of noisiness of apartment' and 'noise disturbance' due to road traffic noise and MRT train noise have been evaluated in absolute evaluation approach during the psychoacoustical experiment and later examined with different psychoacoustical quantities. The following relationships were established which were found statistically significant.

$$\mathit{Rating\ of\ Noisiness\ of\ Apartment\ (Subjected\ to\ Road\ Traffic\ noise)} \\ = 0.063 * L_{mean}\,(dBA) - 0.129 * N_{max}\,(Sone) + 0.235 \\ * N_{mean}(Sone) + 0.025 * R_{max}(cAsper) - 0.1 * R_{mean}\,(cAsper) \tag{2}$$

$$\mathit{Rating\ of\ Disturbance\ due\ to\ Road\ Traffic\ Noise} = \\ 0.06 * L_{mean}\,(dBA) - 0.114 * N_{max}\,(Sone) + 0.252 * N_{mean}(Sone) - 0.098 * \\ R_{mean}(cAsper) \tag{3}$$

$$\mathit{Rating\ of\ Noisiness\ of\ Apartment\ (Subjected\ to\ MRT\ Train\ noise)} \\ = 0.114 * N_{max}\,(Sone) + 1.494 * S_{mean}(Acum) - 0.022 \\ * R_{max}\,(cAsper) \tag{4}$$

$$\mathit{Rating\ of\ Disturbance\ due\ to\ MRT\ Train\ Noise} = 0.115 * N_{max}(Sone) + \\ 0.803 * S_{mean}(Acum) \tag{5}$$

Where,

L_{mean} (dBA) is the A-weighted noise exposure level.

N_{max} (sone) is the maximum signal loudness in sone.

N_{mean} (sone) is the mean loudness (taking into account of temporal masking, ideal for non-stationary sources) in sone.

R_{max} (cAsper) is the maximum roughness in Centi Asper.

R_{mean} (cAsper) is the mean roughness in Centi Asper.

S_{mean} (Acum) is the mean sharpness in Acum.

Equation 2 to Equation 5 are to be used in conjunction with Equation (1) for evaluation of acoustic comfort. For reference, *sharpness* is a measure of the high frequency content of a sound. Unit of sharpness is 'acum'. One acum is defined as a narrow band noise one critical band wide at a centre frequency of 1kHz (8.5 Bark) having a level of 60 dB. The sensation perception of human that corresponds most closely to the sound intensity of the stimulus is *loudness*. 'Sone' is the unit of loudness. The level of 40 dB of a 1 kHz sine tone is defined as a loudness of 1 sone *Roughness* is another important psychoacoustic quantity that quantifies the subjective perception of rapid (15-300 Hz) amplitude modulation of a sound. 'Asper' is the unit of roughness measurement. One asper is defined as the roughness produced by a 1kHz tone of 60dB which is 100% amplitude modulated at 70Hz.

ACOUSTIC COMFORT IN SEMANTIC SPACE

Multidimensional evaluation of road traffic and MRT train noise has been carried out during the psychoacoustic experiment through mixed evaluation approach. Multidimensional evaluations are measured on a 7 point semantic differential scale with 12 adjective pairs. The pairs of adjectives evaluated are: Pleasant-Unpleasant, Relaxing-Stressful, Bearable-Unbearable, Peaceful-Violent, Soft-Loud, Weak-Strong, Dull-Sharp, Mild-Tense, Quiet-Busy, Ignoring-Distracting, Smooth-Rough and Calm-Exciting.

A comparison of road traffic and train noise in semantic space (Figure 6) showed three distinct category where the road traffic and train noises are perceived equally in the same group. The semantic profiles show that in the first category, road traffic sounds from expressways are about equally perceived as the MRT train sounds for a building to track distances of 30m and 40m. The A-weighted noise levels, for which such perceptions are made, ranges between 60 dB and 70 dB. The subjective perceptions of all these sounds are towards the 'fairly' unfavourable semantic adjective pairs (for example, fairly unpleasant, fairly stressful etc). In the second category, the semantic profiles show that the road traffic sounds from Major Arterial, Minor Arterial and Primary Access roads are about equally perceived as the MRT train sounds for a building to track distance of 50m. The A-weighted noise levels, for which such perceptions are made, ranges between 57 dB and 66 dB. The subjective perceptions of all these sounds ranges between 'neutral' and 'moderately' unfavourable semantic adjective pairs (for example, moderately unpleasant, moderately stressful etc).

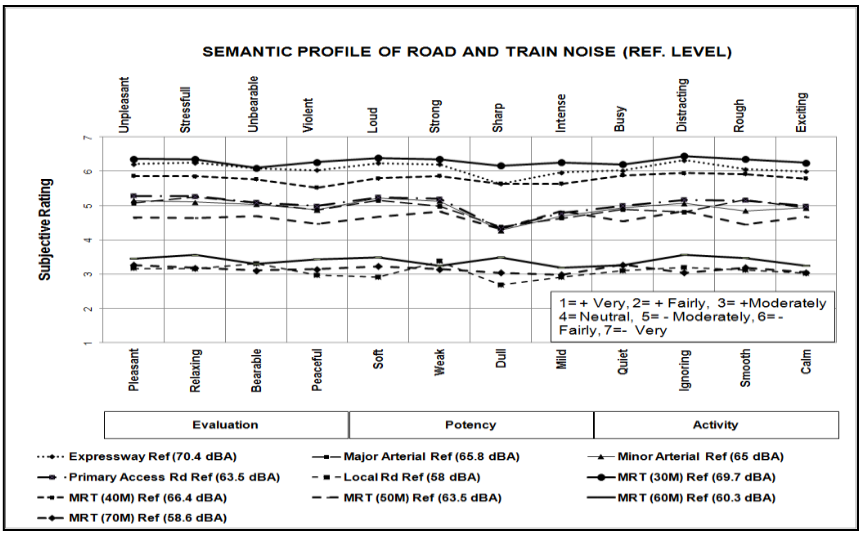

Figure 6. Semantic profile of road traffic and train noise

In the third category, the semantic profiles show that the road traffic sounds from Local roads are about equally perceived as the MRT train sounds for a building to track distance of 60m and 70m. The A-weighted noise levels, for which such perceptions are made, ranges between 52 dB and 60 dB. The subjective perceptions of all these sounds are towards 'moderately' favourable semantic adjective pairs (for example, fairly pleasant, fairly relaxing etc). Analysis were further carried out to establish the relationships between the qualitative aspects of the semantic space and the psychoacoustical quantities.

While evaluating acoustic comfort with respect to psychoacoustic quantities of *Road traffic* sounds in semantic space, it is found from the analysis that at A-weighted equivalent noise level (L_{Aeq}(dBA)) of 55 dB, 'moderate' favourable subjective perceptions is observed across the twelve semantic objective pairs (for example Figure 7). Besides, it was observed that a mean loudness of 10 Sone provided 'moderate' favourable subjective perceptions across the twelve semantic objective pairs. In relation to roughness, at five percentile roughness value of 28 centi-asper, a 'moderate' favourable subjective perceptions is observed across the twelve semantic objective pairs.

Similarly, while evaluating acoustic comfort with respect to psychoacoustic quantities of MRT train sounds in the semantic space, the analysis shows that that a moderate favourable subjective perceptions is observed across the twelve semantic objective pairs at A-weighted equivalent noise level (L_{Aeq}(dBA)) of 56 dB. The analysis also showed that a five percentile loudness value of 10 Sone, 'moderate' favourable subjective perceptions is observed across the twelve semantic objective pairs. At five percentile sharpness value of 1.35 acum ($S_{perc,5\%}$) moderate favourable subjective perceptions are also observed. It is also noted from the analysis that at a mean roughness of 26 centi-asper (R_{mean}), 'moderate' favourable subjective perceptions are observed across the twelve semantic objective pairs.

For reference, $N_{ISO\ 532B}$ is the Zwicker loudness is used for stationary sound signals. $N_{5\%}$ is the five percentile loudness in sone.

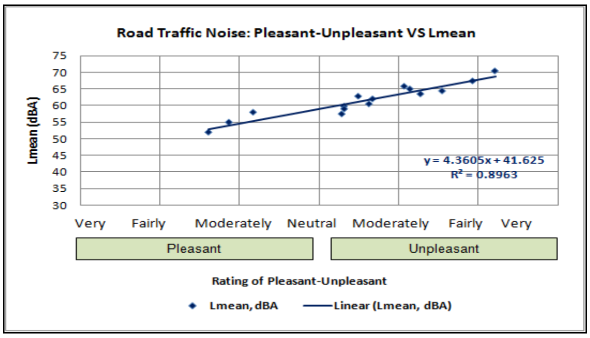

Figure 7(a)

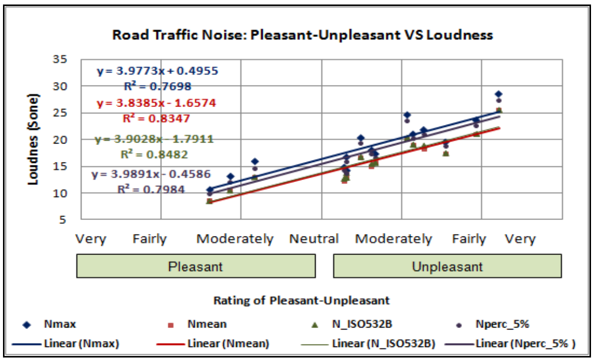

Figure 7(b)

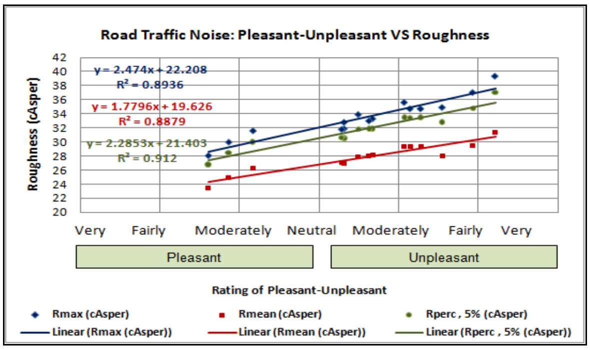

Figure 7(c)

Figure 7: Relationships between psychoacoustical quantities and semantic adjectives (road traffic noise)

CONCLUSION

In this paper a statistical acoustic comfort model is proposed which is founded on Stallen's (1999) theory of noise annoyance and the profound theory of Evaluation Response Model (ERM). The model demonstrates that acoustic comfort in a high-rise dwelling is dependent on the overall noise exposure level as well as several psychoacoustical quantities including Loudness, Roughness and Sharpness. Research on soundscape demonstrates that better acoustic comfort in urban areas may not be achieved even with the reduction in noise level (De Ruiter, 2004). Beside. soundscape does not only quantifies the noise level, it also quantifies the qualitative aspects of the sound and establish the perceptual dimensions (Kang et. al. 2010). This missing link, which was not connected to the evaluation of indoor aural environment in earlier research, has been addressed in this research.

In this research, acoustic comfort is evaluated among the high-rise residential dwellers in tropical Singapore. Given the extensive high-rise living and tropical environment in Singapore, the findings of acoustic comfort evaluation stands to offer important implications on aural comfort to cities considering high-rise housing.

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