Research Article

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Spatial evaluation of environmental noise with the use of participatory sensing system in Singapore

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Abstract: Existing studies in Singapore on environmental noise are scarce and limited in scale due to the need for expensive equipment and sophisticated modelling expertise. This study presents the approach of using participatory sensing and mobile phones to monitor environmental sound levels around Singapore. iPhones running the AmbiCiti application was adopted to sample equivalent continuous 30-second average outdoor sound levels ($L_{Aeq,30sec}$). The aggregated mean of each region was evaluated and the spatial distribution of environmental noise was analysed using noise maps generated from the measurement data. A total of 18,768 $L_{Aeq,30sec}$ measurements were collected over ten weeks. About 93.6% of the daytime measurements (07:00 – 19:00) exceeded the WHO recommended level of 55 dBA to minimise negative non-auditory health effects due to noise. The results of this study suggest that the population of Singapore is potentially at risk of adverse non-auditory health effects and, to a lesser extent, hearing loss due to community noise levels. However, the measurements exceeding 70 dBA were frequent enough to warrant concern about contributions to the cumulative lifetime sound exposure contributing to hearing loss. The work also demonstrates that sound maps of an area can be efficiently generated using calibrated applications running on smart phones.

Keywords: environmental noise, noise exposure, participatory sensing, noise mapping

List of abbreviations

$L_{Aeq,24h}$	Equivalent continuous 24-hour average sound level
$L_{Aeq,30sec}$	Equivalent continuous 30-second average sound exposure
L_{den}	Day-evening-night level. It is the equivalent continuous average noise exposure over a day, with penalty of 5dB and 10dB applied to evening (19:00 – 23:00) and night-time (23:00 – 07:00) noise respectively
CBD	Central business district
dBA	A-weighted decibels
GIS	Geographic information systems
IDW	Inverse distance weighted interpolation
WHO	World Health Organisation

1 Introduction

Environmental noise is an issue commonly faced by the denizens of urbanised and urbanising areas worldwide. It is defined as noise generated from all sources, excluding sources of occupational noise exposure in workplaces [1]. Studies in many large cities over several continents have reported their populations are exposed to high level of environmental noise with traffic and transportation noise as main contributors [2–5].

There is growing evidence regarding the negative impact of noise on health. Non-auditory effects of noise like cardiovascular and metabolic effects [6, 7], sleep disturbance and interference [8], cognitive impairment [9, 23], annoyance [10] and mental health impacts [11, 12] have been described. Lifelong exposure to sound level of more than 70 A-weighted decibels (dBA) equivalent continuous 24-hour average sound level ($L_{Aeq,24h}$) increases the risk of noise-induced hearing loss, especially for vulnerable groups with increased susceptibility to the harmful effects of noise [13].

An evaluation by the World Health Organisation (WHO) on the burden of disease due to environmen-

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tal noise concluded that at least one million disability-adjusted life years were lost annually in western Europe due to the undesirable health impacts caused by traffic related noise. A major part of the burden was contributed by sleep disturbance and annoyance, which accounts for 903,000 years and 654,000 years respectively [14]. This level of burden places environmental noise as the second most pressing environmental issue after air pollution. Significant economic savings and gains with the reduction of environmental noise by 5 dB have been reported in one recent study [15]. The negative health effects due to environmental noise have prompted WHO to introduce guidelines on the recommended sound levels to mitigate effects due to environmental noise [1, 14, 16].

Studies in Singapore on environmental noise are scarce, limited in scale, and have focused mainly on traffic noise in the daytime and evening time [17, 18]. Sy *et al.* conducted a two-phase study, conducting 10-minute measurements from 16:00 to 19:00 at over 300 sites in the first phase and 3-minute measurements at fixed half-hourly intervals at 20 selected sites from 09:00 to 19:00 [17]. Bhanap did continuous sampling at 1-minute intervals from 08:30 to 22:00. The reported sound levels from traffic from these studies ranged from 60 to 74 dBA depending on the traffic conditions [18].

To investigate the impact of localised community noise in high-rise residential environments, Alam, Eang, Tan, & Tiong conducted sound level measurements at 10-minute intervals at building façades and investigated upward noise propagation from five identified sources of community noise. They also interviewed residents from five residential estates that included food centres, children's playgrounds, soccer fields, basketball courts, and waste disposal trucks to investigate their subjective responses to community noise. The measured daytime $L_{Aeq,16h}$ from different scenarios near ground level ranged between 51 and 79 dBA, with increases in elevation leading to reduced $L_{Aeq,16h}$ values. The study also found that 78% of the respondents felt slightly, quite, or very disturbed by these community noises, with a significant proportion (33%) of the respondents experiencing sleep disturbance [19].

Extensive sound mapping has been challenging due to the need for expensive equipment and sophisticated modelling expertise. The need for extensive data on local outdoor noise conditions persists for several reasons:

1. To monitor the levels of environmental noise around the country so as to set a reference for policy makers.
2. To enable the development and enforcement of policies for local noise regulation.

3. To facilitate urban planning, especially in land-scarce countries like Singapore.
4. To improve public knowledge and awareness, and to shape opinion about noise pollution.

There is growing interest in the use of participatory sensing for monitoring environmental noise levels due to the relatively low cost and increasing worldwide penetration of smartphones capable of measuring sound levels [20–22, 24–26]. This strategy is based on a person-centric collection of environmental data. NoiseSPY, EarPhone and NoiseTube were the first few functional outdoor environmental noise sensing systems relying on mobile phones to facilitate mass participation environmental monitoring and assist in environmental data collection on a large scale [25, 27, 28]. Multiple short sound measurements were recorded by volunteers with their smart phones at different locations. Other data captured by these sensing systems includes username, journey ID, the last valid GPS location and time collection. Studies have been carried out on the accuracy of smartphone sound sensors for noise study. When properly calibrated, these smartphone sound sensors could achieve performance similar to professional sound level meters [20]. However, the accuracy of measurements is affected by factors like the types of phones (iOS/ Android), the condition of the phones, the way the users carry their phones and the geographical topology and meteorological factors (altitude, vibration, wind, air pressure, etc.) [20, 29–31]. Comparison with official simulated noise maps is challenging due to the difference in approach and data representation. However, noise maps generated from these data have generally shown similar overall sound level distribution when compared to official simulated noise map [20]. More recent participatory sensing initiatives have included soundscape sensing, which investigated the subjective assessment of sound levels, sound comfort levels and sound harmoniousness levels. The inclusion of a large network of participants in data collection enhanced data collection efficiency and enabled accumulation of large data sets for soundscape research, design and planning [32, 33].

The present study utilized participatory sensing and mobile phones to measure outdoor environmental sound levels in Singapore. The study also compared measured sound levels to recommended guidelines for environmental noise and assessed the associated potential risk of negative non-auditory and auditory effects. Through the utilization of geographic information systems (GIS), this study provided an overview of general trend of the spatial sound distribution and local variations in sound levels across Singapore.

Figure 1: Demarcated regions of Singapore

2 Methodology

2.1 Study area and land use zoning

Singapore is a metropolitan city with an overall population of 5.7 million in 2019 [34]. The city is divided into five main regions: North, North-east, West, East and Central based on the Urban Redevelopment Authority's Master Plan 2019 (Figure 1). There are a total of fifty-five planning zones in the city [35]. The land area has been designated into zones for different uses like industrial, commercial, park, restricted and residential use zones. Data collection for this study focused mainly on publicly-accessible commercial and residential zones.

2.2 Sound measurement application and smart phone platform

The AmbiCiti sound measurement application was first launched in the Apple App Store in late 2016. It is a collabora-

tive effort of mainly French and other European institutions (Ambiciti SAS, Alphand, Paris, France). Only iPhone 5s, 6, 6s and 7 models (Apple Inc, Cupertino, CA, USA) were utilised for this study to minimize measurement variability between devices. Calibration was performed in an acoustically treated room with a Type II Sound Level Meter (3M SoundPro SE/DL). A Genelec 8020C Studio Meter speaker connected to a pre-amplifier (RME Fireface UCX) was used for the presentation of calibration noise. Both the iPhone and the sound level meter were placed 1 m away from the speaker. The mobile application was calibrated with pink noise presented at 75 dBA. Measurements were taken for five seconds by the mobile application and compared to the sound level meter. This process was repeated thrice and the average of the difference of these measurements between the two devices was chosen as the correction factor for any sound measurement made by the phone. Measurements made by three calibrated iPhones (Model: 5s, 6 & 7) were compared with the sound level meter to establish the linear region of the mobile application. The application was verified to operate with the precision and ac-

Figure 2: iPhone sound pressure level versus reference sound pressure level

curacy of ± 2 dB within the range of 40 to 80 dBA under controlled environment (Figure 2) [36]. Greater variations were observed outside this range. All measurements made with this mobile application include geotagging.

2.3 Sound level measurements

This study was reviewed and approved by the National University of Singapore Institutional Review Board (NUS-IRB Reference number: B-16-215). Fifty-two volunteers of aged 24 to 44 years old participated in this study. The volunteers recruited were iPhone users, without consideration on the place of residence. Volunteers were encouraged to take measurements using their iPhones at any time or place with no assignment made to measure specific regions. They were instructed on proper measurement techniques and to take only outdoor sound measurements. Examples of outdoor environmental sounds to measure that were provided to participants included subway station platforms or bus stops, walkways along roads, open areas outside shopping malls or other buildings and common areas in residential estates (e.g., playgrounds, basketball and badminton courts, and soccer fields). Participants had to manually switch the mobile application on and off in order to measure their environmental sounds. The

application was set to acquire 30-second duration sound samples ($L_{Aeq,30sec}$). GPS location coordinates and accuracy were recorded by the application during all sound level measurements. Other collected data include User ID, date, time and bias value of the device. The application measured sound pressure levels, but it did not distinguish the source of noise or collect the frequency spectrum of the measured sounds. All participants exported the measured data files from their phones (.csv format) and emailed the data to the investigator at the end of study. Data measurements were collected for a period of ten weeks from mid-December 2016 to end of February 2017. Only data with a GPS accuracy value of ≤ 50 meters were included for analysis. The collated measurements were segregated into daytime (07:00 – 19:00), evening (19:00 – 23:00) and nighttime (23:00 – 07:00) data.

2.4 Comparison of sound levels to WHO guidelines

Sound measurements taken in this study were compared to WHO guidelines for community noise [16]. These are guideline values to reduce critical health effects due to noise at specific environment. WHO Europe has also recently released a similar guideline for noise level in Eu-

Table 1: WHO guideline values for community noise

<i>Specific environment</i>	<i>Critical health effects</i>	<i>L_{Aeq} / dBA</i>	<i>Duration / hours</i>	<i>$L_{Amax,fast}$ / dBA</i>
Outdoor living area	Serious annoyance & adverse health effects	55	12 [07:00 – 19:00]	
		50	4 [19:00 – 23:00]	
		45	8 [23:00 – 07:00]	
Outside bedroom	Sleep disturbance, window open (outdoor values)	45	8 [23:00 – 07:00]	
Industrial, commercial, shopping and traffic areas, indoors and outdoors	Hearing impairment	70	24	110

rope, with the exception that the recommended standards are set for specific noise source [1]. Comparison between these two guidelines found similar recommendation levels for health effects like annoyance and sleep disturbance. The guideline values used for comparison in this study are presented in Table 1.

WHO uses day-evening-night noise level (L_{den}) to assess the risk of serious annoyance and adverse health effects from environmental noise. The use of L_{den} includes 0 dB, 5 dB, and 10 dB penalties that are applied to daytime (07:00 – 19:00), evening (19:00 – 23:00) and night-time (23:00 – 07:00) measurements respectively. All $L_{Aeq,30sec}$ daytime measurements in this study were compared to the 55 dBA limit, while $L_{Aeq,30sec}$ evening and night measurements were compared to 50 dBA and 45 dBA limits respectively. To assess night-time effects like sleep disturbance, a 45 dBA limit was used to compare data measured in the period between 23:00 and 07:00.

2.5 Sound level measurement data mapping

Collected daytime sound level data sets were collated from all participants and integrated with spatial information using an open-source Quantum Geographic Information System (q-GIS) program (Free Software Foundation, Inc, Boston, MA, USA). Sound level contours of the measured data were constructed with inverse-distance weighted (IDW) interpolation method to identify local areas of relatively high sound levels. The IDW method uses a weighted interpolation algorithm to estimate sound levels at unmeasured locations [26]. GPS locations were based on the World Geodetic System 1984 EPSG:4326, two-dimensional geographical Coordinate Reference System and plotted using Google Maps (Google, Inc., Mountain View, CA, USA) [37].

Map layers with regional boundaries were obtained from an open database established by the Government of Singapore [35].

2.6 Analysis

Descriptive statistics for the overall and individual regions were computed at different period of the day. The exceedance fraction of measurements exceeding each of the relevant WHO guideline values to minimise critical health effects were also computed overall and for individual regions.

Kruskal-Wallis test was used to compare the data sets from the different regions in Singapore. Welch's t-test was utilised to compare between areas inside and outside the Central Business District (CBD) within the central region of Singapore.

3 Results

A total of 18,768 valid sound level measurements were collected over ten weeks, totalling 156.4 hours of measurement time. The measured data covered a total of 597.2 km² of the total 725.7 km² land mass area of Singapore. Daytime sound level measurements comprised 70.4% of the overall data, while evening time and night-time data made up 24.6% and 5% of the overall data respectively. Outdoor $L_{Aeq,30sec}$ levels ranged from 36.4 to 82.2 dBA, with an overall daytime measured mean and standard deviation $L_{Aeq,30sec}$ of 68.0 ± 6.4 dBA. The overall evening time and night-time measured mean and standard deviation were 67.4 ± 7.2 dBA and 63.4 ± 7.2 dBA respectively.

The majority of the data were clustered in the Central, West and North-east regions of Singapore, comprising 52.6%, 22.2% and 11.1% of the total measurements re-

Table 2: Descriptive statistics of measured $L_{Aeq,30sec}$ data points based on regions

Regions	Covered Area (km ²)	N _{Total} ^a	Measured mean (Std. Dev.) (dBA)			N (% ^b) ≥ 55 dBA	N (% ^b) ≥ 50 dBA	N (% ^b) ≥ 45 dBA	N (% ^b) ≥ 70 dBA
			Day	Evening	Night	[07:00 – 19:00]	[19:00 – 23:00]	[23:00 – 07:00]	
			[07:00	[19:00	[23:00				
			– 19:00]	– 23:00]	– 07:00]				
North	112.1	1030	63.5 ^c (5.6)	69.2 ^d (5.7)	68.5 (6.6)	810 (90.1)	105 (98.7)	30 (96.7)	126 (12.2)
North-east	57.9	2088	70.0 ^c (5.5)	64.6 ^d (7.8)	64.5 (8.8)	1228 (98.9)	751 (90.7)	22 (91.7)	638 (30.5)
East	98.2	1612	69.1 ^c (6.3)	65.7 ^d (8.8)	64.7 (7.9)	895 (96.1)	513 (88.6)	108 (99.1)	452 (28.0)
West	195.5	4164	66.4 ^c (6.5)	66.6 ^d (5.5)	61.6 (7.0)	2182 (89.4)	1184 (99.7)	534 (98.7)	722 (17.3)
Central	133.5	9874	68.4 ^c (6.3)	69.1 ^d (6.5)	65.1 (5.5)	7244 (94.1)	1905 (99.5)	262 (100)	3085 (31.2)
Overall	597.2	18768	68.0 (6.4)	67.4 (7.2)	63.4 (7.2)	12359 (93.6)	4458 (96.6)	956 (98.9)	5023 (26.8)

^a N_{Total} refers to the total number of measurements taken in the day, evening and night-time.

^b The exceedance fraction is calculated based on the number of measurements obtained within the stipulated time frame at the location.

^{c-d} Calculated with Kruskal-Wallis test, $p < 0.0001$ for the comparison between different regions of Singapore in the daytime and evening time

Table 3: Descriptive statistics of measured $L_{Aeq,30sec}$ data points in CBD and non-CBD areas on weekdays, weekends, and overall

		Covered Area (km ²)	N _{Day} ^a	Measured daytime mean (Std. Dev.) (dBA)	N (% ^b) of measurements ≥ 55 dBA [07:00 – 19:00]	N (% ^b) of measurements ≥ 50 dBA [19:00 – 23:00]	N (% ^b) of measurements ≥ 45 dBA [23:00 – 07:00]	N (% ^b) of measurements ≥ 70 dBA
CBD	Weekday	24.7	1083	69.8 (6.9)	1007 (93.0)	538 (100)	22 (100)	717 (43.6)
	Weekend		87	68.3 (4.2)	87 (100)	30 (100)	1 (100)	43 (36.4)
	Combined		1170	69.7 ^c (6.7)	1094 (93.5)	568 (100)	23 (100)	760 (43.2)
Non-CBD	Weekday	572.5	8063	68.3 (6.1)	7681 (95.3)	2742 (96.1)	834 (98.9)	3187 (27.1)
	Weekend		3949	66.7 (6.8)	3556 (90.0)	1149 (96.2)	99 (98.0)	1078 (20.5)
	Combined		12012	67.8 ^c (6.4)	11237 (93.5)	3891 (96.1)	933 (98.8)	4265 (25.1)

^a N_{Day} refers to the total number of measurements taken in the daytime.

^b The exceedance fraction is calculated based on the number of measurements obtained within the stipulated time frame at the location.

^c Calculated with Welch's t test (Two-tailed), $p < 0.0001$ for the comparison between combined measured daytime mean in CBD and non-CBD areas.

spectively. The measured means, standard deviations and exceedance fractions of the overall city and the individual regions based on WHO recommended limits at different time of the day were tabulated (Table 2) (see the Appendix for the breakdown of measurements based on planning areas). The fraction of $L_{Aeq,30sec}$ measurements above

the WHO recommended levels to minimise non-auditory effects were calculated. The five regions in Singapore had daytime mean sound levels between 63.5 dBA and 70.0 dBA. The evening time mean sound levels of different regions ranged from 64.6 dBA to 69.2 dBA while the night time mean sound levels ranged from 61.6 dBA to 68.5 dBA.

Figure 3: Interpolation of daytime measured sound levels across Singapore

The measured levels differed significantly between the regions in the daytime and evening time (Kruskal-Wallis test, $p = <0.0001$). Results from this study showed 93.6% of the $L_{Aeq,30sec}$ measurements in the daytime exceeded 55 dBA limit for serious annoyance and adverse health effects. This number increased to 96.6% in the evening time using the 50 dBA recommended limit while 27% of the measurements exceeded 70 dBA, the 24-hour L_{Aeq} guideline for preventing noise-induced hearing loss based on cumulative lifetime sound exposure for 40 years. Nearly all (98.9%) of the $L_{Aeq,30sec}$ measurements at night-time exceeded the guideline limit of more 45 dBA to minimise serious annoyance and sleep disturbance.

The measurement data were segregated based on CBD and non-CBD areas. The data were further stratified into weekdays and weekends to investigate the effect of day of the week on measured levels. The mean daytime sound level measured across all days in CBD areas was 69.7 dBA, compared to a 67.8 dBA mean in non-CBD areas. Levels in CBD and non-CBD areas were significantly different for weekdays and weekends (Welch's t test, $p < 0.0001$). The

CBD areas also revealed 93.5% and 43.2% of sound measurements exceeding the WHO recommended limits of 55 dBA in the daytime and 70 dBA for non-auditory and auditory health effects respectively. Non-CBD areas had 93.5% and 25.1% exceeding the same limits respectively (Table 3).

Over 90% of the sound measurements were gathered in residential and commercial areas of planning areas in Singapore. A few of the planning areas have no recorded data. These include Lim Chu Kang, Simpang, North-Eastern Islands, Changi Bay, Paya Lebar and Western Islands.

Interpolation of the measurement data revealed that areas with relatively high sound levels were mainly located in the Central Business District (demarcated by a blue line) and from Hougang extending to Serangoon in the north-east region of Singapore (Figure 3).

4 Discussion

4.1 Overall findings

This study is the first outdoor sound level assessment that involved public participation to document sound levels around Singapore using a phone application. More than three-quarters of the area in the country was covered within the ten weeks of this study, with an overall measured daytime mean $L_{Aeq,30sec}$ of 68.0 dBA. The overall measured means were reduced to 67.4 dBA and 63.4 dBA in the evening time and night-time respectively. Results from the study suggests a large proportion of the local population are potentially exposed to levels of environmental noise that exceed WHO recommended standards, putting them at risk for negative health effects. Over 90% of the measurements exceeded the WHO guideline levels to mitigate serious annoyance and adverse health effects, regardless of the period of day. An average of 25% of the measurements exceeded 70 dBA $L_{Aeq,24h}$ guideline limit for preventing noise-induced hearing loss based on cumulative lifetime sound exposure for 40 years. Close to 98% of the data points collected between 23:00 and 07:00 were found to exceed the recommended levels of 45 dBA to minimise sleep disturbance in the night-time. Differences in sound levels were found between regions in Singapore and between CBD and non-CBD areas. The spatial variability in sound measurements may indicate variation in the impacts of environmental noise in different areas of the country. This variability in measurements could be utilised to identify areas for intervention and noise abatement.

4.2 Comparison between regions

The results revealed that the main areas identified having high measured sound levels are in the CBD and in the northeast regions of Singapore consisting of mature residential neighbourhoods. The CBD area is the main commercial hub of the city-state with high density of high-rise buildings and an extensive network of roads in place. A number of small residential estates are located within the CBD areas. The residential areas with high measured sound levels comprised mainly mature neighbourhoods with more than 20 years of development (Ang Mo Kio, Bedok, Bukit Merah, Geylang, Kallang/Whampoa, Queenstown, Tampines and Toa Payoh) and the first suburban regional centres (Tampines) in the country. These areas have higher road density as compared to other areas of Singapore [38, 39].

Significant differences in environmental sound levels were found between the five regions in Singapore. The north and west regions of Singapore recorded lower daytime mean levels as compared to other regions of Singapore. Local census revealed that close to half of the population in the north region takes public transport (Mass Rapid Transit) to work [40]. This region encompasses the central water catchment area and agricultural and industrial zones, which are generally less populated than residential zones. The west region includes a heavy industrial zone with low population density. Road density is also lower in these two regions as compared to other regions. These features are reflected in Figure 3, which illustrates those acoustic characteristics vary between regions, with relatively quiet areas found in the north and west. Significant difference was identified in the daytime sound level measurements between the CBD and non-CBD areas on both weekdays and weekends. The combined mean sound level measured in the CBD area was 2 dB higher than non-CBD areas in the daytime. This finding is consistent with results shown in Figure 3 which illustrate the CBD as an area with higher measured sound levels in the daytime as compared to other parts of Singapore.

4.3 Comparison of current study with past local studies

The measurements made in this study revealed mean daytime sound levels ranging from 60.6 dBA to 74.3 dBA recorded from different planning areas in Singapore. This result is comparable to previous local studies done in the past 35 years [17–19]. The main difference between the current study and past studies is that sound measurements were made without specifying the source of noise. The sound measurements recorded in this study could therefore include traffic noise, community noise and other non-occupational noise. Sound measurements were also made over an extensive area of Singapore, instead on the previous focus on small or specific areas in Singapore. Similar to the findings from past studies, there was an overall trend of higher sound levels for measurements made close to roads with heavy traffic as compared to areas with light traffic.

4.4 Health implications

The findings made in this study indicate that the community is at risk for negative non-auditory health impacts due to noise. Noise annoyance and sleep disturbance were

identified as two key negative health impacts potentially affecting the local population. The impact of annoyance is influenced by the time of day, with penalty applied to the WHO recommended level L_{Aeq} of 55 dBA for evening and night time [16]. The sound level L_{Aeq} at the outside façade of buildings should not exceed 50 dBA and 45 dBA during evening and night-time respectively.

An aspect to highlight about annoyance is that its effect is not entirely determined by the acoustical characteristics of the noise (source and exposure), but also non-acoustical aspects of economic, social or psychological nature. Individual reaction to a specific sound may also have an influence on the impact of the sound on the individual. Vulnerable and sensitive groups like elderly, young children, individuals with mental health issues and shift workers are likely to be more affected by environmental noise than the general population. One reported effect is sleep disturbance. The impact of night-time noise is considered more deleterious as compared to daytime noise over the long term due to its impact on sleep. Continuous undisturbed sleep of a certain length is required for daytime alertness and performance, quality of life (QoL), and health [41]. Human beings perceive, assess, and respond to environmental sounds even while asleep [42]. The implication of night time noise is evident from the release of 'Night Noise Guidelines for Europe' in 2009 [43] and also 'Environmental Noise Guidelines for the European Region' in 2018 [1].

The recommended limit $L_{Aeq,24hr}$ of 70 dBA is intended to reduce the risk of any measurable hearing loss in the population to nearly zero over a 40-year exposure period [13]. Chronic sound exposure due to leisure and occupational activities beyond the recommended limit contributes to the risk of hearing loss in addition to environmental noise. As decibels are in logarithmic scale, a small increase in exposure level can significantly increase the risk of noise-induced hearing loss. The proportion of measurements exceeding 70 dBA were frequent enough to warrant concern about contributions to the cumulative lifetime sound exposure contributing to hearing loss.

The mean daytime outdoor environmental noise level of 68.0 dBA recorded in this study is comparable to normal conversational speech at 60 to 70 dBA. Listening effort is known to increase with ambient environmental sound, with listeners having to use additional cognitive resources to understand speech [44]. This is particularly a challenge for individuals with hearing impairment, who need a higher signal-to-noise ratio compared to normal-hearing individuals for speech comprehension. Young children in school are also particularly prone to external environmental noise outside classroom, which can lead to distraction

from learning in addition to potential speech masking effects.

4.5 Limitations

One main limitation of this study is that measurements recorded by the application in this study were averaged over 30 seconds and therefore may not be reflective of the acoustic characteristics in one location over a prolonged period. The guideline values used in this study are also an average of measurements over the period of 24 hours (L_{den}) or 8 hours (L_{night}). The use of mobile phones for sound level measurements in this study does not serve to replace traditional noise mapping. Instead, these point-in-time measurements served as a complimentary survey tool for acquiring a large number of sound measurements to screen and evaluate potential areas with high measured sound levels and ascertain the potential risk of health effects resulting from environmental noise in the country. Future investigations using standard sound level measuring equipment may be used to focus on areas with relatively high measured sound levels and to determine the sources of noise in these areas. This idea is supported by some studies which have described that short-term measurements are generally similar across both time and location. D'Hondt *et al.* demonstrated that noise maps collated from a week-long measurement in a large city in Belgium with NoiseTube phone application were similar to their official city data [20].

To quantify noise exposure risk by the population, it is still important to collect personal dosimetry measurements to determine daily noise exposure levels for individuals [45]. This is particularly important to determine the risk of auditory effects or noise-induced hearing loss. This study likely underestimated the risk of noise-induced hearing loss as it did not account for the indirect consequences of environmental noise. The tendency to modify listening habits (e.g., increasing TV volume at home, increasing music level from personal music player) to overcome ambient noise may put individuals at greater risk for noise-induced hearing loss. The study also did not account for noise exposure from occupational activities.

The current study focused on sound pressure levels but not on the sound quality aspect of the measured sounds. Differences in the quality and characteristics of sounds may have an impact on human reactions, even at the same intensity levels [16, 32]. Future studies could look into this aspect to ascertain the relationship between the sound quality and the psychological and physiological

cal responses in humans (*i.e.*, annoyance and sleep disturbance).

The spatio-temporal density of the map was under sampled in many areas, especially at night-time, limiting the interpretation of the results in those areas and periods. Future work should more comprehensively address night-time noise exposures.

Singapore has many built-up areas with high-rise commercial and residential buildings in different regions. As sound measurements took place mainly at the ground level, the current study did not address how residents at different elevations above ground were affected by the same noise source. The geographical topology and meteorological factors were also not addressed in this study. These factors can help to improve the quality of noise mapping [46].

5 Conclusions

This study describes the first effort in Singapore to utilise participatory sensing as a strategy to screen and map out the country's outdoor sound level distribution. The approach made in this study deviates from conventional noise mapping which relies on professional sound level meters located at strategic positions and subsequent extensive computer modelling to generate simulated noise maps. The results from this study suggested that Singapore has a number of areas that exceed WHO health-based guidelines for community noise levels. More than 90% of the measurements, irrespective of the recorded time frame (day, evening or night), exceeded the recommended levels by WHO to minimise serious annoyance and other negative non-auditory health effects due to noise. The levels exceeding 70 dBA were frequent enough to warrant concern about contributions to the cumulative lifetime sound exposure contributing to hearing loss. The study highlights that a large proportion of the local population are potentially at risk of adverse noise-related health effects and underscores the need for policies and programs to address this problem. It also demonstrates that noise maps can be effectively and efficiently created with volunteers using calibrated phones and sound measurement applications. Noise maps obtained from this strategy can complement data obtained from traditional noise mapping.

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Data Availability Statement: The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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Appendix

Table S1: Descriptive statistics for measured $L_{Aeq,30sec}$ sound levels at different regions and planning areas

Region	Planning Areas	Area (km ²)	N _{Total} ^a	Mean $L_{Aeq,30sec}$ (Std. Dev.) (dBA)		N (%) ≥ 55 dBA (07:00 – 19:00)	N (%) ≥ 50 dBA (19:00 – 23:00)	N (%) ≥ 45 dBA (23:00 – 07:00)	N (%) ≥ 70 dBA
				Daytime	Evening time				
North	Central Catchment Area	37.15	815	62.7 (5.4)	–	726 (89)	–	–	48 (5.9)
	Woodlands	13.59	91	68.6 (5.6)	61.1 (6.7)	68 (100)	15 (88.2)	5 (83.3)	19 (20.9)
	Yishun	21.24	106	68.6 (3.8)	70.7 (3.1)	8 (100)	74 (100)	24 (100)	54 (50.9)
North-East	Ang Mo Kio	13.94	436	68.9 (6.0)	62.0 (9.6)	144 (97.3)	208 (74.2)	6 (75.0)	87 (20.0)
	Hougang	13.93	266	69.2 (5.6)	63.6 (5.6)	189 (96.9)	69 (97.2)	2 (100)	80 (30.0)
	Punggol	9.34	535	67.0 (4.2)	64.2 (5.6)	272 (100)	251 (98.8)	9 (100)	73 (13.6)
	Sengkang	10.59	354	67.9 (4.7)	67.5 (5.4)	147 (98.7)	202 (100)	5 (100)	83 (23.4)
	Serangoon	10.1	497	72.2 (5.5)	68.9 (4.2)	474 (99.8)	22 (100)	–	314 (63.1)
East	Bedok	21.69	1392	69.1 (6.4)	65.5 (9.0)	753 (95.9)	469 (87.7)	72 (98.6)	385 (27.7)
	Pasir Ris	15.02	135	68.4 (4.2)	66.6 (5.9)	80 (100)	23 (100)	32 (100)	31 (23.0)
	Tampines	20.89	83	70.1 (7.2)	68.1 (6.7)	57 (93.4)	19 (100)	3 (100)	34 (41.0)
West	Bukit Batok	11.13	2099	65.0 (6.8)	64.1 (5.5)	1048 (82.8)	445 (99.3)	379 (98.2)	252 (12.0)
	Bukit Panjang	8.99	57	68.3 (5.5)	75 (3.4)	22 (91.7)	29 (100)	5 (100)	35 (61.4)
	Choa Chu Kang	6.11	824	67.1 (3.7)	67.0 (3.9)	277 (99.6)	478 (100)	68 (100)	124 (15.0)
	Clementi	9.49	169	69.7 (4.2)	73.8 (6.5)	146 (100)	22 (100)	1 (100)	62 (36.7)
	Jurong East	17.83	342	69.0 (6.7)	68.0 (5.3)	183 (93.8)	65 (100)	82 (100)	122 (35.7)
	Jurong West	14.69	336	67.8 (6.1)	66.1 (5.3)	212 (98.1)	120 (100)	–	75 (22.3)
	Pioneer	12.1	69	66.6 (8.5)	67.3 (4.1)	43 (86.0)	19 (100)	–	12 (17.4)
	Western Water Catchment	69.46	225	65.3 (5.4)	62.6 (4.1)	208 (95.0)	6 (100)	–	33 (14.7)
Central	Bishan	7.62	223	70.0 (4.9)	67.1 (4.1)	184 (100)	38 (100)	1 (100)	82 (36.4)
	Bukit Merah	14.34	970	67.1 (6.0)	71.4 (6.0)	763 (95.0)	160 (100)	7 (100)	217 (22.4)
	Bukit Timah	17.53	226	71.7 (7.3)	70.7 (7.3)	142 (96.6)	75 (96.2)	1 (100)	134 (59.3)
	Downtown Core ^b	4.34	717	70.0 (3.3)	70.8 (4.7)	531 (99.8)	163 (100)	22 (100)	327 (45.6)
	Geylang	9.64	245	69.7 (4.8)	67.6 (5.2)	162 (99.4)	82 (100)	–	84 (34.3)
	Kallang	9.17	216	70.6 (5.7)	66.5 (4.4)	192 (100)	24 (100)	–	110 (50.9)
	Marina South ^b	1.62	185	65.8 (1.9)	69.9 (5.1)	11 (100)	174 (100)	–	66 (35.7)
	Marine Parade	6.12	177	70.8 (4.4)	67.8 (3.6)	79 (100)	98 (100)	–	57 (32.2)
	Museum ^b	0.83	69	69.1 (3.8)	–	68 (100)	1 (100)	–	21 (30.4)
	Newton ^b	2.07	54	69.8 (3.4)	65.7 (3.4)	21 (100)	33 (100)	–	13 (24.1)
	Novena ^b	8.98	50	71.5 (6.1)	77.1 (3.3)	43 (100)	7 (100)	–	23 (46.0)
	Orchard ^b	0.96	298	71.4 (6.6)	72.7 (4.5)	187 (96.4)	103 (100)	1 (100)	192 (64.4)
	Outram ^b	1.37	131	72.4 (3.2)	69.3 (6.2)	113 (100)	18 (100)	–	95 (72.5)
	Queenstown	20.43	5409	67.7 (6.3)	67.6 (7.5)	4262 (92.8)	719 (99.1)	90 (100)	1432 (26.5)
	Rochor ^b	1.62	61	69.9 (3.1)	67.0 (5.8)	55 (100)	6 (100)	–	25 (41.0)
	Tanglin	7.63	162	60.6 (8.7)	65.3 (2.3)	78 (53.4)	16 (100)	–	14 (8.6)
	Toa Payoh	8.17	591	68.9 (5.5)	70.0 (4.7)	316 (99.4)	132 (100)	141 (100)	185 (31.3)

^a N refers to the number of sound measurements.

^b Planning areas within the Central Business District (CBD).