The effects of visual landscape and traffic type on soundscape perception in high-rise residential estates of an urban city.

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Abstract

In dense urban cities with high-rise estates where large population of residents live in close proximity, the increasing noise exposure in soundscapes due to traffic noise, construction and other undesirable anthropophony in urban lived environments may cause adverse effects on the wellbeing of residents. In this study, soundscapes around such urban spaces are investigated using Singapore as a case study. This study aims to discover the current conditions of soundscapes around such spaces and whether traffic and landscape features have a sizeable effect on soundscape perception, as well as to develop a predictive model using soundscape indicators based on acoustics, psychoacoustics, and audio features. The results show that the soundscapes in the selected urban city's heartlands are generally dominated by traffic (40%) and biophonic (36%) sources. This study identifies the significant effects of both traffic conditions and landscape features that affect soundscape perception. A predictive model is developed based on identified objective indicators and an alternate method to derive the total mask duration of positive sound events. The visibility of roadways and vehicles correlates negatively with soundscape perception and reaffirms the effects of road visibility on noise annoyance. However, light traffic conditions do not adversely affect the soundscape perception as compared to heavy traffic, suggesting tolerance for light traffic by the participants in residential settings. Thus, the present study recommends that urban planners should take into consideration the type of traffic infrastructure when planning residential developments.

Keywords: soundscape, high-rise, residential, urban city, psychoacoustic, audio features

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1. Introduction

Noise in urban cities around the world caused by increasing road and air traffic has affected many communities. Constant urban development and redevelopment to meet the various demands of a growing population have contributed to noise problems over the years. The adverse effects of community noise cause many negative health effects such as aural discomfort, cardiovascular effects, sleep disturbances, sleep interference, learning, work performance reduction, and annoyance responses [1]. The effects of community noise are not only limited to physical and mental health but also lead to aggravating societal impacts such as reduced social cohesions and activities in the communities [2]. The WHO community noise guideline describes the need to consider other effects which are not immediately apparent, such as absenteeism in workplaces and schools, increased drug and health-care use, accidents, and loss of property value in residential spaces exposed to noise pollution [3].

In a recent WHO report [4], noise has become the second most important environmental stressor that impacts public health in Western Europe. In urbanized countries, there is a growing need to investigate the noise impact in high-density urban residential settings such as high-rise housing. A recent household survey in Singapore indicates that noise has been continuously regarded as one of the most disliked aspects of life in public estates [5]. The situation is unlikely to improve if there is no intervention to manage the growing noise pollution, especially for residents who live close to traffic.

The existing noise control strategies implemented by many countries mainly rely on energy-based indicators such as A-weighted sound pressure levels measured in decibels (dBA). A recent study done in Singapore shows that the daily average of non-occupational outdoor sound level in the city was 69.4 dBA [6], which is higher than the permitted daytime (7 a.m. to 7 p.m.) limit of 65 dBA (L_{day}) stipulated by statutory noise regulation in the city. A large majority of the measurements (92%) exceeds the WHO guidelines for community noise (55 dBA over 16 hours), causing serious annoyance and complaints. The study also indicates that 57% of the monitored points in Singapore has exceeded the 65 dBA limit for L_{day} [6]. Some of these monitored points were residential zones situated near industrial areas.

While the interventions of noise pollution using noise regulations are essential for reducing noise exposure to make residential spaces livable, the regulation on noise level limits does not necessarily lead to better acoustic comfort and acceptance [7-8]. In Europe, despite implementations of a European Union (EU) noise directive to limit noise exposure in residential places to below prescribed control limits, noise complaints are still frequently received [9].

Additionally, traditional sound monitoring methods using A-weighted Sound Pressure Level (SPL) only give a single value indication of energy levels without the context of sound sources. In this approach, the limits for SPL consider all sounds as 'noise' once a threshold level is crossed without considering the sound sources that contribute to annoyance or acoustic comfort, failing to account for the acoustic environment fully. In the soundscape context, instead of using traditional sound monitoring methods. Soundscape research have also moved towards the use of other sound-related measurement indicators such as psychoacoustic indicators of loudness, sharpness or roughness as well as sound-source composition indicators in their analysis. [10]

A new emerging science of soundscape that was first introduced in 1969 by Michael Southworth, a city planner, help set a direction for improving the living environment and acoustic ecology by considering the perception of sounds with context [11]. The soundscape approach to noise intervention shows a promising environmental noise management approach. It has been defined, validated, and supported by the ISO standard (ISO 12913), which conceptualizes soundscape research, planning, design, and management of soundscape environments. Some of these soundscape improvement projects include green landscaping, green belts, and the addition of water features, which could be used to modify the acoustic ecology [12]. Recent literature also suggests that visual scenery and landscape features in the environment can influence soundscape and noise perception [13-14]. For example, a study led by Van Renterghem and Botteldooren found that in living spaces, the self-reported extent to which vegetation is visible when looking out of a window showed a strong and significant predictor of the self-reported noise annoyance [15]. Natural visual elements such as greenery, water bodies, and natural auditory elements can help moderate the noise annoyance in an environment dominated by traffic noise [16]. The visual aspect of the environment should be considered in context with the acoustic environment in order to improve soundscape quality and the satisfaction of the overall urban environment [17]. However, there is still a lack of existing publications addressing the effects of visual landscape features on soundscape perception in dense living spaces such as those found in high-rise residential urban setting.

In the present study, the soundscapes around Singapore's public housing and residential spaces are investigated through an audio-visual approach as well as through soundscape appraisals using questionnaires. The following research questions are addressed;

(1) What is the current condition of soundscape of the residential heartlands in an urban setting?

(2) How do different landscape features within various traffic conditions around residential spaces affect the soundscape quality perceived by people?

(3) What indicators are most effective in predicting the overall sound quality (OSQ) of the soundscapes of urban residential estates?

2. Methodology

2.1. Site selection

In Singapore, residential spaces are incredibly varied with different planning, design, varying amenities such as parks, rivers, facilities, and different road infrastructure. Thus, in order to gather a comprehensive view of the urban residential spaces, thirty locations spread across the city were identified for the present study as shown in Figure 1, which included varying traffic conditions (e.g., heavy, light, none) and landscape features (e.g., greenery, building, waterbody) to cover the possible residential estates around the city.

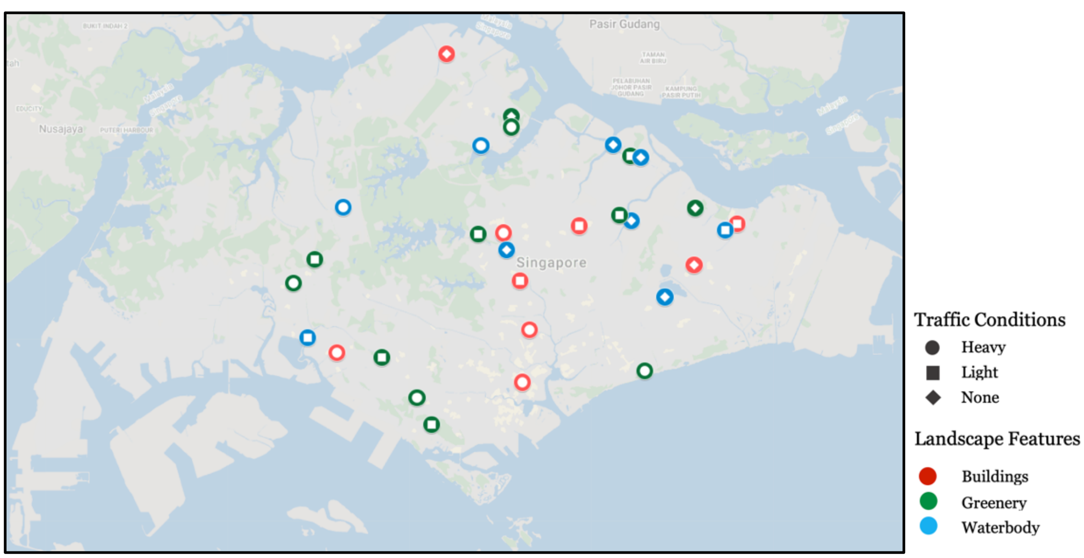

Figure 1. Selected sites (image from Google Maps)

Traffic conditions were categorized based on different categories of roads classified in Singapore's Urban Redevelopment Authority (URA) [18]. These road categories include 1. Expressways, 2. Major arterial, 3. Minor arterial, 4. Primary access, and 5. Local access road. The use of URA's classification of roads in Singapore has been applied in local traffic noise studies [19-20] and the technical guideline for land traffic noise impact assessment developed by the National Environmental Agency (NEA) in Singapore [21]. In this study, URA's five categories of road traffic were further reduced to three main groups (heavy, light, and none) where heavy traffic consisted of 1. Expressways and 2. Major arterial with a speed limit of 80 km/h and 60 km/h respectively while light traffic consisted of 3. Minor arterial, 4. Primary access, and 5. Local access with the speed limit below 50 km/h. Finally, 'none' traffic consisted of sites where there is no road traffic in the vicinity whereby traffic elements cannot be visually or audibly perceived, these sites includes spaces of varying visual landscapes away from road traffic such as inside parks, at a riverside, reservior, or in a residential pavilion. The three groups of traffic conditions chosen in this study can also be represented by the number of traffic lanes, heavy traffic which represented expressways and major arterial roads typically have more than 3 traffic lanes in each direction (two-way), whereas light traffic from minor arterial, primary access, and local access roads typically have 1-2 traffic lanes in each direction. The traffic categories are summarized in Table 1. In regards to the landscape, three visual landscape features found in the city were studied. These included the visual landscape of greenery, buildings, and waterbody. The selected sites that were categorized as greenery visual landscapes are characteristic of green spaces like park, garden, fields, forest, and plains whereas waterbody visual landscape sites consist of spaces with a waterbody present like rivers reservoir and lake. The sites that were categorized as building visual landscapes included highly urbanized spaces like market, court, hub, town centre, and streets with buildings on both sides. Careful consideration was made in the site selection to avoid sites that have a competing visual scenery such as strong combinations of waterbody and greenery elements, like a swamp found in a mangrove forest or strong combinations of waterbody and man-made (buildings) elements such as habours. Nine sites surrounded by man-made structures were categorized as ‘building’, while twelve sites with visual green spaces or forests were categorized as ‘greenery’. Finally, nine sites with a visible waterbody were categorized as ‘waterbody’. The number of sites represented by the landscape features is shown on the horizontally stacked bar chart in Figure 2.

Table 1. Categorization of traffic conditions

URA Traffic Classification	Road Types	Traffic Conditions	No. of Lanes (Two-way)	Speed limit
1	Expressways	heavy	3-4	80 km/h
2	Major Arterial Roads	heavy	3	60 km/h
3	Minor Arterial Roads	light	2	50 km/h
4	Primary access	light	1-2	50 km/h
5	Local access	light	1	50 km/h

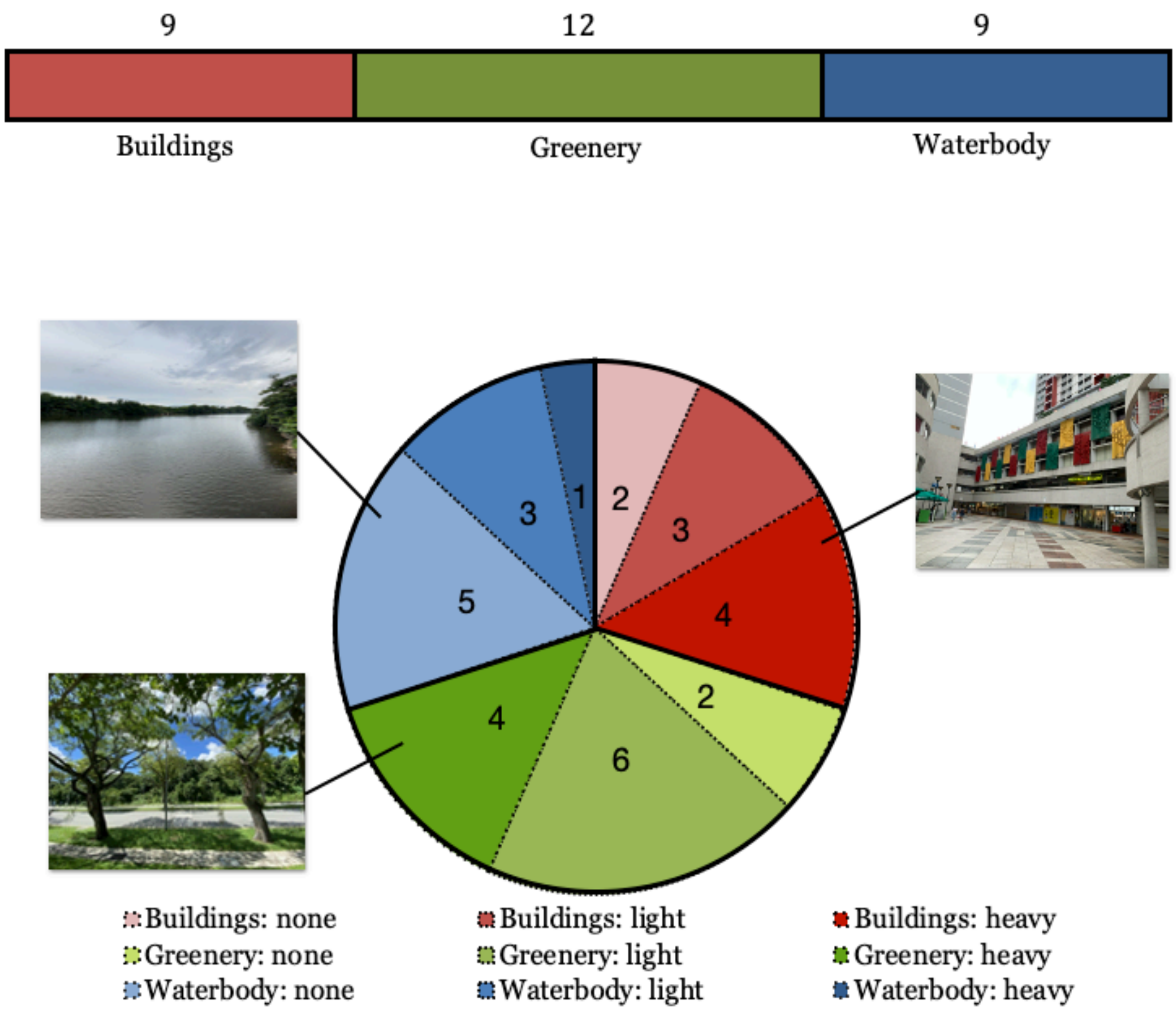

Figure 2. Site count; Landscape Primary Feature & Traffic Conditions

2.2 Objective measurements

2.2.1 Acoustic measurements

In the present study, acoustic measurement has been carried out as outlined in the soundscape ISO 12913-2 standards, which describes the noise level of the sites. The measurement was collected at each individual site for 15 minutes under nominal conditions using a Sound Level Meter (Model: Brüel & Kjær 2250 L). The acoustic measurements collected consisted of the acoustic indicators, A-weighted and C-weighted equivalent continuous sound pressure levels, L_{Aeq} and L_{Ceq}, respectively, as well as percentile levels where sound pressure levels were exceeded 5%

and 95% of the measurement period (15 minutes) with A-frequency weighting and Fast time weighting, L_{AF5}, and L_{AF95}. The acoustic measurement data across the sites are reported in Appendix Table A1.

2.2.2 Binaural recordings and other indicators

Binaural recordings have been used in the present study as an assessment tool because it closely represents the experience of human hearing. A 15-minute-long binaural recording (sampling frequency: 44.1 kHz, resolution: 24 bits) was collected at each individual site in a stationary position representing the typical sonic environment in the surroundings. The measurement time interval of 15 minutes was used because it would be sufficiently long enough to cover at least one period of all regularly occurring sounds and above the recommended measurement interval of 3 minutes [22]. The device used is a wearable Sennheiser AMBEO Smart Headset (ASH) that fits onto the ears like an earpiece. From the binaural recordings, psychoacoustic features and audio features calculations were extracted using MATLAB Audio Toolbox, Psysound3 [23], and MIRtoolbox (Music Information Retrieval) [24]. The audio features contain spectral and temporal information that may be meaningful to the soundscape. The usefulness of such audio features for predicting soundscape perception based on the Swedish Soundscape-Quality Protocol [25] is also evaluated in this study.

The use of psychoacoustic indicators in soundscape research has been growing in recent years due to its advantage over traditional acoustic measurements that cannot fully account for the effects of spectral patterns in a complex soundscape [26]. On the other hand, psychoacoustic indicators are more related to the actual auditory perception of people since the perception of sound involves more than just SPL but also the low-frequency content, duration, and frequency spectrum. A study in Brussels shows that annoyance ratings within a small sample of test subjects differed widely even though the L_{Aeq} acoustic indicator remained the same [26]. Psychoacoustic indicators have also contributed to noise annoyance studies [27-29]. Therefore, selected psychoacoustic indicators are investigated in the present study, including loudness [30], sharpness [31], and roughness [32].

A list of objective indicators with its description is shown in Table 2, the collected measurements of psychoacoustic features and audio features can also be found in Appendix Table A1.

Table 2. Objective soundscape indicators collected

Indicators	Abbrv.	Description
A-weighted, equivalent continuous sound level	$L_{Aeq,15}$	*A-weighted, the equivalent continuous sound level in decibels measured over 15 minutes.*
C-weighted, equivalent continuous sound level	$L_{Ceq,15}$	*C-weighted, the equivalent continuous sound level in decibels measured over 15 minutes.*
Statistical Noise Levels	L_{AF5}, L_{AF10} L_{AF90}, L_{AF95}	*Statistical noise levels where sound pressure levels is exceeded n% of the measurement time with A-frequency weighting and Fast time weighting.*
Loudness	*N*	*Loudness in sones; a subjective measure of perceived sound intensity, adjusted for human hearing. (ISO 532-1)*
Sharpness	*S*	*Sharpness in acums, a subjective measure of the sensation of high-frequency component. (ISO 532-1)*
Roughness	*R*	*Roughness; an estimation of sensory dissonance related to the auditory perception of fast amplitude modulations which sounds 'rough'*
Zero Crossing Overall Average	ZCOA	*The average of zero crossings in the audio for every frame where the signal crosses zero line in the audio signal.*
Spectral Centroid	SC	*Statistical indicator of spectral distribution in the audio. Indicates the mean or geometric center of the distribution of spectrum.*
Spectral Spread	SSp	*Statistical indicator of spectral distribution in the audio. Indicates the standard deviation or 'spread' from the centroid of the recording.*
Spectral Rolloff	SR	*Indicates the frequency, f_0 where 85% of the total energy is contained below that frequency. Estimates the amount of high frequency in the signal.*
Spectral Flatness	SF	*Statistical indicator of spectral distribution in the audio. Indicates the smoothness of the distribution of frequencies. Greater positive values reflect less unevenness (spikes) in the frequencies.*
Spectral Brightness	SB	*Similar to Spectral Rolloff indicates the percentage of energy above f_0 = 1500Hz. An estimate of the amount of spectral content that is above 1500Hz.*
Spectral Skewness	SSk	*Statistical indicator of spectral distribution in the audio. Indicates the symmetry in the distribution of frequencies. Greater positive values reflect more energy inherits the lower frequencies.*
Spectral Kurtosis	SK	*Statistical indicator of spectral distribution in the audio. Indicates the level of excess kurtosis in the distribution of frequencies. Greater positive values reflect more peakedness in the distribution of energy surrounding the spectral centroid.*

2.2.3 Binaural recordings and spectral analysis

Spectral analysis of the recordings was conducted using the visual information provided in the spectrographic representation of the audio recording. The spectrograms were then used to manually identify and categorize sound events by elimination into three different commonly heard sound taxonomy comprising of biophony, geophony, and anthrophony. [33-34] Anthrophony sound sources were further segregated to traffic, mechanical sounds, and sounds of human activities. The sound events were then revealed, including foregrounded and backgrounded events as well as the Mask Duration, M_D, of the identified sound events which compose the soundscape and are classified into their respective acoustic taxonomy. The analysis provided a representation of the common sound sources and composition of the soundscape, which has been disaggregated into its components, offering insights into the current acoustic environment beyond just traditional energy-based measurements. Taking reference from a preliminary study [35] and commonly used sound classification by existing literature, sound events were categorized into different groups as shown in Table 3.

Table 3. Categorisation of sound sources

Category	Sound events
Human	conversation children music footsteps
Traffic	car motor train
Mechanical	airplanes ship boat engine
Biophonic	animals bird insects
Geophonic	wind water

2.3 Questionnaire Survey

The subjective perception of the soundscape at various locations was collected via an online questionnaire conducted at the sites. The questionnaire was based on the Swedish Soundscape-Quality Protocol (SSQP) [25] and ISO 12913-2 recommendations (soundscape data collection and reporting requirements) [22]. Participants were asked to rate on a 5-point semantic differential scale *(1: very annoying, 2: annoying, 3: moderately, 4: calm, 5: very calm)* to mark their impression of the overall environment based on tranquility (a state). A similar 5-point semantic differential scale was used in the questionnaire to mark the participant's impression of the overall environment based on satisfaction (an expectation), and pleasantness (a feeling). Participants were also asked to rate the perceived occurrence of different sound sources classified into five categories (*traffic, mechanical, human, biophonic, geophonic)* presented on a 5-point scale from (*1: not at all, 2: a little, 3: moderately, 4: a lot, 5: dominates completely*). A similar question also asked participants about the visual environment and how much can be seen of specific visual elements (i.e., *vehicles, buildings, roads, greenery*) as shown in Figure 3.

Assessment of **VISUAL** environment.
To what extent do you presently see the following visual elements?

	not at all	a little	moderately	a lot	dominates completely
Vehicle	○	○	○	○	○
Building	○	○	○	○	○
Road	○	○	○	○	○
Greenery (vegetation, garden, park, fields)	○	○	○	○	○
People	○	○	○	○	○
Sky	○	○	○	○	○
Water Features	○	○	○	○	○

Figure 3. Questionnaire example on visual assessment

Furthermore, based on the recommendation by the soundscape protocol ISO 12913-2, eight-dimensional semantic profiles representing the perceived affective quality of soundscape in the present study was assessed on a 7-point Likert scale *(1: strongly disagree, 2: disagree, 3: somewhat disagree, 4: neither agree nor disagree, 5: somewhat agree, 6: agree, 7: strongly agree).* The eight soundscape attributes adopted (pleasant, chaotic, vibrancy, uneventful, calm, annoyance, eventful, and monotonous) were first developed through the Swedish Soundscape-Quality Protocol (SSQP) as a means of describing the soundscape in emotional attribute scales. The SSQP has been used, validated, and adopted by ISO 12913 [22], [36-37] for soundscape research, these scales represent the different emotional magnitude of soundscape perception which can be further collapsed to represent a bi-dimensional orthogonal components of pleasantness and eventfulness. [38]

The soundscape ISO protocol recommends the use of a 5-point Likert scale. However, in this study, a 7-point scale was used for the perceived affective quality of soundscape in order to allow more choices for respondents by providing two more options of *'somewhat disagree'* and *'somewhat agree'* as compared to the 5-point Likert scales. The additional options gives the participants more choices for answers near to the neutral option of *'neither agree nor disagree'* while still retaining a completely neutral option should the respondents find their evaluation of the soundscape attributes to be truly neutral. The 7-point Likert scale still remains relatively compact and easy to use [39-41], some soundscape literature has also used 7-points Likert scales instead of 5-points Likert scale. [42-44]

2.4 Participants

A total of 11 participants, including undergraduate and graduate students, were recruited into the study. Since the commitment to the project was extensive, all the participants were remunerated for their time. Of the 11 participants, eight were male and three were female. The participants' age ranged from 21 to 27 years old. The participants were all visitors to thirty sites selected as outlined in Section 2.1 and all participants self-reported with normal hearing and vision. A training session was conducted to brief the participants on the objectives of the study and to provide some general information on soundscape appraisal and the perceived affective quality of soundscape (pleasantness, eventfulness, etc.). The participants were instructed to spend 15 minutes to experience the soundscape and complete the questionnaire. Appendix Table A2 shows the result of the questionnaire's mean responses from the participants.

2.5 Perceived affective quality of soundscape

The integration of soundscape attributes by Axelsson, Nilsson & Berglund [45] using principal components analysis revealed three basic components of soundscape perception called pleasantness, eventfulness, and familiarity which can account for 50%, 18%, and 6% of the variance. The first two main components of pleasantness and eventfulness have been proposed to represent a bi-dimensional model of different urban soundscapes perceptions when plotted and organized into an orthogonal circumplex pattern. An example of the two components plot is shown in Figure 4. In such a bi-dimensional configuration, the representation of vibrant soundscapes (both pleasant and eventful), calm soundscapes (pleasant and uneventful), chaotic soundscapes (unpleasant and eventful) as well as monotonous soundscapes (unpleasant and uneventful) can be meaningfully visualized for comparisons between various soundscapes and provide urban planners as well as soundscape designers with insights into soundscape planning and intervention. [45]

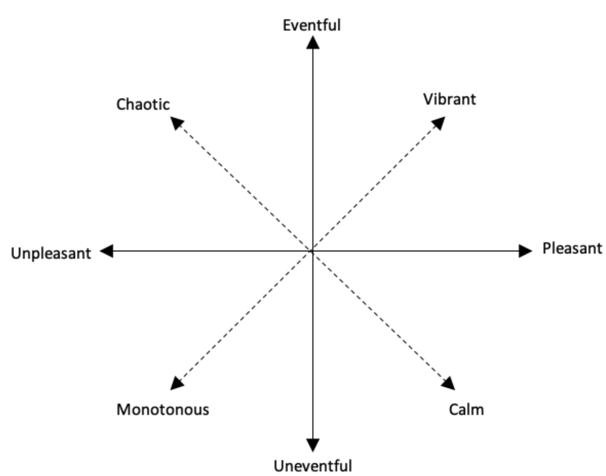

Figure 4. Example of bi-dimensional model

Based on the ISO 12913-3 Data analysis method Annex A3 [37], the pleasantness and eventfulness of the soundscape are derived from Eqs. 1 and 2 using the median values of perceived affective quality collected from the questionnaire responses. A term of $(6 + \sqrt{72})$ was added in the equation to convert the range of the pleasantness and eventfulness results to between the range of ±1 because the questionnaire was based on a 7-point Likert scale in this study. The calculated values based on the equations are reported in Appendix Table A2.

$$Pleasantness = \{(p - a) + cos45°(ca - ch) + cos45°(v - m)\}/(6 + \sqrt{72}) \quad \text{(Eq 1)}$$

$$Eventfulness = \{(e - u) + cos45°(ch - ca) + cos45°(v - m)\}/(6 + \sqrt{72}) \quad \text{(Eq 2)}$$

where p is pleasant, a is annoying, ca is calm, ch is chaotic, e is eventful, u is uneventful, v is vibrant, and m is monotonous.

2.6 Statistical analysis

Before starting the analyses, the normality of the distribution of the collected data was checked using the Shapiro-Wilk test. The results showed that the majority of the sample data had a p-value of more than .05, which indicated normality in the collected data except for roughness values. Log transformation was performed on the roughness values to conform the data to normality, the transformed data had a p-value of more than .05 and shows a normal distribution and was accepted in the study. The inter-rater reliability was checked with the intraclass correlation coefficient (ICC) to verify the internal consistency in the questionnaire responses from participants. To identify relationships between audio features, acoustic indicators, psychoacoustic indicators, and affective soundscape descriptors, subjective soundscape appraisals from participants were analyzed with Spearman's rank correlation coefficient, the use of Spearman's rank correlation coefficient is proposed by the ISO 12913-3 [37] due to the nature of the subjective soundscape appraisals being rank-ordered. To develop a predictive model that can describe the soundscape quality of pleasantness and eventfulness, stepwise multiple linear regression analysis was performed. Thereafter, a two-way repeated measure within-subject analysis of variance (ANOVA) was tested with two factors; traffic conditions and landscape features. Statistical analysis was performed using the statistical software package, SPSS (v26, IBM, USA).

3. Results

The collection of acoustic measurements shows the $L_{Aeq,15}$ (A-weighted equivalent continuous sound level in decibels measured over 15 minutes) between the range of 46 dBA to 70 dBA with a mean of 57.6 dBA and standard deviation, SD = 6.6 dBA. Residential estates that are situated near heavy traffic conditions have a higher $L_{Aeq,15}$ levels with a mean of 65.3 dBA and SD = 3.6 dBA, while residential estates situated near light traffic or no traffic has a similar average $L_{Aeq,15}$ of 54 dBA. The residential sites that are situated near heavy traffic conditions (major arterial roads or expressways) are the most exposed to high continuous sound levels as expected. Table 4 summarizes the mean measurements taken of acoustic and psychoacoustic indicators.

Table 4. Acoustic & Psychoacoustic indicators (mean & standard deviation)

Traffic Condition	Landscape Feature	$L_{Aeq,15}$ (dBA)		$L_{Ceq,15}$ (dBC)		Loudness (sone)		Sharpness (acum)		Roughness (asper)	
		M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Heavy, 9 sites	Building, 4 sites	66.7	4.6	76.1	2.8	22.102	5.552	1.336	0.128	0.921	0.521
	Greenery, 4 sites	65.2	1.3	76.9	2.2	21.320	1.747	1.50	0.245	0.796	0.419
	Waterbody, 1 site	60.1	N/A	71.5	N/A	15.114	N/A	1.138	N/A	0.609	N/A
Light, 12 sites	Building, 3 sites	55.7	5.2	70.8	7.6	11.578	3.521	1.381	0.103	0.058	0.028
	Greenery, 6 sites	53.9	4.9	68	2.9	10.662	3.178	1.711	0.113	0.083	0.052
	Waterbody, 3 sites	53.8	0.9	69.9	1.0	10.430	0.703	1.147	0.073	0.101	0.066
None, 9 sites	Building, 2 sites	59.4	6.0	73.5	10.1	13.239	3.173	1.679	0.227	0.072	0.073
	Greenery, 2 sites	48.6	2.9	64.7	0.3	7.639	1.602	1.575	0.012	0.054	0.043
	Waterbody, 5 sites	54.2	3.8	69.2	2.8	10.072	2.893	1.608	0.398	0.049	0.014

3.1 Soundscape composition based on M_D

The soundscape composition is analyzed using the binaural recordings collected and classified into their acoustic taxonomies. A general overview of the types of sound events for all 30 sites that makes up the acoustic environment and the mask duration (in seconds) of sound events are presented in Figures 5 and 6. Mask Duration, M_D refers to the cumulative time during which sound events of a sound category (Table 3) are detected in spectrographic representation.

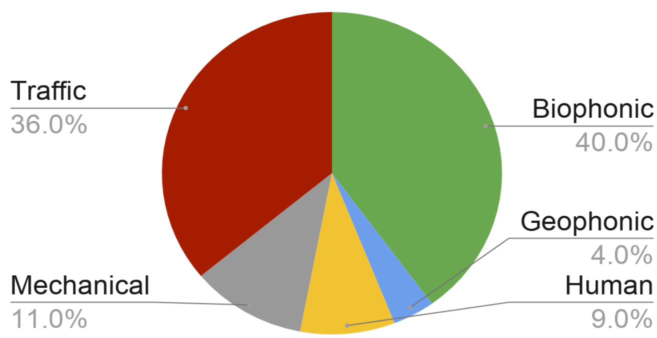

Figure 5. Pie Chart of soundscape composition

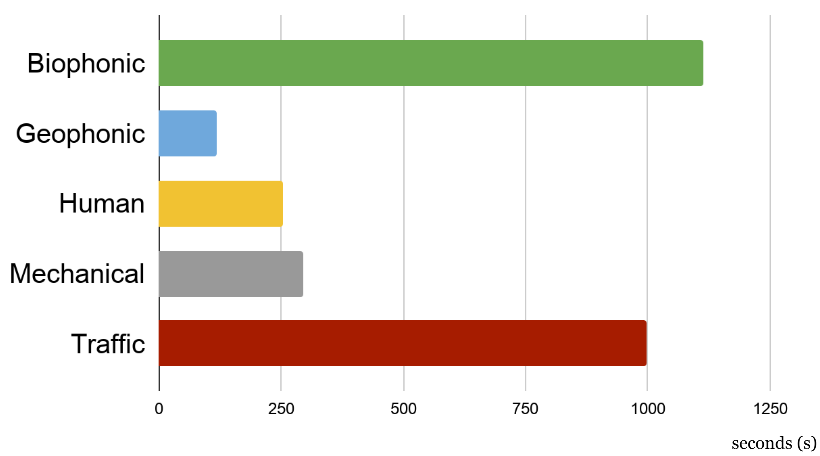

Figure 6. Logged Mask duration of sound events by category

Biophonic and anthrophonic (specifically traffic noise) sounds have been found to be the dominant sound categories identified. In general, across all the study sites with varying landscape features, 40% of soundscapes were composed by M_D of biophonic sounds and 36% by M_D of traffic noise. Within the sounds categorized under the biophonic group, a major contributor to biophonic sounds are from birdsongs and sounds produced by crickets, while the main contributor to traffic noise is from the sounds of passing vehicles.

Within specific landscape features such as building (Figure 7), the soundscape composition is found to have a much lesser proportion of natural sounds (biophonic) identified. Residential spaces linked to the greenery in its landscape have a larger proportion of M_D of biophonic sounds detected, while residential spaces linked to waterbody in its landscape accounted for geophonic sounds and a larger M_D proportion of human sounds detected.

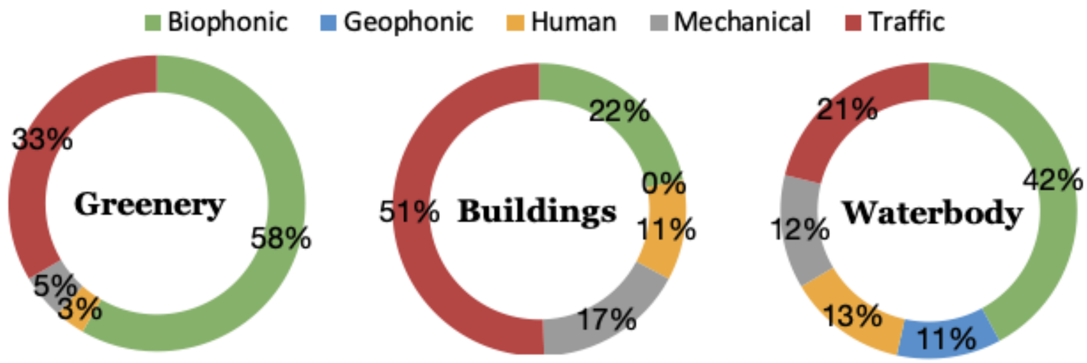

Figure 7. Soundscape composition of varying landscape features

The M_D of individual sound categories collected also contributed to a calculation of the percentage of mask duration that contains positive sound events (M_DSe^+). Existing literature in soundscape and noise annoyance studies has shown that sounds related to traffic and mechanical are considered undesirable, whereas biophonic, geophonic, and human (social activities) sounds are desirable [46]. The calculation for M_DSe^+ based on the M_D of different types of sound events is derived from Eq. 3, the results of this calculation for each site can be found in Appendix Table A1.

$$M_DSe^+ = \frac{M_{DBio}+M_{DGeo}+M_{DHuman}}{M_{DTraff}+M_{DMech}} \times 100\% \quad \text{(Eq 3)}$$

where M_{DBio} refers to the M_D (Mask duration) of biophonic sound events, M_{DGeo} the M_D of geophonic sound events, M_{DHuman} the M_D of human sound events, M_{DTraff} the M_D of traffic sound events and M_{DMech} the M_D of mechanical sound events.

3.2 Relationships between soundscape indicators and descriptors

An inter-rater reliability test was performed on the perceived affective quality scale of pleasantness, eventfulness, and OSQ. The results showed that pleasantness and eventfulness inter-rater reliability has an Intraclass Correlation Coefficient (ICC) value of 0.959 and 0.500, respectively, while OSQ have an inter-rater reliability ICC value of 0.942, which shows moderate to excellent agreement between raters on soundscape appraisal scores [47]. Thus, the reliability of the questionnaire responses from the participants is acceptable.

The median value of rater's appraisals collected from questionnaire responses are taken as the measure of central tendency at each site and tested using Spearman's rank correlation coefficient with objective data from acoustic, psychoacoustic, and audio features.

3.2.1 Correlation: Sound pressure levels and perceived sound sources

Traditional acoustic parameter L_{Aeq} collected in-situ is the most highly correlated with perceived sound sources of traffic ($r_s = .701$, $p < .01$) as well as the subjective visual perception of vehicle elements ($r_s = .682$, $p < .01$) and roads ($r_s = .691$, $p < .01$). The perceived sound sources of human and biophony show negative correlations to L_{Aeq} ($r_s = -.458$, $p < .05$) and ($r_s = -.616$, $p < .01$) respectively. These results reflect that the acoustic parameters are heavily influenced by noise generated from traffic in the context of residential spaces rather than from other sound sources.

The perceived affective quality of the soundscape is found to be well correlated with the acoustical parameters, L_{Aeq}, L_{Ceq}, and $L_{\mathrm{Ceq}} - L_{\mathrm{Aeq}}$ (low-frequency content). The Spearman's rho correlation coefficients ranged between 0.6 to 0.8. L_{Aeq} was negatively correlated with pleasantness ($r_s = -.754$, $p < .01$), vibrancy ($r_s = -.713$, $p < .01$) and positively correlated to annoyance ($r_s = .740$, $p < .01$). The correlation results for sound pressure level and perceived sound sources are shown in Appendix Table B1.

3.2.2 Correlation: Psychoacoustic measurements

The Spearman rank correlation analysis revealed that traffic-related factors such as M_{DTraff}, appears to have significant positive relationships with psychoacoustic features of loudness and roughness (r_s = .617, $p < .01$) and (r_s = .744, $p < .01$), suggesting that traffic contributed to not just loudness but also roughness. However, loudness and roughness are also strongly correlated to each other (r_s = .749, $p < .01$) and subjective studies found that subjects tend to match rough texture with sounds that are loud. [48]. Thus, the two psychoacoustic features of loudness and roughness may not be mutually exclusive. In terms of appropriateness, loudness is negatively correlated (r_s = -.806, $p < .01$), and L_{Aeq} is also negatively correlated (r_s = -.780, $p < .01$), which indicates that the appropriateness of an acoustic environment is dependent on the intensity of sound levels.

The overall soundscape quality and perceived affective quality of pleasantness are significantly correlated with loudness (r_s = -.782, $p < .01$) and roughness (r_s = -.785, $p < .01$), which is aligned with findings from other studies [28].

Sharpness is only found to be well correlated with M_{DBio} (r_s = .509, $p < .01$) and M_DSe^+, the percentage of M_D that consisted positive sound events (r_s = .520, $p < .01$). It is likely that M_DSe^+ in high-rise urban environments was mostly contributed by biophonic sound events, as sharpness is closely related to biophony since sounds from birds and insects tend to occupy the higher frequency range in order to overcome the low-frequency anthrophonic noises [49]. Appendix Table B1 summarizes the correlation results for psychoacoustic indicators.

3.2.3 Correlation: Audio features

Audio feature extraction tools such as MIR Toolbox have been widely used by musicologists and music researchers to identify musical features such as rhythm, pitch, harmony, or timbre, which has been used to classify music genres [50]. The application of audio features can similarly be applied to acoustic ecology.

Spectral skewness and kurtosis are widely correlated with soundscape factors, in regards to the perceived affective quality of soundscapes, inverse correlation was identified with some positive affective qualities, OSQ (r_s = -.481, p < .01), vibrancy (r_s = -.475, p < .01) and calm (r_s = -.476, p < .01). This suggests that soundscapes are undesired in cases of high spectral skewness and kurtosis, where the soundscape either has skewed frequencies or an excess level in a small region of frequencies.

Spectral roll-off was connected to the perceived sound sources of traffic (r_s = -.419, p < .05), since traffic noise causes a dominant low frequency spectral, creating a lower spectral roll-off. Spectral spread is correlated with a few perceived affective quality of soundscape, namely vibrancy (r_s = .398, p < .05) and calm (r_s = .405, p < .01). A larger spread of frequencies across the audible range where there are no excess level in any specific region of the audible range of our hearing likely contributes to a more calm and vibrant soundscape.

The audio feature for spectral flatness and brightness did not show significant correlation results. The results of audio feature correlations are shown in Appendix Table B1.

3.2.4 Correlation: Visual

Interestingly, visual factors that describes the visual dominance of vehicles and roads correlated negatively with OSQ (r_s = -.844, p < .01) and (r_s = -.812, p < .01) respectively. The negative correlation are also found in the affective qualities of the soundscape for pleasantness (r_s = -.845, p < .01), vibrancy (r_s = -.826, p < .01), and calm (r_s = -.800, p < .01). This suggests that the visibility of roadways and vehicles may have an influence on soundscape perception. On the other hand, a positive correlation can be seen on some affective qualities of the soundscape such as pleasantness with visual factors associated with greenery ($r_s = .544$, $p < .01$) and water bodies ($r_s = .487$, $p < .01$) as well as vibrancy with visual greenery ($r_s = .518$, $p < .01$) and visual waterbodies ($r_s = .584$, $p < .01$). The visual element of people is strongly correlated with eventfulness ($r_s = .718$, $p < .01$) which is within expectation, visual element of people also correlated with vibrancy ($r_s = .541$, $p < .01$), perhaps due to the sounds created by human activities. The visual factor of the sky is correlated with OSQ and pleasantness ($r_s = .625$, $p < .01$ and $r_s = .609$, $p < .01$, respectively) while the visual factor of buildings did not show any significant correlation with affective soundscape qualities. This suggests that the visibility of buildings does not influence the perception of soundscapes. In terms of appropriateness, both the visual factor of vehicles and roads correlated negatively with appropriateness ($r_s = -.841$, $p < .01$ and $r_s = -.798$, $p < .01$, respectively) while the visual factor of the sky, greenery, and people had positive correlations with appropriateness. The visual correlations results are summarized in Appendix Table B2.

3.3 Perceived affective quality of soundscape

Spearman's rank correlation coefficient is performed on the derived pleasantness and eventfulness, showing a positive correlation ($r_s = .402$, $p < .05$). Although previous literature has found an inverse relationship between the two derived attributes [51], this is largely dependent on the context or function of a space. In terms of the high-rise urban residential heartlands in this study, which function as living spaces, the positive correlation between pleasantness and eventfulness indicates that sounds of social activities and the sense of eventfulness are desirable and could complement the pleasantness of the soundscape in living spaces.

The bi-dimensional model of Pleasantness - Eventfulness (Figure 8) shows that the urban high-rise spaces near water bodies form the highest group in pleasantness and eventfulness ratings, which mostly occupies the first quadrant (vibrant) whereas spaces with heavy traffic conditions form the lowest pleasantness group (second and third quadrant).

The second and third quadrants can be considered as sites that are ‘chaotic’ and ‘monotonous’ respectively, the nine sites that occupy them only consist of sites with ‘heavy’ traffic [52].

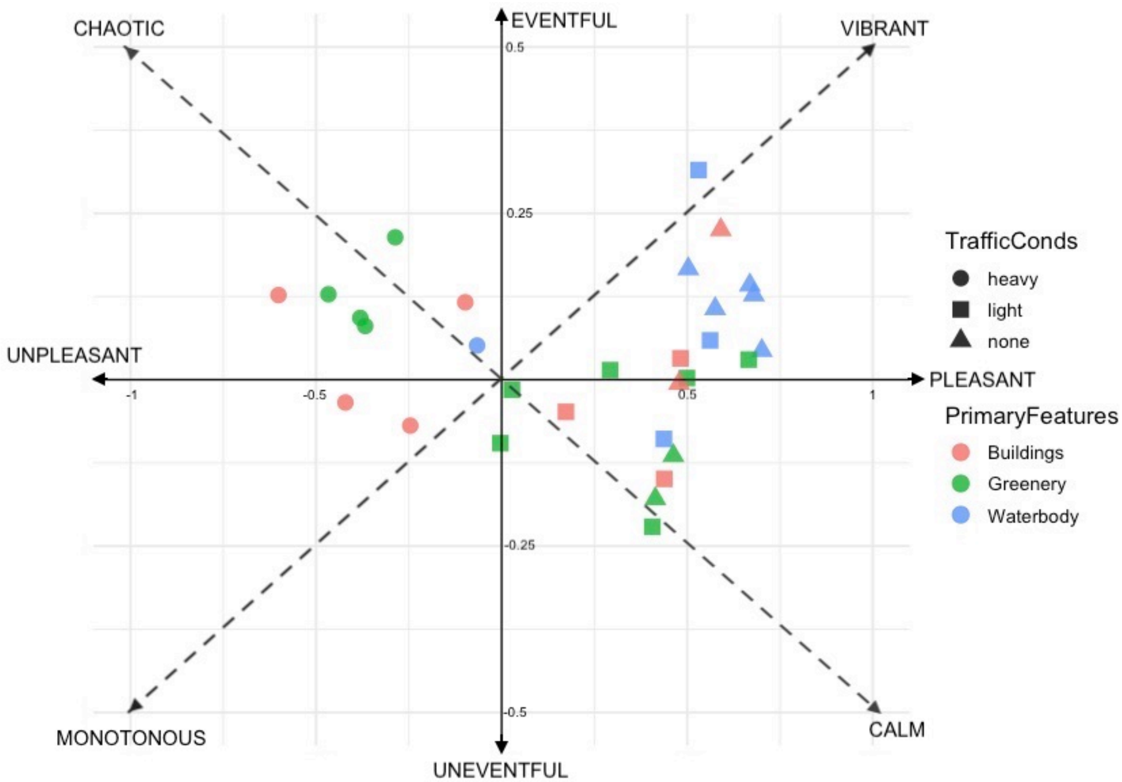

Figure 8. Pleasantness – Eventfulness bi-dimensional model (ISO 12913-3)

3.4 Modelling and prediction of soundscape’s overall sound quality

A predictive model for the soundscape has been sought to connect the physical and the perceptual experience of soundscapes. In this study, we propose a model to predict the effects of the objective indicators on soundscape using multiple linear regression analyses performed in a forward-backward stepwise selection.

Some objective indicators are removed from the analysis to avoid multicollinearity, while the highest explanatory variables are kept in the selection. L_{Ceq}, loudness, and L_{Aeq} are found to be highly correlated with each other ($|r_s| > 0.80$, $p < .01$) Thus, both $L_{Ceq,}$ and loudness are excluded from the selection. Spectral skewness is also excluded due to its collinearity with spectral kurtosis ($|r_s| > 0.80$, $p < .01$). Spectral brightness and spectral flatness both had no significant correlation with OSQ to be modeled and are excluded from the selection ($|r_s| < 0.30$, $p > .05$). In the forward-backward stepwise selection, the inclusion criteria for the F-statistics significance value of each variable is preset to 0.05 while the exclusion criteria for each variable is preset to an F-statistics significance value of .10. This allows for all the variables to be tested, then each variable is removed or entered one at a time to determine the most significant variables and optimal model for the prediction of OSQ. Additionally, variables that have a variance inflation factor (VIF) of greater than 10 are excluded from the regression model [53-55], the eventual model had a VIF factor lower than 5 for each variable retained in the model. [56]

The resulting model (Eq 4) optimized through backward stepwise selection for predicting OSQ has an adjusted R^2 = .854 and is formed with the following variables L_{Ceq} - L_{Aeq}, $M_D Se^+$, and roughness. (Table 5) The use of L_{Ceq} - L_{Aeq} which is calculated from the difference between the C – weighted and A – weighted equivalent sound levels in the model represents the low frequeny content of the soundscape, psychoacoustic roughness included in the model helps to complement the model's prediction of overall sound quality as it accounts for sensory dissonance that may be contributed from engine noise from motorcycles, ships or airplane. $M_D Se^+$ represents the mask duration of unique sound events that contribute positively to the soundscape such as from natural or geophonic sounds.

$$Overall\ Sound\ Quality = 2.302 - 1.008R + 0.973(M_D Se^+) + 0.07(LCeq - LAeq) \quad \text{(Eq 4)}$$

Table 5. Optimised regression model for overall sound quality in Singapore high-rise residential spaces

		Unstandardised Coefficients		**Standardised Coefficients**			**Collinearity**
Model	Predictors	Regression Coefficient	Std. Error	Beta	Sig.[a]	Sig.[b]	VIF
Overall Sound Quality (Eq 4) R^2 = 0.869 R^2 adj = 0.854	(Constant)	2.302	0.509		<.001**	<.001**	
	Roughness	-1.008	0.291	-0.473	<.001**		2.312
	$M_D Se^+$	0.973	0.317	0.365	<.001**		1.750
	L_{Ceq} - L_{Aeq}	0.07	0.03	0.261	.007**		1.544

*** = p < 0.01 and p = < 0.05 ; [a] means significance of regression coefficient, [b] means significance of regression equation*

3.5 Effects of traffic and landscape on overall sound quality

To establish the effects of the traffic condition and varying landscape features on soundscape perception, a two-way repeated-measures ANOVA is conducted, examining the within-subject effects of traffic and landscape features, as well as the interactions between traffic and landscape features on OSQ. Partial eta-squared, η_p^2 values were reported to indicate the effect size.

The result shows that the main effect of traffic [$F(1.283,12.829) = 41.812$, $p < .01$, $\eta_p^2 = 0.807$] and the main effect of landscape features [$F(2,20) = 6.803$, $p < .01$, $\eta_p^2 = 0.405$] are both statistically significant, as shown in Table 6. However, there is no significant interaction between traffic conditions and landscape features on OSQ. [$F(1.903,19.028) = 1.601$, $p = .228$, $\eta_p^2 = 0.138$] Thus, we can conclude that traffic conditions and landscape features independently has a main effect on OSQ in the case study of residential spaces.

Table 6. Summary of ANOVA results for Overall Sound Quality (OSQ)

Factors of OSQ	df_1	df_2	F	p	η_p^2
Traffic Conditions [a]	1.283	12.829	41.812	<.001	0.807
Landscape Features	2.000	20.000	6.803	.006	0.405
Traffic * Landscape [a]	1.903	19.028	1.601	.228	0.138

[a] *Assumption of sphericity was violated and Greenhouse-Geisser correction was applied*

A post-hoc test of pairwise comparisons using Bonferroni correction reveals that between no traffic and light traffic, the OSQ ratings only elicited a slight reduction ($OSQ_{None} = 4.071 \pm 0.166$ vs $OSQ_{Light} = 3.747 \pm 0.083$), which was not statistically significant ($p = .293$). (Table 7)

However, in the case of heavy traffic, there are statistically significant differences between heavy to light or no traffic ($p < .05$). Therefore, we can conclude that heavy traffic condition elicits a significant reduction in OSQ to no traffic, but light traffic does not elicit a significant reduction in OSQ to no traffic. The mean rating score of OSQ drops significantly in the condition of heavy traffic (OSQ = 2.379 ± 0.123) as compared to light traffic (OSQ = 3.747 ± 0.083) and no traffic (OSQ = 4.071 ± 0.166) as shown in Table 7. Thus, light traffic conditions may be considered tolerated in the context of the urban high-rise residential environment. However, this finding may only be of relevance to residents who have lived for a long period of time in a dense urban city, as traffic is prevalent in urban cities like Singapore even in some residential areas.

Table 7. Pairwise comparisons of traffic types

(I) Traffic	Mean OSQ	Std. Error	(J) Traffic	Mean Difference (I-J)	Std. Error	Sig.[b]	*95% Confidence Interval for Difference [b]*	
							Lower Bound	Upper Bound
None	4.071	0.166	Light	0.323	0.177	.293	-0.185	0.831
			Heavy	1.692*	0.258	<.001	0.952	2.432
Light	3.747	0.083	None	-0.323	0.177	.293	-0.831	0.185
			Heavy	1.369*	0.134	<.001	0.983	1.754
Heavy	2.379	0.123	None	-1.692*	0.258	<.001	-2.432	-0.952
			Light	-1.369*	0.134	<.001	-1.754	-0.983

* the mean difference is significant at the .05 level. [b] Adjustment for multiple comparisons: Bonferroni

In regards to landscape features, the mean rating scores of OSQ are similar between the landscape of greenery (OSQ = 3.265 ± 0.093) and building (OSQ = 3.301 ± 0.070). However, across sites with the landscape of waterbody, there is a higher mean rating of OSQ (3.631 ± 0.098). The post-hoc test of pairwise comparison using Bonferroni correction (Table 8) shows that there are significant differences between the landscape of waterbody and the landscape of building ($p < .05$) but there is no significant differences between the landscape of greenery and building ($p > .05$) as well as between the landscape of waterbody and greenery ($p > .05$). This suggests that the features of waterbody can help improve the quality of soundscapes as compared to building landscapes.

Table 8. Pairwise comparisons of landscape features

(I) Landscape	Mean OSQ	Std. Error	(J) Landscape	Mean Difference (I-J)	Std. Error	Sig.[b]	*95% Confidence Interval for Difference* [b]	
							Lower Bound	Upper Bound
Greenery	3.265	0.093	Building	-0.035	0.112	1.000	-0.356	0.285
			Waterbody	-0.366	0.134	.064	-0.752	0.019
Building	3.301	0.070	Greenery	0.035	0.112	1.000	-0.285	0.356
			Waterbody	-0.331*	0.074	.004	0.543	-0.118
Waterbody	3.631	0.098	Greenery	0.366	0.134	.064	-0.019	0.752
			Building	0.331*	0.074	.004	0.118	0.543

* the mean difference is significant at the .05 level. [b] Adjustment for multiple comparisons: Bonferroni

An independent samples *t*-test demonstrates significant difference in OSQ scores for the landscape of waterbody (M = 4.02, SD = 0.52) as compared to the landscape of greenery (M = 3.23, SD = 0.92); $t(19)=-2.295$, p = .033. Supporting the previous findings, there is also significant differences in OSQ scores for the landscape of waterbody (M = 4.02, SD = 0.52) as compared to the landscape of building (M = 3.15, SD = 0.96); $t(16)=2.369$, p = .031. However, there is no significant effect on OSQ between the landscape of greenery and the landscape of building; $t(19)$ = 0.202, p = .842, and the mean values are quite similar for both landscapes as shown in Figure 9. This similarity in OSQ ratings in the vastly different landscapes may be due to different factors moderating the experience of the soundscape. One possible explanation may be that the lack of natural sounds in the landscape of building is made up for by the sounds of human and social activities which may be preferred in residential settings. Figure 7 in Section 3.1 shows that the soundscape composition in the landscape of greenery has a large proportion of biophonic sounds M_{DBio} = 58% but only a small percentage of M_{DHuman} = 3% while the landscape of building has a higher proportion of sounds from human activities M_{DHuman} = 11% while still retaining some amount of biophonic sounds M_{DBio} = 22%. In the landscape of waterbody, the OSQ ratings are the highest which may be explained by the large proportion of both biophonic M_{DBio} = 42% and sounds from human activities M_{DHuman} = 13%.

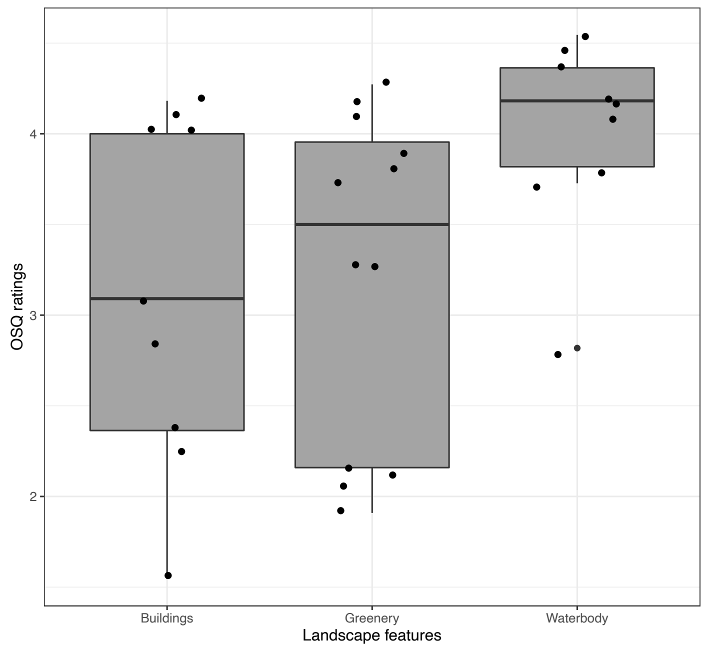

Figure 9. Boxplot of landscape features and OSQ ratings

4. Discussion

When we consider the overall sound quality of the soundscape, the effects of heavy traffic had the most potential to be detrimental to the soundscape, we found insufficient evidence for the visual landscape to alleviate or moderate on the soundscape with the exception of the visual landscape of waterbody. Rather, we recognized that the soundscape composition which is comprised of individual sound sources from the environment may have strong contributions to the soundscape, further research on the experience of specific individual sound sources will be studied in the future. This is also reinforced by the OSQ model (Eq 4), which revealed that the mask duration of positive sound events is a significant factor for OSQ predictability.

4.1 Soundscape composition

The main contributor of the soundscape composition in the study sites based on MD belonged to biophonic and traffic sound sources. In general, biophonic sounds contributed 40% of the soundscape composition while traffic sounds contributed 36% (Figures 5, 6) and the contribution varied in different landscape features (Figure 7). For comparison, Liu, J. (2015) case studies in Germany and China detected between 9.1% to 29.4% of birdsongs in the study's sampled sites, which also differed in landscapes. [57] The importance of biophonic sounds from sources such as birdsongs cannot be overstated. [58-59][45] In a biophilic city such as Singapore, the urban green spaces provides birds with the natural ecosystem to flourish, Didem, D. (2020) proposes that a key indicator for a biophilic urban ecosystem is the soundscape quality associated with green spaces. [60]

4.2 Effects of visual landscape features

In regards to the effects of different visual landscape features, only the landscape of waterbody had significant differences in OSQ ratings, a study by Liu, J. (2013) found that visual landscapes did not seem to have a considerable effect on preference for sounds [35] and indicated that preference for certain sounds is formed in their life experience which could not be affected by short term visual satisfaction. A more recent in-situ soundwalk study by Li, H. et al. (2021) also concluded that natural sound sources produce more restorative benefits through EEG experiments than simply strengthening positive visual aspects of the environment. [61] Thus, the significant differences in OSQ ratings found in the visual landscape of waterbody for the current study may be moderated via the perception of individual sounds (biophonic, geophonic, and human activities) in the landscape rather than directly from the visual landscape itself. While the OSQ ratings for the landscape of greenery and building did not show significant differences, both landscapes could also be moderated by individual sound sources in the soundscape such as the sounds of human social activities for building landscapes and biophony for greenery landscape. Nielbo, F. et al. (2013) found that human activities in the urban environment have a strong link to soundscape perception if the activities are afforded to in the soundscape. [62-63]

Moreover, the bi-dimensional model of Pleasantness-Eventfulness (Figure 8) when we only consider light and none traffic conditions reveal a tendency for visual landscapes of waterbody to be in the first quadrant (vibrant) while the visual landscapes of building and greenery occupying the fourth quadrant (calm). This indicates that dominant sound sources in the landscape of waterbody provided a more 'vibrant' soundscape while sound sources in landscapes of greenery and building provided a 'calm' soundscape. This suggests that vibrant soundscapes in waterbody landscapes may be rated more highly in OSQ ratings as compared to calm soundscapes from landscapes of greenery and building, since only waterbody visual landscapes had a significant difference in OSQ ratings while building and greenery visual landscapes did not. In a study by Aletta, F. & Kang, J. (2018) study of urban vibrancy, it was concluded that the presence of people (in both aural and visual cues) was relevant for the perception of a vibrant soundscape. [64-65] It may be possible that the vibrancy in the landscape of waterbody was mainly contributed by the sounds of human social activities followed by biophonic sounds.

4.3 Effects of traffic conditions

In regards to the effects of traffic conditions, Li, H. & Xie, H. (2021) indicated that 75% of roadside residents identified traffic noise as 'very' or 'extremely' annoying. [66] Careful consideration by urban planners and developers should be given to residential developments situated near heavy traffic (expressways, major arterial roads). In comparison to light traffic, the significant reduction in OSQ reflects the potential for noise annoyance to affecting health, social cohesion, and other detrimental effects. [2-3] Besides conventional noise control interventions, traffic noise can also be moderated by reducing direct line-of-sight to visual elements related to traffic.

We discovered from Spearman's correlation that the visibility of roadways and vehicles had a significant negative correlation on soundscape appraisals and more specifically the ratings of OSQ by participants. Bangjun, Z. et al. (2003) studied the visibility of noise sources coming from road traffic and concluded that noise annoyance was higher corresponding to the visibility of the road traffic noise source. [67] With that in mind, the ratings of OSQ in spaces with traffic visibility could be moderated by blocking the direct line-of-sight to the vehicles and roads using various greenery or artificial elements like green belts or artificial man-made elements. Yang, F. et al.

(2011) study on landscape plants found that greenery could provide psychological noise reduction to road traffic noise. [68] The efficacy of controlling the visibility of roadways and vehicles and its effect on the soundscape could be investigated further in the future with an emphasis on using greenery elements in particular while comparing to artificial elements like conventional road barriers. [69]

4.4 Prediction of Overall Sound Quality (OSQ)

The regression model developed in the study (Eq 4) on OSQ revealed the most important factors from multiple indicators and variables that were included in the study. The variables used in Eq 4 demonstrated that the psychoacoustic indicator of roughness and the soundscape composition factor ($MDSe^{+}$) could be applied in a regression model to predict OSQ. The regression models can be useful in future soundscape research. For instance, a soundscape mapping of a city based on OSQ which is similar to that of a noise map may be beneficial for urban planners in soundscape management. However, it is not straightforward to extend a soundscape map of a subjective quality such as OSQ over an entire city as it will require collections of subjective experiences at every location of interest. An alternate method is proposed through the use of OSQ derived from the regression model based on the multiple variables identified in this study may be useful for simulating soundscape maps of urban cities with high-rise residential living without the need to collect a large data of subjective experiences. The applicability of soundscape maps as a tool for urban planners was demonstrated by Aletta, F. & Kang, J. (2015) and Margaritis, E. & Kang, J. (2017) in two UK studies when the soundscape mappings were used complementarily with noise maps and ‘sound’ maps. [70-71] However, soundscape mapping research is still at an early stage especially in regards to simulation and prediction of soundscape maps, more studies in this area will be beneficial for soundscape research.

5. Limitations

Several limitations are inherent in the study, firstly, the small size of participants of 11 may cause higher variability in our results and the results presented may be different in a similar large-scale study. Secondly, because there are more females than males in the study, there may be more gender-related discrepancies in our study. One such discrepancy may be the emotional aspect of rating each soundscape since females are generally found to be more sensitive in emotional appraisals of sounds that are emotionally meaningful such as church bells, music, or children's voices. [38, 72] There could be a bias towards favoring more extreme ratings in the appraisals for affective soundscape qualities. Thirdly, the range of participant's age group is between 21 to 27 years old. Thus, the results may not reflect the preferences of other age groups. Finally, because of the nature of the study in the context of residential urban environments, the predictive model of sound quality (Eq 4) may not accurately represent that of other spaces such as rural environments or differences in space functions and context.

While participants agree on certain affective qualities of the soundscape in the urban high-rise environment, we found that there may be definitional and conceptual differences in the interpretation of eventfulness for soundscapes. Some participants may deem that social activities and the sounds of social events lead to a more eventful soundscape. On the other hand, some participants may deem an environment that has a myriad of discrete sound events such as biophony leads to a more eventful soundscape, even if the sound does not originate from anthrophonic sources such as human social activities. Thus, it may be beneficial for future research to address the interpretation of eventfulness by briefing participants or making a clearer contextual definition for eventfulness in soundscape evaluations.

6. Conclusion

High-rise urban residential environment averaged $L_{\mathrm{Aeq},15}$ was 57.6 dBA in Singapore, which reflects the sound levels around housing and lived environments. The noise level of the city is expected to be higher in business districts and industrial regions. Beyond acoustic sound levels, we find that the soundscape composition in Singapore's high-rise residential spaces are generally dominated by biophonic (40%) and traffic (36%) sounds which are based on the proportion of M_D (mask duration) in different categories of sounds. It is beneficial to have a positive soundscape for residents to live comfortably where desirable sound sources such as birdsongs, water sounds or human activities are the dominant sounds that can be heard by individuals. The overall sound quality of the soundscape can also help identify spaces with positive soundscape quality or pinpoint areas where with the need for soundscape intervention is required. In the present study, various traffic conditions and landscape features are identified and the differences in overall sound quality ratings with different combinations were analyzed using two-way repeated-measures ANOVA, the results identify the statistically significant main effect of traffic conditions as well as landscape features on overall sound quality. We conclude that there is no statistically significant difference between light and no traffic in the context of an urban city on overall sound quality, which may suggest tolerance to light traffic but not to heavy traffic. With that in mind, we recommend that urban planners and designers should take into consideration the type of traffic and its proximity to residents when planning residential projects and infrastructure developments.

In regards to soundscape indicators, acoustic and psychoacoustic indicators such as L_{Aeq}, loudness, and roughness correlated strongly with affective soundscape qualities, whereas audio features correlated moderately with affective soundscape qualities. A predictive model for the overall sound quality of soundscapes is developed with proposed soundscape indicators based on Eq 4, which uses roughness, L_{Ceq} - L_{Aeq}, and the mask duration of positive sound events. This model explains 85.4% of the variance. The sound quality regression model can be used to predict soundscape overall sound quality in a residential urban setting, which may be useful to monitor and manage the soundscape perception of residents as well as applicability in soundscape mapping.

Declaration of competing interests

The authors declare that they have no competing financial interests or personal relationships that could have influenced the research or conclusions of this paper.

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Appendices

Table A.1 : Measurement data for Acoustic, Psychoacoustic and Audio Parameters

S/N	Site names	Traffic Conditions	Primary Features	LAeq (dBA)	LCeq (dBC)	Loudness (sones)	Sharpness (acums)	Roughness (aspers)	M_DSe^+	ZCOA	Spectral Centroid	Spectral Spread	Spectral Rolloff	Spectral Flatness	Spectral Brightness	Spectral Skewness	Spectral Kurtosis	L_{AF5}	L_{AF10}	L_{AF90}	L_{AF95}
1	Yishun 430B	heavy	Greenery	63.4	74.1	19.520	1.604	0.293	0.280	1052	3031	3805	7370	0.070	0.483	1.586	4.75	67.2	65.64	54.96	52.9
2	Yishun 816	heavy	Waterbody	60.1	71.5	15.114	1.383	0.609	0.480	720	2205	3226	4097	0.047	0.385	2.279	8.06	63.7	63.04	53.14	51
3	Punggol 305D	light	Greenery	59.4	72.5	13.544	1.675	0.159	0.138	745	3526	4181	8242	0.091	0.531	1.403	4.14	63.3	60.89	48.74	49.1
4	Punggol 678	none	Waterbody	58.6	69.4	15.109	1.959	0.050	0.952	1765	5459	5317	12034	0.133	0.629	0.667	2.08	63.2	58.92	49.31	47.7
5	Bishan 126	light	Buildings	59.9	70.2	14.976	1.324	0.080	0.095	802	2701	2998	3652	0.056	0.362	2.484	9.25	64.9	63.13	51.3	50.1
6	Bishan 241	none	Waterbody	50.1	64.87	8.550	2.054	0.054	0.962	1392	3956	4546	10382	0.058	0.491	0.735	1.91	54.1	51.23	46.01	45.7
7	Ang Mo Kio 119	heavy	Buildings	65.2	73.9	19.340	1.462	0.653	0.186	550	2201	3539	4894	0.055	0.345	2.193	7.35	66.7	64.24	55.88	55.1
8	Yishun 407	none	Greenery	50.7	64.9	8.772	1.567	0.084	0.730	1532	3757	4764	11646	0.060	0.459	1.056	2.60	55.1	53.31	47.15	46.9
9	Admiralty Link 490	none	Buildings	55.2	66.1	10.995	1.839	0.123	0.935	1454	3577	4400	9722	0.064	0.456	1.086	2.78	57.3	55.65	50.07	49.6
10	Clementi 428	heavy	Buildings	70.8	79.8	28.310	1.426	1.457	0.000	971	2522	3573	5279	0.059	0.410	2.199	7.42	72.9	72.3	68.74	68.2
11	Pandan Gardens 405	light	Waterbody	54.6	71	11.147	1.384	0.175	0.244	642	2386	3631	6156	0.059	0.355	1.902	5.82	57.7	56.52	51.98	51.7
12	Hougang 653	light	Buildings	49.8	63.5	7.946	1.500	0.068	0.759	917	2901	4189	7263	0.083	0.409	1.784	5.31	43.6	52.63	45.82	64.5
13	Upper Serangoon 470	light	Greenery	48.9	64.2	7.551	1.597	0.037	1.000	953	3016	4157	9658	0.055	0.395	1.310	3.26	44.3	50.46	46.26	65.6
14	Hougang 476B	none	Waterbody	54.8	69.9	9.920	1.211	0.060	1.000	507	2012	3381	4213	0.039	0.283	2.193	6.98	57.1	56.05	52.37	52.1
15	Pasir Ris 707	none	Greenery	46.6	64.5	6.507	1.584	0.023	0.853	808	2846	3817	7252	0.050	0.451	1.528	4.32	49.3	48.3	44.4	44.1
16	Pasir Rise 534	light	Waterbody	52.9	69.1	9.742	1.505	0.080	0.542	720	2804	3726	6773	0.057	0.467	1.673	5.03	55.3	53.97	49.02	48.5
17	Pasir Ris 414	light	Buildings	57.3	78.7	11.813	1.320	0.026	0.252	685	2539	3647	6370	0.081	0.396	1.818	5.58	63.7	58.89	45.79	45.3
18	Fajar 405	light	Waterbody	53.8	69.5	10.402	1.515	0.049	0.448	1250	2822	3942	6674	0.040	0.423	1.644	4.47	56.6	55.77	50.42	49.9
19	Bukit Batok 523	light	Greenery	56.6	69.5	12.704	1.618	0.126	0.506	1066	3474	4493	8911	0.078	0.486	1.484	4.34	61.1	59.15	51.55	50.8
20	Bukit Batok 180	heavy	Greenery	65.4	76.3	21.240	1.372	0.606	0.457	668	2258	3527	5206	0.063	0.335	2.131	6.86	67.5	66.59	62.93	62.2
21	Punggol 323	none	Waterbody	56.9	72.6	8.148	1.215	0.058	0.411	355	2145	3463	4694	0.049	0.345	2.198	7.33	61.6	52.56	47.28	49.3
22	Ang Mo Kio 259	light	Greenery	51.3	65.8	8.808	1.905	0.033	0.763	742	3000	3651	7206	0.052	0.475	1.365	4.16	54.4	53.37	47.99	47.2
23	Whampoa 85	heavy	Buildings	70	76.8	24.870	1.197	1.244	0.000	680	1776	2738	2991	0.041	0.314	2.938	12.40	71.7	71.16	68.49	68.2
24	Bain St 233	heavy	Buildings	60.8	74	15.886	1.260	0.329	0.113	421	1644	2833	3049	0.050	0.288	2.805	11.21	63.3	62.48	57.37	56.9
25	Tampines 856	none	Buildings	63.7	81	15.483	1.519	0.020	0.571	847	3715	4412	9090	0.088	0.546	1.247	3.51	68.9	64.56	44.67	44.2
26	Bedok 740	none	Waterbody	50.6	69.2	8.633	1.603	0.024	0.821	1128	3442	3987	7943	0.085	0.555	1.381	4.13	54.4	52.79	45.82	45.1
27	Ghim Moh 22	light	Greenery	48.7	67	7.155	1.704	0.045	0.867	630	2587	3733	6897	0.070	0.406	1.691	4.91	52.3	50.69	45.61	45.2
28	Stirling 167	heavy	Greenery	66.5	79.1	23.700	1.788	1.149	0.178	1184	4053	4287	9196	0.092	0.599	1.130	3.40	70.5	69.16	61.51	60.3
29	Telok Blangah 84	light	Greenery	58.6	68.7	14.214	1.771	0.095	0.631	1354	3409	4197	8273	0.070	0.503	1.351	3.83	62.8	60.2	49.28	48.8
30	Marine Parade 29	heavy	Greenery	65.5	78.2	20.820	1.236	1.135	0.006	403	1669	2901	3187	0.028	0.275	2.724	10.54	69.1	67.61	61.95	61.4

M_DSe^+ = Mask duration of positve sound events, ZCOA = Zero crossings overall average

Table A1. Collected Measurement Data for Acoustic, Psychoacoustic and Audio Parameters

Table A.2 : Collected questionnaire data (mean)

S/N	Site names	Traffic Conditions	Primary Features	Pleasant	Chaotic	Vibrant	Uneventful	Calm	Annoying	Eventful	Monotonous	OSQ	Overall Tranquility	Overall Satisfaction	ISO Pleasantness	ISO Eventfulness
1	Yishun 430B	heavy	Greenery	2.73	5.36	3.27	3.73	2.18	5.55	3.27	3.91	2.18	2.64	2.55	-0.381	0.093
2	Yishun 816	heavy	Waterbody	4.09	4.64	4.27	3.82	3.82	4.73	3.73	3.91	2.82	3.45	3.45	-0.066	0.051
3	Punggol 305D	light	Greenery	4.18	4.09	3.64	4.09	4.45	3.91	3.55	4.45	3.27	3.45	3.55	-0.003	-0.095
4	Punggol 678	none	Waterbody	6.09	2.73	5.82	3.27	5.73	2.00	4.82	2.82	4.18	4.36	4.18	0.575	0.107
5	Bishan 126	light	Buildings	4.91	3.36	4.64	4.18	4.09	3.36	3.55	4.00	3.09	3.73	3.55	0.173	-0.048
6	Bishan 241	none	Waterbody	6.45	1.73	5.91	2.91	6.27	1.64	4.64	2.91	4.55	4.55	4.64	0.701	0.044
7	Ang Mo Kio 119	heavy	Buildings	2.45	5.18	2.82	4.36	2.64	5.27	3.55	4.91	2.36	2.91	2.73	-0.421	-0.034
8	Yishun 407	none	Greenery	5.36	2.64	4.55	4.36	5.82	2.00	3.64	4.00	3.82	4.27	3.91	0.414	-0.179
9	Admiralty Link 490	none	Buildings	6.09	2.45	6.18	2.73	4.91	1.91	5.09	2.45	4.18	3.64	4.18	0.590	0.225
10	Clementi 428	heavy	Buildings	1.82	5.91	2.45	3.45	1.73	6.09	3.82	4.55	1.55	1.55	2.27	-0.601	0.127
11	Pandan Gardens 405	light	Waterbody	5.64	2.82	4.91	4.00	5.64	2.45	3.55	3.27	3.73	4.00	4.18	0.437	-0.089
12	Hougang 653	light	Buildings	6.00	2.73	4.91	3.27	5.73	2.36	4.64	3.18	4.00	4.36	4.09	0.482	0.032
13	Upper Serangoon 470	light	Greenery	5.73	2.36	5.27	3.55	5.91	2.55	4.55	3.09	3.91	4.36	4.27	0.499	0.002
14	Hougang 476B	none	Waterbody	6.18	2.73	5.73	3.00	6.00	1.64	4.55	1.73	4.36	4.55	4.55	0.669	0.142
15	Pasir Ris 707	none	Greenery	5.73	2.36	5.18	4.36	5.64	2.82	3.55	3.09	4.09	4.45	4.36	0.463	-0.114
16	Pasir Rise 534	light	Waterbody	5.82	3.00	6.09	2.09	5.27	2.18	5.82	2.64	4.09	3.91	4.18	0.531	0.315
17	Pasir Ris 414	light	Buildings	5.73	2.18	4.45	4.00	5.82	2.27	4.09	4.00	4.00	4.27	3.91	0.438	-0.149
18	Fajar 405	light	Waterbody	6.00	2.55	5.64	3.55	5.64	2.36	4.27	2.36	3.82	4.36	4.36	0.562	0.059
19	Bukit Batok 523	light	Greenery	5.36	3.27	4.64	3.64	5.09	3.64	3.91	2.91	3.73	3.91	3.91	0.292	0.014
20	Bukit Batok 180	heavy	Greenery	2.82	5.09	3.64	3.09	2.73	5.36	4.45	3.55	2.09	2.82	3.45	-0.287	0.214
21	Punggol 323	none	Waterbody	6.09	2.91	5.73	2.82	5.45	2.73	4.91	2.73	4.18	4.18	4.27	0.503	0.167
22	Ang Mo Kio 259	light	Greenery	5.73	2.36	4.64	4.55	5.64	2.55	3.27	4.09	4.18	4.00	4.00	0.406	-0.221
23	Whampoa 85	heavy	Buildings	3.00	4.55	3.00	4.36	3.18	4.64	3.36	4.36	2.27	2.91	3.18	-0.246	-0.069
24	Bain St 233	heavy	Buildings	3.91	4.27	3.82	3.36	3.36	4.36	4.73	4.27	2.82	3.27	3.64	-0.098	0.116
25	Tampines 856	none	Buildings	5.82	2.55	5.36	3.36	5.64	2.36	4.18	3.55	4.09	4.18	4.18	0.478	-0.006
26	Bedok 740	none	Waterbody	6.36	2.36	5.82	3.09	6.09	1.73	5.00	2.18	4.45	4.36	4.55	0.680	0.127
27	Ghim Moh 22	light	Greenery	6.18	1.91	5.64	3.09	6.36	2.00	4.36	2.36	4.27	4.36	4.09	0.666	0.030
28	Stirling 167	heavy	Greenery	2.18	5.91	3.55	4.00	2.00	5.73	3.55	4.18	1.91	2.09	2.18	-0.467	0.128
29	Telok Blangah 84	light	Greenery	4.00	4.18	4.00	3.91	4.36	3.73	3.82	4.00	3.27	3.91	3.55	0.028	-0.015
30	Marine Parade 29	heavy	Greenery	2.82	5.27	3.45	4.27	2.55	5.64	4.09	4.27	2.09	2.45	2.55	-0.368	0.081

Table A2. Collected Questionnaire data (mean values)

Collected questionnaire responses are represented in mean values except for ISO Pleasantness and ISO Eventfulness derived from questionnaire responses
Pleasant, Chaotic, Vibrant, Uneventful, Calm, Annoying, Eventful and Monotonous are based on a 7-point Likert scale
OSQ, Overall Tranquility and Overall Satisfaction are based on a 5-point Likert scale
ISO Pleasantness and ISO Eventfulness are derived median values based on the ISO 12913-3 [34]

Table B.1 : Results of Spearman Coefficient Correlation for Acoustic, Psychoacoustic and Audio parameters

	Acoustic Parameters			Psychoacoustic Parameters			Audio Features	
	L_{Aeq}	L_{Ceq}	L_{Ceq}-L_{Aeq}	Loudness	Sharpness	Roughness	SSkewness	SKurtosis
OSQ	-.770**	-.617**	.651**	-.801**		-.822**	-.459*	-.481**
Pleasant	-.754**	-.587**	.656**	-.782**		-.785**	-.390*	-.423*
Chaotic	.831**	.637**	-.735**	.822**		.883**	.481**	.517**
Vibrant	-.713**	-.595**	.596**	-.724**		-.715**	-.450*	-.475**
Calm	-.842**	-.639**	.735**	-.829**		-.824**	-.437*	-.476**
Annoying	.740**	.600**	-.603**	.719**		.727**	.472**	.494**
Eventful				-.368*				
Monotonous	.660**	.511**	-.554**	.651**		.601**		
Appropriate	-.775**	-.606**	.705**	-.806**		-.837**	-.420*	-.454*
MD Traffic	.600**	.473**	-.527**	.617**		.744**		
Perc. Traffic Sounds	.701**	.526**	-.663**	.734**		.821**	.470**	.494**
Visual Vehicles	.682**	.557**	-.580**	.701**		.748**	.467**	.499**
Visual Roads	.691**	.577**	-.569**	.697**		.706**	.512**	.545**
MD Biophony	-.554**	-.622**		-.457*	.509**		-.567**	-.588**
Perc. Biophony Sounds	-.616**	-.422*	.591**	-.568**		-.734**		
Perc. Human Sounds	-.458*	-.376*	.376*	-.488**		-.504**		
MDSE+	-.752**	-.759**	.413*	-.712**	.520**	-.677**	-.642**	-.661**

** . Correlation is significant at the .01 level (2-tailed).* . Correlation is significant at the .05 level (2-tailed).

N = 30 *Table B1. Spearman Correlation Coefficient for Acoustic, Psychoacoustic and Audio Features Correlation*

Table B.2 : Results of Spearman Coefficient Correlation for visual dominance of visual elements

	Visual dominance of elements based on subjective evaluations					
	Visual Vehicles	Visual Roads	Visual Greenery	Visual People	Visual Sky	Visual Water
OSQ	**-.844****[**]	**-.812****[**]	**.509****[**]	.459[*]	**.625****[**]	.392[*]
Pleasant	**-.845****[**]	**-.806****[**]	**.544****[**]	.454[*]	**.609****[**]	**.487****[**]
Chaotic	**.782****[**]	**.786****[**]	**-.478****[**]		-.408[*]	
Vibrant	**-.826****[**]	**-.791****[**]	**.518****[**]	**.541****[**]	**.564****[**]	**.584****[**]
Uneventful	.383[*]	.372[*]		**-.701****[**]	-.363[*]	**-.573****[**]
Calm	**-.800****[**]	**-.789****[**]	**.630****[**]		.408[*]	
Annoying	**.842****[**]	**.828****[**]	**-.529****[**]	**-.475****[**]	-.457[*]	-.378[*]
Eventful	**-.488****[**]	**-.490****[**]		**.718****[**]		**.507****[**]
Monotonous	**.690****[**]	**.675****[**]	**-.652****[**]	-.453[*]	**-.539****[**]	**-.699****[**]
Appropriate	**-.841****[**]	**-.798****[**]	**.521****[**]	**.474****[**]	**.580****[**]	.435[*]

** . Correlation is significant at the .01 level (2-tailed).* . Correlation is significant at the .05 level (2-tailed).
N = 30 *Table B2. Spearman Correlation Coefficient for visual dominance of visual elements.*