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Title

Acoustical measurements and prediction of psychoacoustic metrics with spatial variation

Author names and affiliations

Kuen Wai Ma[a], Cheuk Ming Mak[b, *], Hai Ming Wong[a, **]

[a] *Faculty of Dentistry, The University of Hong Kong, Pok Fu Lam, Hong Kong Island, Hong Kong*

[b] *Department of Building Services Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong*

* Corresponding author. Tel.: 2766 5856; fax: +852 2765 7198; E-mail address: cheuk-ming.mak@polyu.edu.hk (C.M. Mak); address: Department of Building Services Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong.

** Corresponding author. Tel.: +852 2859 0261; fax: +852 2559 3803; E-mail address: wonghmg@hku.hk (H.M. Wong); address: Paediatric Dentistry and Orthodontics, 2/F Prince Philp Dental Hospital, 34 Hospital Road, Hong Kong.

Abstract

The use of sound pressure levels is not adequate to assess and predict environmental sound quality at different locations. Moreover, there is a lack of studies investigating the psychoacoustic metrics with spatial variation. This study aims to investigate (1) the effects of spatial factors (distance and sound emission orientation) on three physical acoustic metrics (root-mean-square sound pressure (P_{rms}), unweighted sound pressure level (L_Z), and A-weighted sound pressure level (L_A)) and two psychoacoustic metrics (total loudness (N) and sharpness (S)); and (2) the role of the metrics and their statistical parameters in characterizing acoustical properties, through measurements of steady directional high-frequency sound at different points in an anechoic chamber. The results indicate that the sound intensity metrics L_Z or L_A as well as the subjective loudness metric N are distance-dependent. The value of N was approximately equal to 0.727 times the original loudness when doubling the distance from the source. Strong correlations were found between four sound energy content-related metrics (P_{rms}, L_Z, L_A, and N). However, the fifth metric (S) was closely related to sound spectral content. Moreover, the interquartile range of N was found to be an option of representing sound temporal content. This is the first study to establish the predictability of psychoacoustic metrics with spatial variation. These findings provide new insight into environmental sound quality assessment and prediction.

Keywords: acoustic environment, loudness, sound quality prediction, psychoacoustics, spatial variation

1. Introduction

1.1.Acoustic metrics – physical acoustic metrics and psychoacoustics metrics

Successful acoustical measurements [1-3] are essential to assess and predict [4] the sound quality of the acoustic environment. Acoustic metrics are the numerical values used to characterize acoustical properties. Physical acoustic metrics and psychoacoustic metrics are two kinds of acoustic metrics applied in acoustical measurements. The determination of the physical acoustic metrics of sound energy content is the most common approach in traditional acoustical measurements [5-12], which basically relies on the measurement of physical acoustic metrics such as root-mean-square sound pressure (P_{rms}), unweighted sound pressure levels (L_Z), and A-weighted sound pressure levels (L_A). The metric L_A, which considers the frequency weighting of the human ear response, has been found to be correlated with occupants' health [5, 7, 10-12]. Since people are subjected to noise exposure in different environments, there is a trend of conducting both subjective and objective acoustical measurements [3, 13-16] in the analysis of human-environment interactions. One of the ways to improve acoustical measurements is to perform the measurement of physical acoustic metrics and psychoacoustic metrics simultaneously. Psychoacoustic metrics are designed to characterize the influence of sound on human perception [17]. Sound spectral information is converted into specific values during psychoacoustic metric calculations. Total loudness (N) and sharpness (S) are two well-developed psychoacoustic metrics to estimate the influence of sound on human perceptions of loudness and sharpness with subjective experimental data support. Nonetheless, the consideration of psychoacoustic metrics in noise restriction limits [18] is insufficient.

1.2.Knowledge gap in acoustical measurements in terms of psychoacoustic metrics

The configuration for the acoustical measurement of sound sources or the acoustic environment is usually regulated. Although occupants are in the same acoustic environment, the sounds that occupants are exposed to at different locations will be different. Even though there is only one resident, the resident's activities will also produce spatial variation from sound sources. The spatial variation [19-23], such as distance and emission orientation from sound sources, will affect the properties of the exposed sound. For example, road traffic noise in terms of L_A varies with distance from the noise sources [24], Consequently, advanced acoustical measurements require the adjustment of not only physical acoustic metrics but also psychoacoustic metrics for the effects of spatial variation. The accuracy of research findings will be questionable if the distances of the sound measurement points and occupants from the sound sources are different. Advanced acoustical measurements can provide a more accurate environmental evaluation, and hence improved monitoring of environmental sound quality. Nonetheless, the prediction methods for psychoacoustic metrics to describe environmental conditions are inadequate. A systematic search that followed PRISMA guidelines [25] was conducted to find out the studies about prediction of psychoacoustic metrics with spatial variation (see Fig. 1). Total 921 full-text, English, academic, journal articles were identified from two scientific electronic databases (ScienceDirect, including 3500 academic journals, and Scitation of American Institute of Physics). One hundred and twenty-eight articles that contained the measurement of psychoacoustic metrics *N* or *S* were found after the 1st screening of the relevant articles. This provided the evidence that psychoacoustic metrics were commonly applied for objective acoustical measurements (e.g. impulsive sounds [26], exhaust noise [27], motor noise [28], aircraft sound [29], refrigerator noise [30], etc.), with physiological assessments (e.g. [31-34]), with annoyance assessments (e.g. [35-37]), or as predictors of subjective responses to sounds (e.g. wind buffeting noise [1], noise of axial piston pumps [2], air-conditioning noise [3], high-speed train [13], aircraft noise [14], walking vibration noise [38], tyre–road noise [39], sounds in urban public open spaces [40] etc.). Although there were the studies covered either the element "sound quality prediction" [1-3, 14, 38-40] or "spatiotemporal variation" [19, 20, 22, 23, 41] none of them contained both two elements. For example, the acoustical measurements of aircraft noise under take-off and landing was conducted at the fixed distance [14]. The investigation of the psychoacoustic metrics prediction with spatial variation is still not available. Therefore, the first aim of this study is to investigate the effects of spatial variation in terms of distance and emission orientation on physical acoustic metrics (P_{rms}, L_Z, and L_A) and psychoacoustic metrics (N and S).

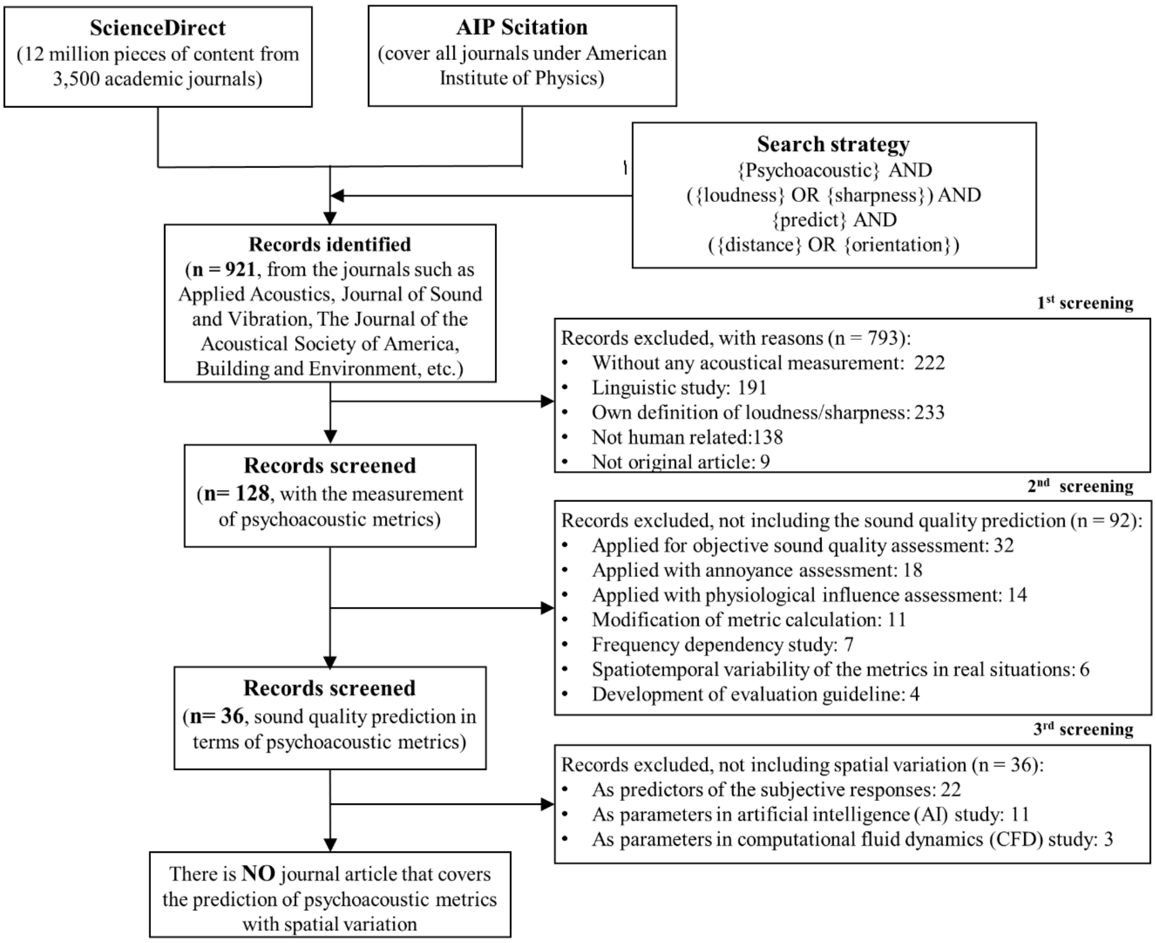

Fig. 1. PRISMA flow diagram of the search process. PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses.

1.3. Characterization of acoustical properties

The awareness of the negative perceptual influences [42-50] of environment on occupants has increased. Understanding the change in acoustical properties during sound propagation [51] is critical to the development of sound prediction methods [52-54]. Systematic review of the human perceptual dimensions of sound [55] has found that human perceptions of sound are influenced by not only the energy content but also the temporal and spectral content of sound. The analysis of the temporal and spectral content of sound is also important to understand occupants' responses [56-60]. The hypothesis of the fundamental structure of acoustic perceptual influences in three dimensions was further confirmed by the study of subjective scale development for sound quality assessment [61]. The multidimensional quantification of the objective acoustic environment by acoustical measurements is essential in the analysis of the influence of sound on occupants. Moreover, the study has found that the evaluation and prediction of different perceptual dimensions require a proper selection of acoustic metrics [14]. It is important to understand the meaning of acoustic metrics and establish a thoughtful and explicit acoustical measurement for future sound quality assessment and prediction activities in the field of characterization and analytical techniques of environmental impacts. Since acoustic metrics are time-varying data, the quantification of the temporal content of noise requires the calculation of the statistical parameters of the metrics. Hence, the second aim of this study is to compare the role of the following acoustic metrics: P_{rms}, L_Z, L_A, N, and S, and their statistical parameters in acoustical measurements and the acoustical properties represented by the metrics.

2. Material and methods

2.1.Experimental configuration

2.1.1. Anechoic chamber

The experiment was conducted in the anechoic chamber of Hong Kong Polytechnic University (outer shell: length × width × height = 9 m × 9 m × 6 m; inner shell: 6 m × 6 m × 3 m; free-field region: 4 m × 4 m × 1.3 m). The sound measurements were made under free-field conditions owing to the pyramidal radiation-absorbent material on the walls of the chamber. The background noise level of the anechoic chamber was controlled to be less than 15 dB. The cut-off frequency of the chamber was 80 Hz. The background noise level was much lower than the noise levels of the sound source in the experiment. The temperature and humidity of the anechoic chamber was recorded as 21.5–23.7 ℃ and 68–72%, respectively.

2.1.2. Sound source and Sound analyser

One criterion of sound source selection was that a sound source can be kept at a constant sound energy. Also, a sound source that can be found in real-life situation was preferred. High-frequency sound is widely accepted as a noise source in the environment [15, 57, 62-64]. A portable dental unit (GU-P206) that can create steady, directional, high-frequency, and continuous sounds from the high-speed dental handpiece was hence selected in this study. The measurements were conducted when the dental handpiece attained its maximum speed of 300, 000 revolutions per minute at idling. The dental handpiece was clamped to a stand and placed at a height of 1 m from the ground (see Fig. 2 (a)). An advanced, two-channel, handheld analyser (Type 2270; Bruel & Kjaer, Naerum, Denmark) was mounted on a tripod at the same height as the dental handpiece.

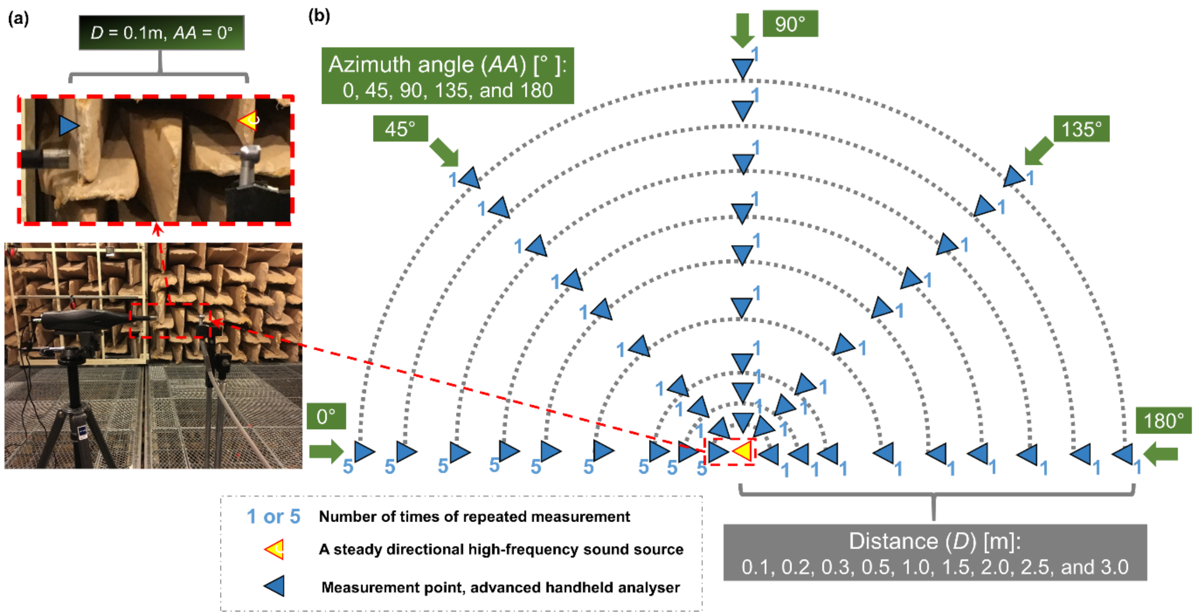

Fig. 2. (a) The zoom-in photo of the advanced handheld analyser at the measurement point 0.1 m from the steady directional high-frequency sound source with 0 azimuth angle in an anechoic chamber; (b) The measurement layout of the experiment.

2.1.3. Measurement layout

The distance (*D*) and azimuth angle (*AA*) between the centres of the 1/2-in prepolarized free-field microphone (Type 4189; Bruel & Kjaer, Naerum, Denmark) of the sound analyser and dental handpiece are the two analysed spatial factors to represent spatial variation (see Fig. 2). Both the sound analyser and dental handpiece were placed at a height of 1 m from the ground to ensure that the altitude angle between them was 0°. The measurements were conducted at points 0.1 m, 0.2 m, 0.3 m, 0.5 m, 1.0 m, 1.5 m, 2.0 m, 2.5 m, and 3.0 m from the sound source with *AA* = 0°, 45°, 90°, 135°, and 180°. A total of 45 measurement points was included in the study.

2.2.Acoustic metric calculation

Sound slices of the high-frequency sound source were recorded using the signal recording option of the analyser. The root-mean-square sound pressure (P_{rms}) of the sounds were recorded every 0.02083 ms to create 48 kHz (sample rate), 24-bit (bits per sample) audio WAV files. The high-resolution audio files allowed data to be logged-in at different time intervals. All the acoustic metrics in the study were logged-in every 2 ms (i.e. $L_{Z\_0.02083ms}$ to L_{Z_2ms}; L_{Z_2ms} to L_{A_2ms}; L_{Z_2ms} to $N_{\_2ms}$; $N_{\_2ms}$ to $S_{\_2ms}$). The time-varying 1/3 octave band unweighted spectrum was obtained by spectrum analysis of the logged L_{Z_2ms} data. The L_{A_2ms} data was then obtained after applying the A-weighting filter to the unweighted spectrum of sounds. For the calculation

of psychoacoustic metrics [17, 65], the 1/3 octave band spectrum was converted into the time-varying 24 Bark band spectrum in terms of specific loudness ($N'_{\_2ms}$; see Eq. (1)). The psychoacoustic metric $N_{\_2ms}$ is the sum total of the $N'_{\_2ms}$ of the 24 critical bands (see Eq. (2)). If the N of a sound is measured to be 1 sone, then it means that the sound is as loud as a 40 dB, 1 kHz tone.

$$Specific\ N' = 0.08\left(\frac{\text{Excitation at threshold in quiet}}{\text{Excitation of reference intensity}}\right)^{0.23} \times\left[\left(0.5+0.5\,\frac{\text{Excitation of the sounds}}{\text{Excitation at threshold in quiet}}\right)^{0.23}-1\right]\left(\frac{sone}{Bark}\right) \quad (1)$$

$$Total\ loudness\ N = \int_0^{24\,Bark} N'\,dz\ \ (sone) \quad (2)$$

At the same time, the psychoacoustic metric $S_{\_2ms}$ [66] was calculated by applying the critical-band-rate dependent on the 24 Bark band spectrum of $N'_{\_2ms}$ in Eqs. (3) and (4). The degree of skewness of the energy distribution of high-frequency components is described by the value of S. The S of a 60 dB, 1 kHz tone is defined as 1 acum.

$$sharpness\ S = 0.11 \frac{\int_0^{24\ Bark} N'\ g(z) z dz}{\int_0^{24\ Bark} N'\ dz}\ (acum) \quad (3)$$

$critical - band - rate\ dependent\ g(z)$:

$$= \begin{cases} 1, z \leq 14 \\ 0.00012Z^4 - 0.0056Z^3 + 0.1Z^2 - 0.81z + 3.51, z > 14 \end{cases} \quad (4)$$

2.3.Data analysis

The duration of each measurement was 4 s. The spatial factors (*D* and *AA*) were the independent variables, while the physical acoustic metrics (P_{rms_2ms}, L_{Z_2ms}, and L_{A_2ms}) and psychoacoustic metrics ($N_{\_2ms}$ and $S_{\_2ms}$) were the dependent variables in statistical analysis. The distributions of acoustic metrics in the 4 s sound slices were plotted to examine the effects of spatial factors. To analyse the effect of distance, the measurements at points with *AA* = 0° were repeated five times. Nonlinear regression was applied to test the dependence of the metrics on distance.

The distributions of the metrics at different distances were also represented by mean percentiles of 5%, 10%, 25%, 50%, 75%, 90%, and 95%. The sound temporal content was analysed by calculating the interquartile range (IQR) of the metrics. Spearman's rank-order correlation tests were applied to test the correlations between the statistical parameters of the metrics and the spatial factors. The time-frequency structure of sound was analysed by spectrum analysis in the 1/3 octave band spectrum and 24 Bark band spectra. All the data from statistical analyses were coded and analysed by the commercial package SPSS, version 23.0 (IBM Corp., Armonk, NY, USA).

3. Results

3.1. Effects of spatial factors

The distributions of P_{rms_2ms}, L_{Z_2ms}, L_{A_2ms}, $N_{\_2ms}$, and $S_{\_2ms}$ at the different measurement points are shown in Fig. 3. The magnitude of the effects of spatial factors are indicated by the shift in the distribution of acoustic metrics across the factors. The obvious decline in P_{rms_2ms}, L_{Z_2ms}, L_{A_2ms}, and $N_{\_2ms}$ values across the spatial factor *D* compared with those across factor *AA* demonstrate the dominant influence of factor *D* in the acoustic environment. The overlap between the distributions of $S_{\_2ms}$ across the factors suggest that the effects of spatial factors are weak.

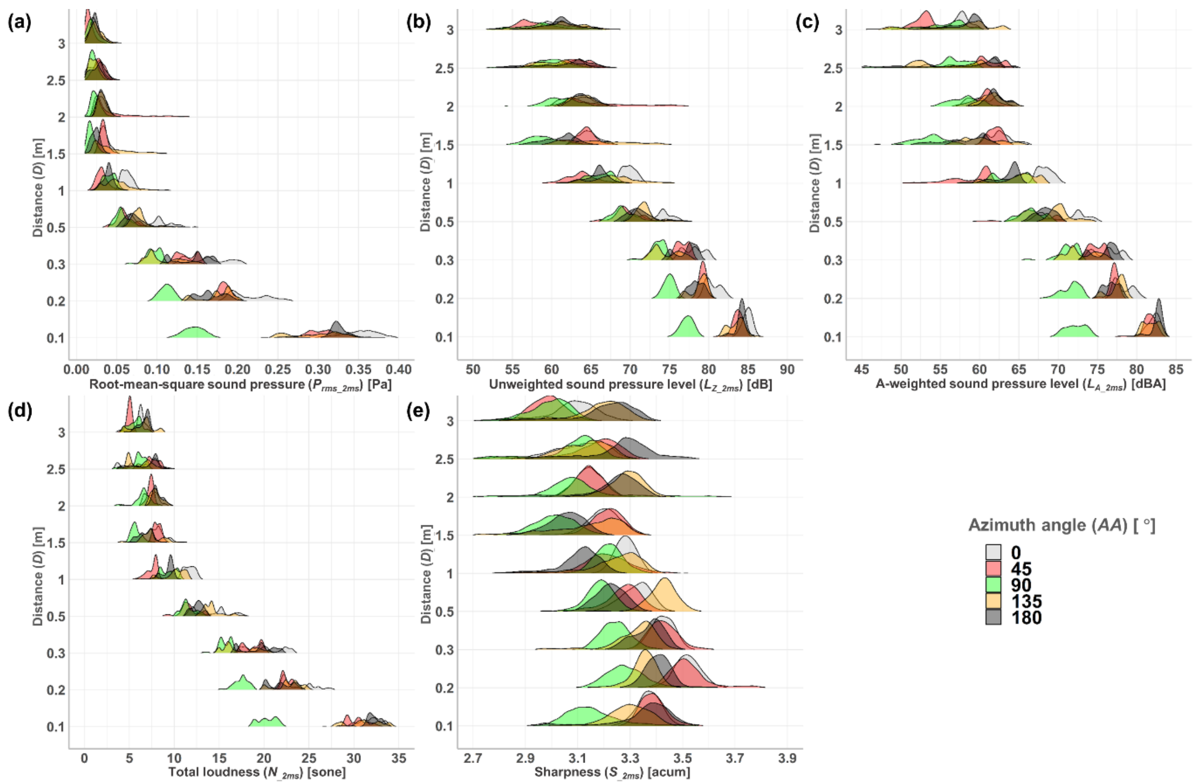

Fig. 3. The distributions of the logged acoustic metrics: (a) root-mean square sound pressure (P_{rms_2ms}); (b) unweighted sound pressure level (L_{Z_2ms}); (c) A-weighted sound pressure level

(L_{A_2ms}); (d) total loudness ($N_{\_2ms}$); and (e) sharpness ($S_{\_2ms}$) in the 4 s sound slices at the 45 measurement points.

3.1.1. *Effect of distance – sound attenuation*

Measurements conducted at each measurement point with *AA*= 0° to analyse the distance dependence of acoustic metrics were repeated five times. Sound attenuation was indicated by the negative association between acoustic metrics and spatial factor *D* (see Table 1). The metrics P_{rms_2ms}, L_{Z_2ms}, L_{A_2ms}, and $N_{\_2ms}$ were strongly correlated [67] with *D*, whereas the metric *S* was moderately correlated with *D*.

Table 1

Means and standard deviations of the logged acoustic metrics at the different distances from the sound source and the Spearman's correlation coefficient (ρ) between the metrics and the distance.

Distance [m]	P_{rms_2ms} [Pa]	L_{Z_2ms} [dB]	L_{A_2ms} [dBA]	$N_{\_2ms}$ [sone]	$S_{\_2ms}$ [acum]	Duration [s]
0.1	0.286 ± 0.076	82.7 ± 2.88	80.1 ± 4.06	29.1 ± 4.62	3.31 ± 0.121	4x5 = 20s
0.2	0.171 ± 0.037	78.4 ± 2.04	76.2 ± 2.58	21.7 ± 2.52	3.42 ± 0.110	4x5 = 20s
0.3	0.129 ± 0.031	76.0 ± 2.10	74.2 ± 2.37	18.2 ± 2.21	3.36 ± 0.092	4x5 = 20s
0.5	0.073 ± 0.020	71.0 ± 2.20	68.5 ± 2.58	12.8 ± 1.69	3.28 ± 0.103	4x5 = 20s
1.0	0.046 ± 0.016	66.7 ± 2.86	63.8 ± 3.85	9.56 ± 1.60	3.21 ± 0.111	4x5 = 20s
1.5	0.031 ± 0.014	63.0 ± 3.52	59.2 ± 3.97	7.32 ± 1.26	3.12 ± 0.125	4x5 = 20s
2.0	0.033 ± 0.016	63.7 ± 3.08	60.4 ± 2.83	7.47 ± 0.88	3.18 ± 0.125	4x5 = 20s
2.5	0.024 ± 0.008	61.2 ± 3.05	57.2 ± 4.90	6.55 ± 1.39	3.14 ± 0.135	4x5 = 20s
3.0	0.022 ± 0.008	60.1 ± 3.11	55.9 ± 3.61	5.98 ± 0.96	3.08 ± 0.139	4x5 = 20s
ρ	-0.908***	-0.908***	-0.903***	-0.928***	-0.625***	-

Note: P_{rms_2ms} = root-mean-square pressure, L_{Z_2ms} = unweighted equivalent sound pressure level, and L_{A_2ms} =

A-weighted equivalent sound pressure level, $N_{\_2ms}$ = total loudness, $S_{\_2ms}$ = sharpness. ***$p < 0.001$.

3.1.2. Effect of distance – distance dependence

The distance dependence of P_{rms_2ms}, L_{Z_2ms}, L_{A_2ms}, and $N_{\_2ms}$ were estimated by nonlinear regression models (M0–M12) with spatial factor D as the independent variable (see Table 2). The smaller the residual error, the better the fit of the curve. The estimated curves and logged data of metrics are plotted in Fig. 4. The inverse distance law 1/D for the distance dependence of P_{rms_2ms} was validated by regression model M0. The estimated curves of regression models M04 and M08 were the best fitted for L_{Z_2ms} and L_{A_2ms}, respectively. The curves of model M01 for L_{Z_2ms} and M05 for L_{A_2ms}, which assumed the inverse square distance law $1/D^2$ for the distance dependence of sound intensity, were also well fitted. The best-fitted curve for $N_{\_2ms}$ was from regression model M11 with the inverse of the power 0.478 of D.

Table 2

The nonlinear regressions of the logged acoustic metrics to the distance (D) from the sound source.

Name	Nonlinear regression model	y	x	Estimated regression curve	Residual standard error
M0	$y \sim b_0/x + b_1$	P_{rms_2ms}	D	P_{rms_2ms} =0.028/D + 0.019	0.034
M01	$y \sim 20*\log(1/x) + b_0$	L_{Z_2ms}	D	L_{Z_2ms} = 20*log (1/D) + 66.6	3.66
M02	$y \sim 20*\log(b_0/x + b_1)$	L_{Z_2ms}	D	L_{Z_2ms} = 20*log (1500/D + 537)	2.91
M03	$y \sim 20*\log(x^{\wedge} b_0 + b_1)$	L_{Z_2ms}	D	L_{Z_2ms} = 20*log (D^ -4.20 + 2142)	6.17

M04	y ~ 20*log (x^ b_0) + b_1	L_{Z_2ms}	*D*	L_{Z_2ms} = 20*log (*D*^ -0.776) + 67.2	2.91
M05	y ~ 20*log (1/x) + b_0	L_{A_2ms}	*D*	L_{A_2ms} = 20*log (1/*D*) + 63.6	3.96
M06	y ~ 20*log (b_0/x + b_1)	L_{A_2ms}	*D*	L_{A_2ms} = 20*log (1207/*D* + 262)	3.68
M07	y ~ 20*log (x^ b_0 + b_1)	L_{A_2ms}	*D*	L_{A_2ms} = 20*log (*D*^ -4.11 + 1465)	7.11
M08	y ~ 20*log (x^ b_0) + b_1	L_{A_2ms}	*D*	L_{A_2ms} = 20*log (*D*^ -0.845) + 64.0	3.65
M09	y ~ x^ b_0	$N_{\_2ms}$	*D*	$N_{\_2ms}$ = *D*^ -1.52	8.49
M10	y ~ x^ b_0 + b_1	$N_{\_2ms}$	*D*	$N_{\_2ms}$ = *D*^ -1.45 + 8.62	3.47
M11	y ~ b_0*x^ b_1	$N_{\_2ms}$	*D*	$N_{\_2ms}$ = 9.80**D*^ -0.478	2.26
M12	y ~ b_0*x^ -0.46+ b_1	$N_{\_2ms}$	*D*	$N_{\_2ms}$ = 10.4**D*^ -0.46+ -0.536	2.26

Note: y = dependent variable of the regression, x = dependent variable of the regression, P_{rms_2ms} = root-mean-square pressure, L_{Z_2ms} = unweighted equivalent sound pressure level, and L_{A_2ms} = A-weighted equivalent sound pressure level, $N_{\_2ms}$ = total loudness. The caret symbol (^) represents an exponent.

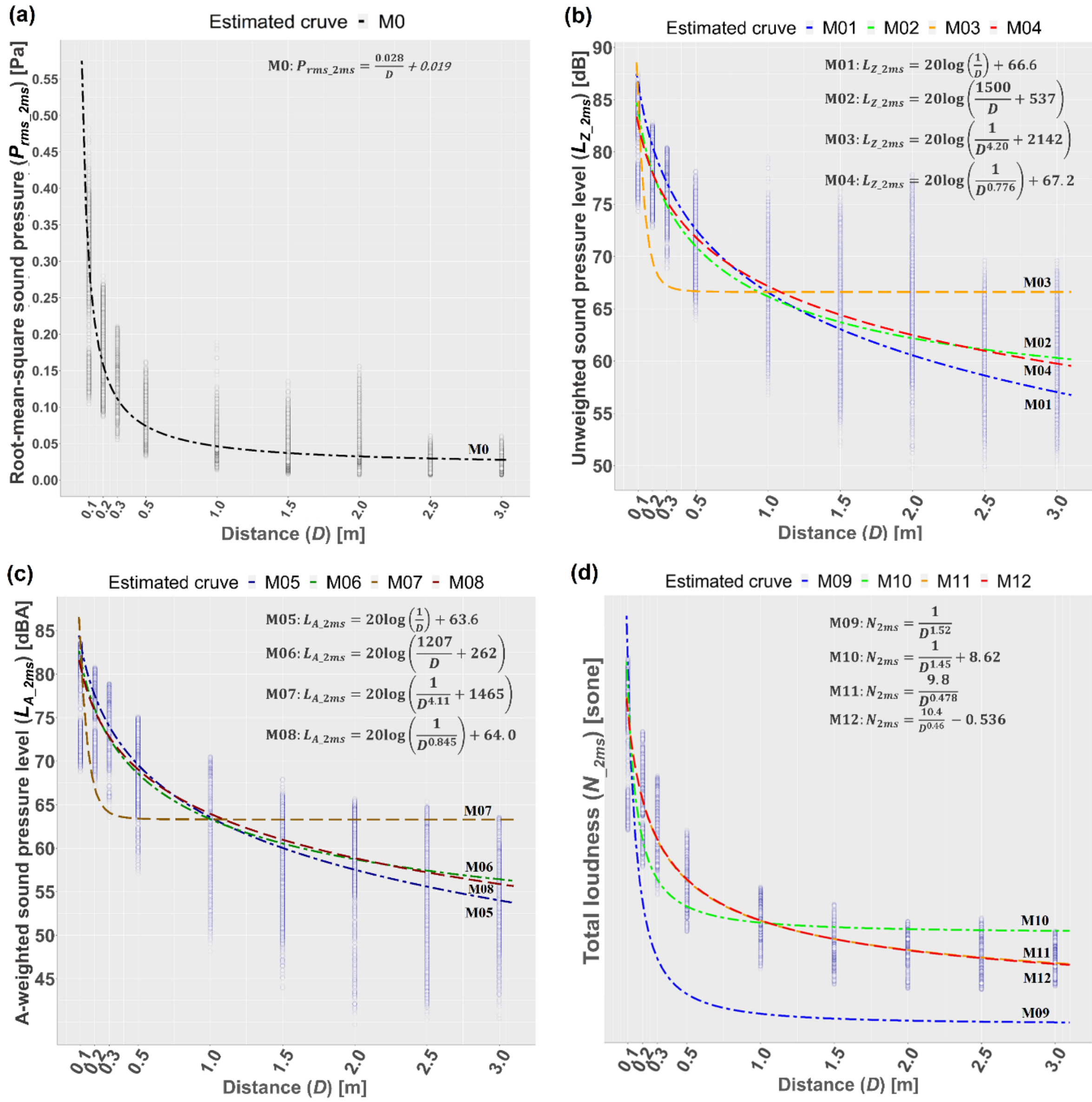

Fig. 4 The estimated curves of the nonlinear regression models (a) M0 of the logged root-mean-square pressure (P_{rms_2ms}); (b) M01-M04 of the logged unweighted sound pressure level (L_{Z_2ms}); (c) M05-M08 of the logged A-weighted sound pressure level (L_{A_2ms}); and M09-M12 of the logged total loudness ($N_{\_2ms}$) to the distance (D) from the sound source.

3.1.3. Effect of emission orientation

Fig. 5 show the detailed plots of Fig. 3(c) and 3(d), respectively. The variations in L_{A_2ms} and $N_{\_2ms}$ across *AA* were more vigorous for smaller *D* (< 0.3m). The drop in values was greatest when the sound source was perpendicular to the sound analyser (*AA* = 90°).

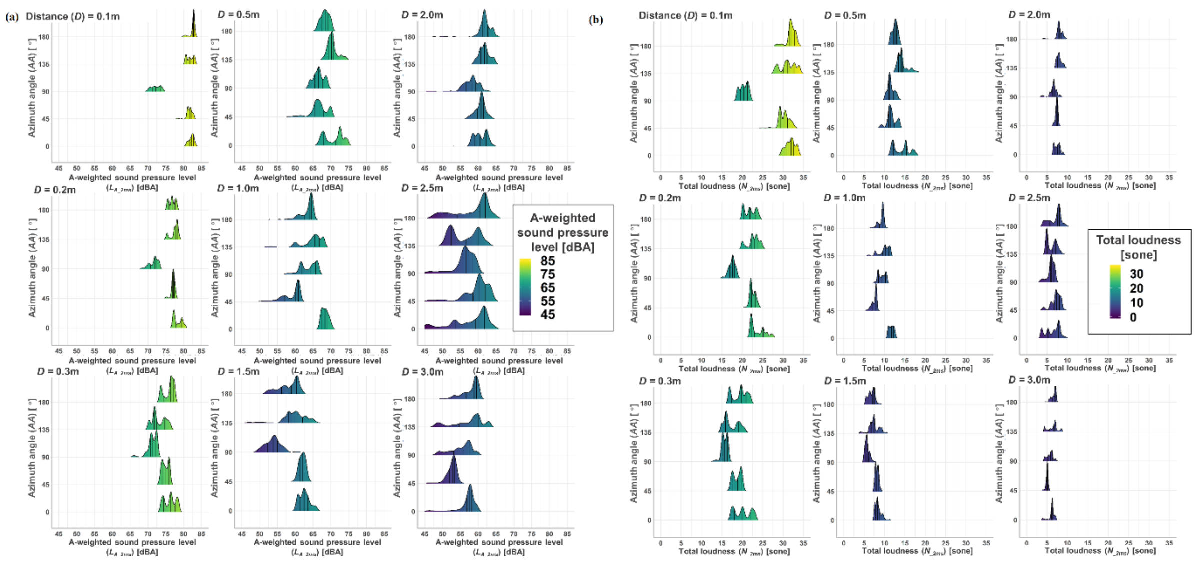

Fig. 5. The detailed distributions of the logged (a) A-weighted sound pressure level (L_{A_2ms}) and (b) total loudness ($N_{\_2ms}$) in the 4 s sound slices at the 45 measurement points.

3.2. Acoustical properties characterization

3.2.1. Energy content

The similar attenuation patterns of P_{rms_2ms}, L_{Z_2ms}, L_{A_2ms}, and $N_{\_2ms}$ indicate that these are related to similar acoustical properties. The values of P_{rms_2ms}, L_{Z_2ms}, L_{A_2ms}, and $N_{\_2ms}$ were also highly correlated (see Fig. 6).

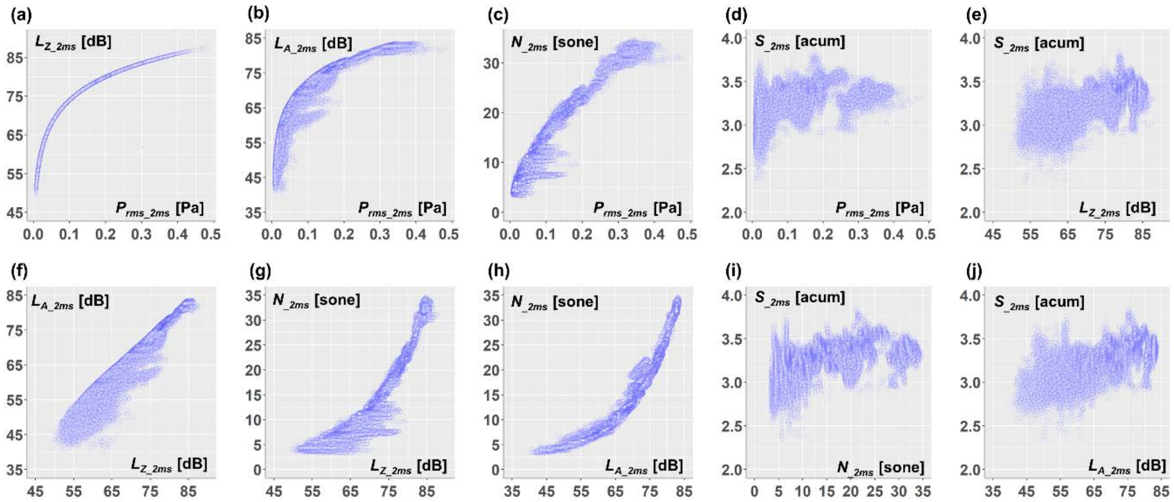

Fig. 6. The scatter plots of the logged root-mean-square sound pressure (P_{rms_2ms}), unweighted equivalent sound pressure level (L_{Z_2ms}), A-weighted equivalent sound pressure level (L_{A_2ms}), total loudness ($N_{\_2ms}$) and sharpness ($S_{\_2ms}$) of the high-frequency sound source: (a) L_{Z_2ms} vs P_{rms_2ms}; (b) L_{A_2ms} vs P_{rms_2ms}; (c) $N_{\_2ms}$ vs P_{rms_2ms}; (d) $S_{\_2ms}$ vs P_{rms_2ms}; (e) $S_{\_2ms}$ vs L_{Z_2ms}; (f) L_{A_2ms} vs L_{Z_2ms}; (g) $N_{\_2ms}$ vs L_{Z_2ms}; (h) $N_{\_2ms}$ vs L_{A_2ms}; (i) $S_{\_2ms}$ vs $N_{\_2ms}$; and (j) $S_{\_2ms}$ vs L_{Z_2ms}.

3.2.2. Temporal content

The percentiles and IQR of the logged acoustic metrics with the spatial factor *D* were plotted in Tables 3 and 4. The IQRs of P_{rms_2ms} and $N_{\_2ms}$ were strongly and negatively correlated with *D*, whereas the IQRs of L_{Z_2ms} and L_{A_2ms} were moderately and positively associated with *D*.

Table 3

The percentiles and interquartile range (IQR) of the logged physical acoustic metrics at the different distances from the sound source and the Spearman's correlation coefficient (ρ) between the statistical parameters of the metrics and the distance.

	Distance [m]									
	0.1	***0.2***	***0.3***	***0.5***	***1.0***	***1.5***	***2.0***	***2.5***	***3.0***	ρ
P_{rms_2ms} **[Pa]**										
5%	0.136	0.106	0.086	0.049	0.025	0.014	0.019	0.012	0.011	-0.983***
10%	0.146	0.112	0.091	0.053	0.028	0.016	0.021	0.014	0.013	-0.983***
25%	0.260	0.145	0.102	0.059	0.034	0.022	0.025	0.018	0.016	-0.983***
50%	0.315	0.180	0.130	0.070	0.043	0.029	0.030	0.024	0.021	-0.983***
75%	0.334	0.192	0.151	0.080	0.056	0.035	0.035	0.030	0.025	-1.00***
90%	0.359	0.208	0.168	0.103	0.065	0.043	0.043	0.035	0.032	-1.00***
95%	0.372	0.235	0.184	0.115	0.071	0.055	0.056	0.038	0.036	-0.983***
IQR	0.075	0.047	0.049	0.022	0.022	0.014	0.010	0.012	0.009	-0.949***
L_{Z_2ms} **[dB]**										
5%	76.7	74.5	72.6	67.7	62.0	57.2	59.6	55.7	54.8	-0.983***
10%	77.3	75.0	73.1	68.4	63.0	58.1	60.5	57.2	56.0	-0.983***
25%	82.3	77.2	74.2	69.4	64.5	60.7	62.0	59.1	58.1	-0.983***
50%	83.9	79.1	76.2	70.8	66.6	63.3	63.4	61.6	60.4	-0.983***
75%	84.5	79.6	77.6	72.1	68.9	64.9	64.9	63.4	62.1	-1.00***
90%	85.1	80.3	78.5	74.2	70.3	66.7	66.6	64.8	64.2	-1.00***
95%	85.4	81.4	79.3	75.2	71.0	68.8	69.0	65.6	65.1	-0.983***
IQR	2.19	2.45	3.40	2.71	4.37	4.27	2.88	4.32	3.98	0.667*
L_{A_2ms} **[dBA]**										
5%	71.2	70.7	70.4	64.7	56.5	51.8	56.0	47.0	49.2	-0.967***
10%	72.2	71.9	71.0	65.6	59.0	53.2	57.5	50.4	51.0	-0.967***
25%	80.6	75.5	72.3	66.7	61.1	56.4	59.2	54.0	53.2	-0.983***
50%	81.8	77.1	74.4	68.4	64.4	60.6	60.9	58.3	56.8	-0.983***
75%	82.7	77.8	76.2	70.0	66.8	62.2	62.0	60.9	58.7	-1.00***
90%	83.0	78.5	77.2	72.4	68.4	63.2	63.1	62.3	59.9	-1.00***
95%	83.1	79.4	77.7	73.1	69.0	64.0	63.9	63.1	60.3	-1.00***
IQR	2.10	2.31	3.82	3.30	5.70	5.84	2.84	6.88	5.48	0.683*

Note: P_{rms_2ms} = root-mean-square pressure, L_{Z_2ms} = unweighted equivalent sound pressure level, and L_{A_2ms} =

A-weighted equivalent sound pressure level. *$p < 0.05$. **$p < 0.01$. ***$p < 0.001$.

Table 4

The percentiles and interquartile range (IQR) of the logged psychoacoustic metrics at the different distances from the sound source and the Spearman's correlation coefficient (ρ) between the statistical parameters of the metrics and the distance.

	Distance [m]									
	0.1	***0.2***	***0.3***	***0.5***	***1.0***	***1.5***	***2.0***	***2.5***	***3.0***	ρ
$N_{\_2ms}$ [sone]										
5%	19.6	16.9	15.0	10.8	6.97	5.27	6.14	3.99	4.41	-0.967***
10%	20.4	17.6	15.3	11.1	7.59	5.52	6.51	4.69	4.75	-0.967***
25%	28.7	20.2	16.3	11.6	8.14	6.33	7.03	5.51	5.13	-0.983***
50%	30.9	22.2	18.0	12.6	9.62	7.51	7.52	6.74	6.09	-0.983***
75%	32.2	23.3	19.8	13.7	10.8	8.24	7.97	7.69	6.77	-1.00***
90%	33.1	24.4	21.2	15.2	11.7	8.75	8.51	8.16	7.10	-1.00***
95%	33.5	25.1	22.2	16.6	12.2	9.28	8.90	8.51	7.26	-1.00***
IQR	3.51	3.15	3.46	2.11	2.69	1.91	0.93	2.18	1.65	-0.817**
$S_{\_2ms}$ [acum]										
5%	3.07	3.23	3.19	3.13	3.00	2.91	2.99	2.89	2.87	-0.883**
10%	3.12	3.27	3.23	3.16	3.08	2.95	3.04	2.98	2.91	-0.850**
25%	3.25	3.34	3.29	3.21	3.15	3.03	3.11	3.07	2.98	-0.900**
50%	3.35	3.42	3.37	3.28	3.22	3.14	3.17	3.15	3.07	-0.900**
75%	3.40	3.50	3.42	3.36	3.28	3.22	3.27	3.23	3.19	-0.900**
90%	3.43	3.55	3.46	3.43	3.32	3.26	3.33	3.30	3.27	-0.817**
95%	3.46	3.58	3.48	3.46	3.35	3.29	3.36	3.34	3.30	-0.817**
IQR	0.144	0.156	0.128	0.150	0.131	0.182	0.162	0.156	0.210	-

Note: $N_{\_2ms}$ = total loudness, $S_{\_2ms}$ = sharpness. **$p < 0.01$. ***$p < 0.001$.

3.2.3. *Spectral content*

Both the 1/3 octave spectra of the logged L_{Z_2ms} and L_{A_2ms} and the 24 Bark band spectrum of the logged $N_{\_2ms}$ demonstrate the ability of spectrum analysis to obtain information on the time-frequency structure of the sound source. All the spectra showed the peak at the frequency component of approximately 5 kHz as well as the skewness of the energy distribution toward high-frequency components (see Fig. 7(a)). The magnitudes of frequency components gradually decreased, but the patterns of the spectrums stayed the same with increasing distance from the sound source. This explains the minimal effect of distance on the psychoacoustic metric *S*, as a quantity of skewness of the energy distribution (see Fig.7(b)).

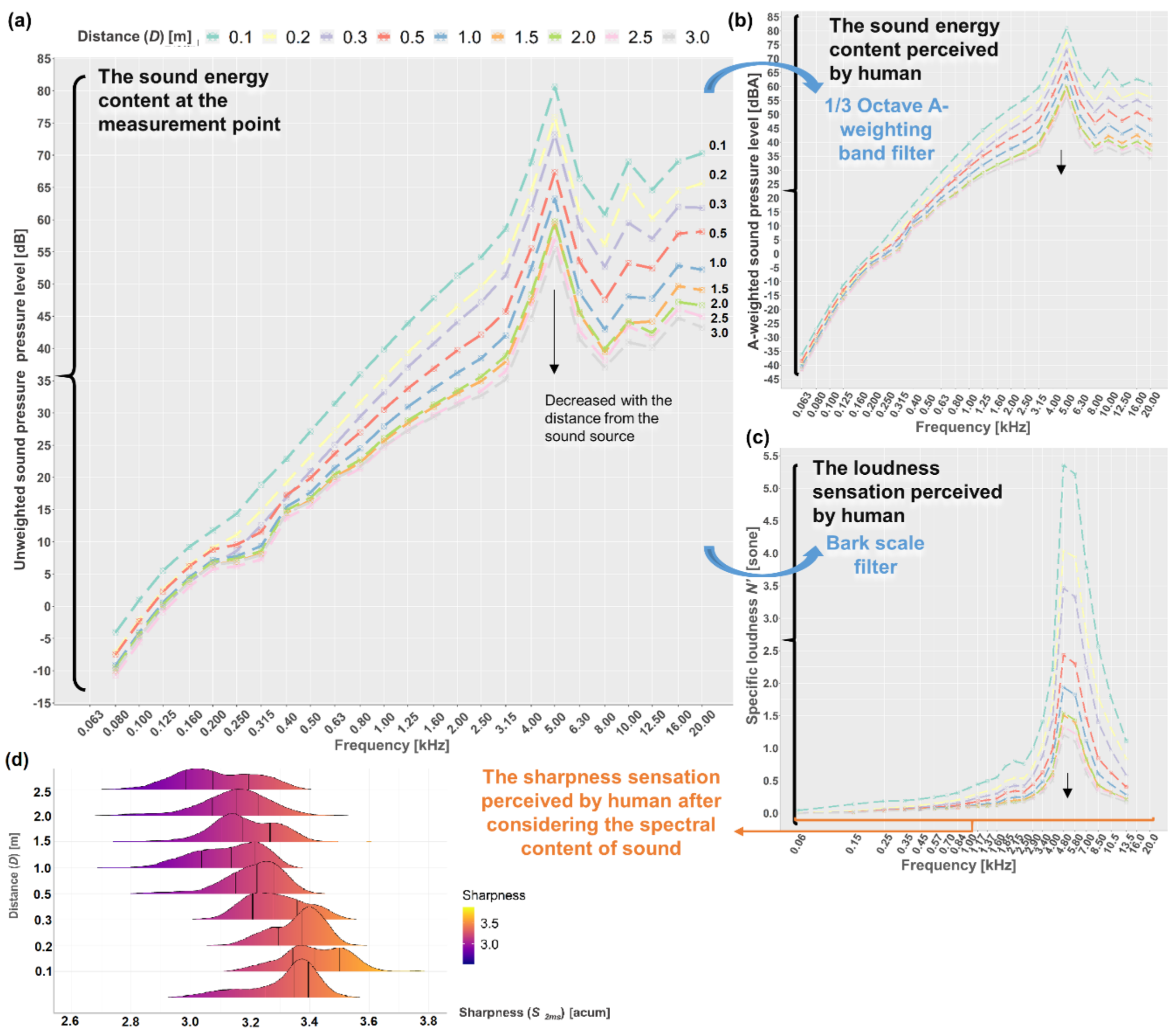

Fig. 7. The spectrum analysis of the high-frequency sound source: (a) 1/3 octave spectrum of the logged unweighted sound pressure level (L_{Z_2ms}); (b) 1/3 octave spectrum of the logged A-weighted sound pressure level (L_{A_2ms}); (c) the 24 Bark band spectrum of the logged total loudness ($N_{\_2ms}$); (d) the distribution of the logged sharpness ($S_{\_2ms}$) at the different distances from the sound source.

4. Discussion

4.1. Principal results and practical significance

Sound quality prediction [4, 68] can be improved by advanced acoustical measurements along with the consideration of spatial variation (see Fig. 8). Better environmental noise control [69] can be achieved by accurately predicting the noise of building elements [70-74] and measurement of noise in existing outdoor and indoor environments [24, 75]. Sound attenuation in propagation is not a new concept in the study of acoustics. The inverse square distance law for the distance dependence of sound intensity is well-known, and further supported in this study. The two key findings of this study are that the effects of distance should be considered by sound energy content-related metrics, and the psychoacoustic metric N of subjects' perceived loudness sensation is also predictable in sound propagation. There is a subjective life experience that loudness decreases as the distance increases. However, the systematic search result of this study shows that the scientific and objective method for predicting the loudness decrement in terms of psychoacoustic metrics is not available. The study findings provide a new approach to succinctly estimate the values of psychoacoustic metric N at different positions from a noise source. The numerical approximation of N in the inverse power 0.46 of D is firstly proposed from the study results. Owing to the nonlinearity of logarithmic functions in L_Z and L_A calculations, the magnitude of environmental change cannot be easily interpreted by changes in L_Z and L_A values. For example, the magnitude of changes in environmental sound energy and occupants' loudness perception of the 6-dBA decrement in 30 dBA and 50 dBA rooms are different. The changes in L_Z and L_A values may not be suitable metrics in the statistical analysis and prediction of environmental effects on subjective responses. The *N* measurement serves as the alternative to environmental assessment and prediction. Since a unit of *N* is a linear scale (sone scale), the difference between the *N* values can be interpreted. As mentioned previously, the 6-dBA decrement when doubling the distance from the sound source cannot clearly explain the environmental influence on acoustical properties or subjective responses. By comparison, the decreased *N* value in sound propagation lets people know how much the environment has quieted down. The offhand prediction of psychoacoustic parameters is possible in this study. In Eq. (1), when the excitation (sound intensity) of sounds is much larger than that of the reference intensity (10^{12} Wm^{-2}), *N'* is approximated to the power 0.23 of the excitation. Therefore, *N'* is approximated to the inverse power 0.46 of *D*. Although the estimated curve of the regression model M12 is not the best, the curve-fitting for the assumption of the inverse power 0.46 of *D* is acceptable (see Eq. (5)). In other words, doubling the distance from the sound source makes the value of *N* 0.73 times smaller. The predictability of psychoacoustic metrics with spatial variation is hence firstly demonstrated in this study.

$$\frac{N_{D\prime}}{N_D} \sim \left(\frac{D\prime}{D}\right)^{-0.46} \qquad (5)$$

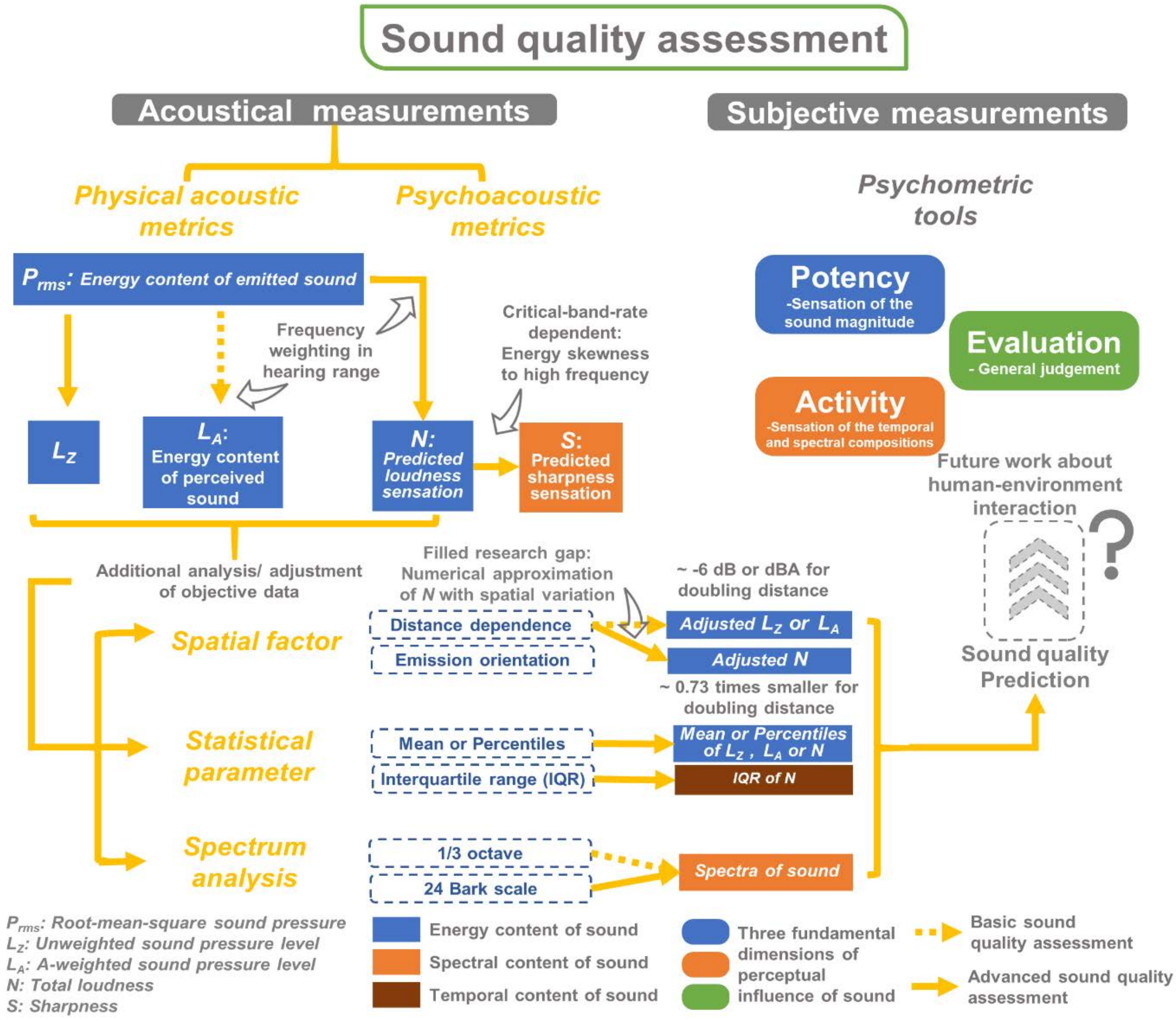

Fig. 8. The summary of the study findings in acoustical measurements and prediction of sound quality.

In the study of human-environment interaction, proper and careful variable selection in objective measurements is as important as that in subjective measurements. Human perceptions of the acoustic environment are influenced by the multidimensional responses to sound magnitude, temporal and spectral compositions of sound, and the general judgement of sound [55]. Likewise, the acoustical properties of the acoustic environment have multiple dimensions. Sound energy-related metrics are not enough to explain the environmental influence on occupants [15, 42, 56, 57, 60, 76]. Therefore, a multidimensional acoustical measurement is needed to quantify environmental acoustical properties. Multidimensional assessment cannot simply be achieved by increasing the number of acoustic metrics. This is because different metrics may characterize the same acoustical property. The second contribution of this study is to compare the similarities and differences between acoustic metrics in acoustical measurements. Despite the different frequency weightings in the calculations of P_{rms}, L_Z, L_A, and N, the metrics were found to be highly correlated. The similar attenuation patterns of these metrics across the spatial factors suggest that they are sensitive to changes in sound energy content. Thus, P_{rms}, L_Z, L_A, and N are accurate metrics that represent sound energy content. The decrease in the percentiles of acoustic metrics not only provided an alternative point of view of sound attenuation for the factor D, but also implied that those statistical parameters characterize sound energy content.

The most common approach for the analysis of human-environment interaction is to determine how environmental changes cause changes in subjective responses. Since the changes in environmental sound energy could be detected by the changes of P_{rms}, L_Z, L_A, and N and their statistical parameters (mean and percentiles), these metrics are expected to be accurate predictors of the subjective responses to the sensation of sound magnitude. The consistency between the decrease in the IQRs of P_{rms_2ms} and $N_{\_2ms}$ with increasing distance from the sound source also suggests that the IQR of N can describe the temporal content of sound energy. By contrast, S did not have a good response to changes in total environmental sound energy, but it was sensitive to sound energy distribution among different spectral compositions. Although the time-frequency structure of sound can be disclosed by spectrum analysis, a list of parameters on frequency compositions will increase the difficulty of post-analysis of data. The complexity of spectrum analysis data affects researchers' willingness to investigate the spectral content of the acoustic environment. S as an explicit metrics of energy skewness toward high-frequency components is a valuable predictor [57, 60] of subjective responses to featured sounds.

The reduced variations in *S* across the spatial factor means that the associated subjective responses cannot be eliminated simply by noise reduction. The similar result in which the magnitudes of all frequency components decreased with increasing distance from the sound source is consistent with another study [77]. For example, the uncomfortable feeling one gets from hearing fingernails scratching a blackboard does not simply come from the response to the sound magnitude. An accurate and multidimensional acoustical measurement provides not only a precise description of the acoustic environment, but also a thoughtful evaluation and prediction of the influence of the environment on occupants.

4.2.Limitations and future work

The effects of emission orientation in terms of the variations in the metrics of sound energy content were detected when the sound source was very close ($D < 0.3$ m). However, additional investigations are needed to determine how the spatial factor *AA* contributes to the variation in metrics and the effective range of the effect. In order to eliminate the effects of complex interactions of different sound sources, the high-speed dental handpiece was the only sound source in the anechoic chamber. Therefore, mere single-source sound field from a steady and repeatable source was analysed in the studies. In a real-world situation, environmental noise is a combination of sound sources [78]. Whether the distance dependences of metrics are valid for combined noise, the effective range of distance dependences (effects of near field and far field on complexed sound fields), the effects of the magnitude of sound source on distance dependences, and the distance dependence of other psychoacoustic loudness models [79] should be further investigated. Moreover, the ability of the proposed advanced acoustical measurement to understand human-environment interactions requires more analysis [80].

5. Conclusion

The change in distance from the sound source had a great impact on the attenuation of sound magnitude. The energy content related properties were distance-dependent. It is well known that the distance dependence of P_{rms} is based on the inverse distance law and the increment of the values of L_Z and L_A was approximated as 6 dB or 6 dBA when doubling the distance from the sound. The value of N was found to be approximately equal to 0.73 times the original loudness when doubling the distance from the sound source. The distance dependence of the psychoacoustic metric N was primarily explored. The effect of emission orientation was observed when the distance from the sound source was less than 0.3 m. The analysis of the effect of emission orientation requires further investigation. The properties of sound energy content were found to be characterized by the metrics P_{rms}, L_Z, L_A, and N, while those of sound spectral content were characterized by the metric S. In contrast, the spectral content-related properties were not sensitive to the change in spatial variation. The findings of the study filled the research gap in acoustical measurements containing psychoacoustic metrics and provided guidance to future environmental assessment and prediction on sound energy content, and temporal and spectral content.

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