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ACOUSTIC INDICATORS OF SOUNDSCAPE QUALITY AND NOISE ANNOYANCE IN OUTDOOR URBAN AREAS

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ABSTRACT
Acoustic indicators grounded in soundscape perception are needed for predicting the quality of soundscapes in urban outdoor areas. The present paper explores the predictive power of various acoustic indicators. A questionnaire study was conducted in 16 city parks and green open spaces in Stockholm. In total, 1116 respondents answered questions on, inter alia, perceived soundscape quality and road-traffic noise annoyance. One-third octave band levels were continuously logged during data collection. From these acoustic measurements, a number of indicators were calculated representing overall level, spectral content and time-variability of the soundscape. These indicators were calculated for each respondent separately, referring to the 10-min period during which the participant filled in the questionnaire. Indicators related to the overall sound level explained a substantial part of the variance in perceived soundscape quality and road-traffic noise annoyance. Indictors related to the spectral content only explained a small part of the variance not accounted for by overall sound level. Perception of nature sounds and technological sounds, as measured in the questionnaire, were strong predictors of soundscape quality and noise annoyance, also after adjustment for overall sound level. This suggests that prediction of soundscape quality would benefit from the development of acoustic indicators of sound source audibility within soundscapes.

INTRODUCTION
Outdoor environments, particularly parks and green areas, provide invaluable opportunities for physical exercise and psychological restoration. Walks in urban parks constitute preventive measures for ill-health caused by a sedentary or stressful life style. The risk is that noise pollution hinder people's outdoor stay, which in a long-term perspective is a threat to public health. Therefore, the EC-directive on environmental noise points to the need for protection of existing quiet urban areas [1]. It also stresses the need for supplementary noise indicators for quiet areas (Annex I.3).

Alternative acoustic indicators relevant for soundscape perception in outdoor spaces has been proposed [2,3]. The present paper explores the relationship between visitor's assessments of outdoor soundscapes and various acoustic indicators, using data collected in several city parks and open green spaces in Stockholm. Previous studies has suggested that sound source identification is a main determinant of perceived soundscape quality [4,5,6]. Therefore, the relationship between sound-source identification, as measured in the questionnaire, and soundscape assessment was also explored.

METHOD

Study areas
Sixteen areas in Stockholm were investigated. The areas were all popular places for walks and recreation. Three areas were located outside the city, at large distances from major roads, railways and airways. The remaining areas were city parks located close to major

roads, but not to major railway or airway lines. According to noise maps produced by the Stockholm City, the city park's exposure ranged between 45 and 65 dB (Lday).

Data collection

All data was collected during June-August 2006. Data collection was conducted in two separate days in each area, once in the morning (0900-1300) and once in the afternoon (1500-1800). During data collection, personnel from Stockholm University were stationed at one selected place in each area. Everyone that passed this place was approached and asked to fill in the questionnaire in exchange of a small gift. In total, 1116 visitors completed the questionnaire, approximately 70 in each area.

Questionnaire

The questionnaire contained 19 questions, which were answered in approximately 10 min. The questionnaire consisted of questions on person factors (age, sex, etc), general assessments of the area, and questions on the sound environment. Overall soundscape quality was assessed on a five-point bipolar category scale with the response alternatives "Very good", "Good", "Neither good, nor bad", "Bad" and "Very bad" [4]. Road-traffic noise annoyance was assessed on a five-point category scale, with the response alternatives "Extremely", "Very", "Moderately", "Slightly" and "Not at all" (cf. [7]). These questions appeared early in the questionnaire as part of a set of several questions on various environmental factors, such as perceived quality of the landscape and annoyance due to littering. Thus, the focus on sound environment was not obvious to the respondent when he or she answered questions on soundscape quality and noise annoyance.

The questionnaire also included questions on identification of sounds from three broad categories of sounds: (1) sounds from humans, e.g., people talking, children at play, (2) sounds from nature, e.g., bird song, wind in the leaves, and (3) technological sounds, e.g., road-traffic noise, ventilation noise. For each of the three source categories, the participant indicated to which degree the source was heard during today's visit to the area. Responses were given on a five-point category scale with the response alternatives "Never heard", "Heard a little", "Heard sometimes", "Heard a lot" and "Completely dominating".

Sound level measurements

During data collection, 1/3-octave-band sound levels were measured continuously (time-interval = 0.1 s) at a place close to where the respondents filled in the questionnaire. Measured equivalent sound levels during data collection ranged from 43 to 62 dB (LAeq,4h).

For each participant, we identified the 10-min time period during which the questionnaire was filled in. For each such 10-min period, a number of acoustic indicators were calculated from the measured 1/3-octave-band sound levels. Table I gives a description of the acoustic indictors used in the following analyses. These were related to the overall sound level (LAeq, LA50, LA95, N), the average spectrum (LCeq-LAeq, CoG) and the time-pattern of the soundscape (ML, NCN, LA10-LA90). Several of these indicators have previously been identified as potentially relevant for perceived soundscape quality [2,3]

Table I.- Acoustic variables

Acoustic variable	Description
LAeq	Equivalent continuous sound pressure level
LA50	Sound pressure level exceeded 50 % of the time
LA95	Sound pressure level exceeded 95 % of the time
N	Zwicker loudness (sone), (ISO 532 B [8])
LCeq-LAeq	Difference between C- and A-weighted sound pressure level [9]
CoG	Spectrum centre of gravity (1/3-octave spectrum) [10]
ML	Music-likeness [2]
NCN	Number of noise events (LAeq,1s 3 dB above LA50 for at least 3 seconds) [3]
LA10-LA90	Difference between A-weighted sound pressure level exceeded 10 % and 90 % of the time [9]

Time period: 10 min for individual level (approx. time for filling in the questionnaire), 8 h for area level (two 4-h measurements during data collection in the morning or afternoon).

RESULTS & DISCUSSION

The main focus of the present paper is the relationship between acoustic indicators (Table I), measured while the participants filled in the questionnaire, and the participant's assessments of perceived soundscape quality and road-traffic noise annoyance. Furthermore, the relationship between sound-source identification, as measured in the questionnaire, and soundscape quality or road-traffic noise annoyance will be explored.

The five-point category scales of soundscape quality, noise annoyance and sound-source identification were coded from 1 to 5, and they were treated as interval scales in the following analyses. The upper part of Table II gives bivariate coefficients of correlation (Pearson) between, on the one hand, acoustic variables and, on the other, perceived soundscape quality and perceived road-traffic noise annoyance. Coefficients were calculated both at the individual level (N = 1116) and at the area level (N = 16). In the former case, each individual assessment was correlated with acoustic variables referring to the 10-min period during which the individual filled in the questionnaire. In the later case, the arithmetic average of approx. 70 individual assessments in each area was correlated with acoustic variables referring to eight hours of measurements (two 4-h measurements during data collection in the morning and afternoon).

The lower part of Table II gives coefficients of correlation between, on the one hand, questionnaire responses regarding identification of sounds from nature, human activity and technological sources, and, on the other hand, soundscape quality and road-traffic noise annoyance.

Soundscape quality

At the individual level, the correlation (r) between soundscape quality and LAeq was -0.50. This corresponds to 25 % (r^2) of the total variance in perceived soundscape quality (Table II). Slightly higher coefficients were obtained for LA95 and N (-0.53) and for LA50 (-0.55), corresponding to 28-30 % of the total variance. At the area level, the coefficients were considerably higher. The highest coefficient was found for LA50, r = -0.94, which corresponds to approx. 88 % of the total variance in average soundscape quality across the 16 areas. The coefficient was lower for LAeq, r = -0.86 (74 % explained variance). These results agree with previous research, which found that LA50 was superior to LAeq as indictor of perceived soundscape quality in quiet areas [3].

Table II. Coefficient of correlation (Pearson) between perceived soundscape quality or road-traffic noise annoyance and various predictor variables.

	Bivariate coefficient of correlation (Pearson)			
	Soundscape Quality[2]		Road-traffic noise annoyance[2]	
	Individual level (N=1116)	Area level (N = 16)	Individual level (N=1116)	Area level (N = 16)
Acoustic variables[1]				
LAeq	-0.50	-0.86	0.41	0.82
LA50	-0.55	-0.94	0.46	0.93
LA95	-0.53	-0.89	0.46	0.93
N	-0.53	-0.89	0.44	0.87
LCeq-LAeq	-0.17	-0.50	0.22	0.61
CoG	0.21	0.47	-0.26	-0.56
ML	0.05	-0.05	-0.08	0.12
NCN	0.18	0.48	-0.15	-0.47
LA10-LA90	0.24	0.49	-0.22	-0.61
Source identification[2]				
Human sounds	-0.12	-0.24	0.12	0.27
Nature sounds	0.36	0.89	-0.25	-0.79
Technological sounds	-0.59	-0.95	0.54	0.93

[1]See Table I. [2]Questionnare response on five-point category scale. Soundscape quality coded from 1 (very bad) to 5 (very good), Annoyance coded from 1 (not at all annoyed) to 5 (extremely annoyed); Source identification coded from 1 (never heard) to 5 (dominates completely). See the Method section.

Table III. Sequential regression of acoustic variables and sound-source identification on perceived soundscape quality.

Model	Model fit (R^2)	F-change	Independent variables	Coefficient	Standardized coefficient	p-value
1	0.30	468.5***	LA50	-0.09	-0.55	<.001
2	0.31	17.4***	LA50	-0.09	-0.53	<.001
			LCeq-LAeq	-0.04	-0.11	<.001
3	0.45	147.3***	LA50	-0.05	-0.29	<.001
			LCeq-LAeq	-0.00	-0.01	.71
			Nature sounds	0.19	0.17	<.001
			Technological sounds	-0.40	-0.40	<.001

***p <.001

The association between perceived soundscape quality and acoustic variables related to time-patterns (NCN, LA10-LA90, ML) and spectral content (LCeq-LAeq, CoG) was moderate. Coefficients of correlation ranged between -0.17 and 0.24 at the individual level and between -0.50 and 0.49 at the area level. A sequential linear regression analysis with soundscape quality as dependent variable was employed to determine the additional predictive power of various acoustic variables over and above the effect of overall sound level. These analyses were conducted at the individual level only (N = 1116). In the first step of the sequential regression analysis, LA50 was entered as the only independent variable in the regression model. LA50 was chosen because it had the highest correlation with perceived soundscape quality (Table II). In the second step, additional acoustic variables related to spectral content (LCeq-LAeq, CoG) or time-pattern (ML, LA10-LA90, NCN) were entered one by one, and the resulting models were evaluated. Variables that increased the explained variance by at least 1 % were kept in the final model. This was true only for LCeq-LAeq, which is a measure of the relative level of low-frequency sound [9].

Table III displays model-fit (R^2) and coefficients for the multiple regression analyses. For Model 1, with LA50 as the only independent variable, R^2 = 0.30. For Model 2, with LCeq-LAeq added to the equation, R^2 = 0.31. Thus, LCeq-LAeq only contributed with 1 % of the explained variance in perceived soundscape quality.

Soundscape quality was highly correlated with identification of technological sounds (negative correlation) and identification of nature sounds (positive correlation). Only a weak association was found between soundscape quality and identification of human sounds (Table II). In order to explore the effect of sound-source identification on perceived soundscape quality, identification of nature sounds and technological sounds were included in a multiple regression model (Model 3, Table III). The model fit was 0.45, which was considerably higher than the model with acoustic indicators only (R^2 = 0.31, Model 2). This agrees with previous research which has shown that the type of audible sources within he soundscape is a main determinant of perceived soundscape quality [4,5,6].

Noise annoyance

At the individual level, the correlation (r) between road-traffic noise annoyance and LAeq was 0.41 (Table II). This corresponds to 17 % (r^2) of the total variance in noise annoyance. Slightly higher coefficients were obtained for N (r = 0.44) and for LA95 and LA50 (r = 0.46), corresponding to 19-21 % of the total variance. At the area level, the coefficients were considerably higher. The highest coefficient was found for LA95 and LA50, r = 0.93, which corresponds to approx. 86 % of the total variance in road-traffic noise annoyance across the 16 areas. The coefficient was lower for LAeq, r = 0.82 (67 % explained variance). The difference in explained variance between individual and area level agrees with results from questionnaire studies on residential noise annoyance [11].

Moderately strong associations were found between noise annoyance and acoustic variables referring to spectral content (LCeq-LAeq, CoG) and time variability (NCN, LA10-LA90, ML). Coefficients of correlation ranged between -0.26 and 0.22 at the individual level and between -0.61 and 0.61 at the area level.

Table IV. Sequential regression of acoustic variables and sound-source identification on perceived road-traffic noise annoyance.

Model	Model fit (R^2)	F-change	Independent variables	Coefficient	Standardized coefficient	p-value
1	0.21	294.0***	LA50	0.08	0.46	<.001
2	0.24	39.2***	LA50	0.07	0.44	<.001
			LCeq-LAeq	0.06	0.17	<.001
3	0.35	100.0***	LA50	0.04	0.22	<.001
			LCeq-LAeq	0.03	0.09	<.001
			Nature sounds	-0.08	-0.07	.006
			Technological sounds	0.39	0.39	<.001

***p <.001

A sequential linear regression analysis with noise annoyance as dependent variable was employed to determine the predictive power of additional acoustic variables over and above the effect of overall sound level. These analyses were conducted at the individual level only (N = 1116). In the first step of the sequential regression analysis, LA50 was entered as the only independent variable in the regression model. LA50 was chosen because it had the highest correlation with noise annoyance (Table II). In the second step, additional acoustic variables related to spectral content (LCeq-LAeq, CoG) or time-patterns (ML, LA10-LA90, NCN) were entered one by one, and the resulting models were evaluated. Variables that increased the explained variance by at least 1 % were kept in the final model. This was true only for LCeq-LAeq (R^2-increase = 0.03) and CoG (R^2-increase = 0.02).

Table IV displays model-fit (R^2) and coefficients for the multiple regression analyses. For Model 1, with LA50 in the equation, R^2 = 0.21. For Model 2, with LCeq-LAeq added to the equation, R^2 = 0.24. Thus, LCeq-LAeq contributed with 3 % of the explained variance in road-traffic noise annoyance. Adding CoG to the model with LA50 and LCeq-LAeq did not increase model fit significantly (R^2 = 0.24, $F_{inc}(1, 1111) < 1.0$).

Road-traffic noise annoyance was highly correlated with identification of technological sounds (Table II). This was expected because road-traffic was the main noise source in the investigated areas. For nature sounds, a substantial negative correlation was found, whereas identification of human sounds was only weakly related to road-traffic noise annoyance. In order to explore the effect of sound-source identification on perceived noise annoyance, identification of sounds from nature and sounds from technological sources were added to the multiple regression model (Model 3). The model fit, R^2 = 0.35, was considerably higher than for the model with acoustical variables only (Model 2, Table IV). Road-traffic noise and other technological sounds may be perceived as unwanted and intrusive also at low levels, especially in areas intended for recreation [6,12]. Thus, it is not surprising that identification of technological sounds was related to perceived annoyance, also after adjustment for the overall sound level of the soundscape.

CONCLUSIONS

(1) Acoustic indictors related to overall sound level (LAeq, LA50, LA95, N) explained a substantial part of the variance in perceived soundscape quality and road-traffic noise annoyance. LA50 was found to be the best predictor, explaining approx. 20-30 % of the variance of individual assessments (N = 1116) and 85-90 % of the variance of averages across areas (N = 16).

(2) Acoustic indicators related to spectral content (LCeq-LAeq, CoG) and time-patterns (ML, LA10-LA90, NCN) were not strongly related to perceived soundscape quality and road-traffic noise annoyance. Only indictors related to spectral content were found to explain a significant, but small, part of the variance not accounted for by overall sound level (LA50).

(3) The degree to which nature sounds and technological sounds were heard within the soundscapes was strong predictors of perceived soundscape quality and road-traffic noise annoyance. Source identification explained a substantial part of the variance over and above the variance shared with overall sound level (LA50) and other acoustic indictors. This suggests that prediction of soundscape quality would benefit from the development of acoustic indicators of sound source audibility within soundscapes.

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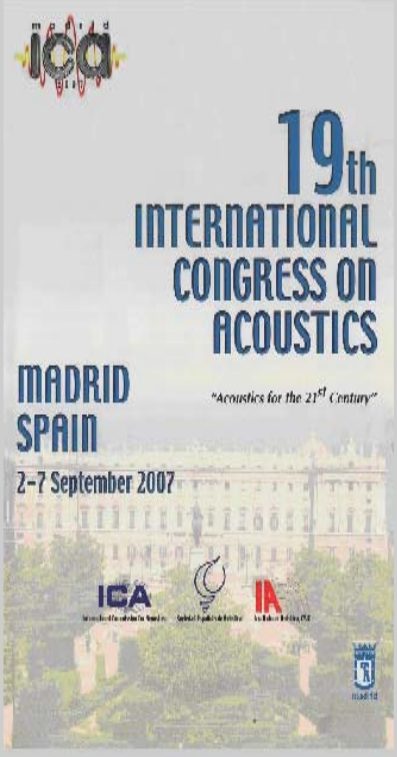

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