Assessing the relationship of indoor and outdoor noise at residential dwellings in London

Faridah Naim[1,2], John Gulliver[3], Daniela Fecht[4], Anna Hansell[4]

[1] Imperial College London, Department of Epidemiology and Biostatistics, London, UK (corresponding author)
[2] Universiti Sains Malaysia, School of Health Sciences, Kelantan, Malaysia (corresponding author)
[3] MRC-PHE Centre for Environment and Health, Imperial College London, London, UK
[4] UK Small Area Health Statistics Unit, MRC-PHE Centre for Environment and Health, Imperial College London, London, UK

Corresponding author's e-mail address: f.naim14@imperial.ac.uk

ABSTRACT

Most epidemiological studies investigating the association between noise and health use modelled outdoor noise estimates as exposure proxy. This study explores the relationship of indoor and outdoor noise at residential dwellings in London to establish how well outdoor noise levels represent indoor noise levels. Continuous noise measurements were made inside and outside each home for three consecutive days using an Optimus CR:171B sound level meter. Selected homes were located close to major roads, railway, under an aircraft flight path or any combination of them. Measurements from 18 homes found average daytime noise levels ($L_{eq,16h}$) of 44.7±7.1 dBA indoors and 61.7±7.3 dBA outdoors, and night-time noise levels (L_{night}) of 39.1±7.8 dBA indoors and 55.9±7.6 dBA outdoors. Analysis of indoor and outdoor noise showed similar temporal patterns, with attenuation of 10-30 dB indoors. Correlations between indoor and outdoor were moderate for both night-time (r=0.69, $p<0.001$) and day-time noise levels (r=0.51, $p<0.001$). No significant differences were found between noise levels recorded in occupied and unoccupied rooms (p=0.29). More homes will be measured and repeat measurements taken in the summer period.

INTRODUCTION

The main source of noise in most developed urban areas is transport, particularly for those who live near to either a major road, over ground railway, under a flight path or any combination of them. Around 20% of European Union’s population are exposed to noise levels which are considered unacceptable because they can cause annoyance, sleep disturbance and adverse health effects [1]. It is estimated that 125 million people in European countries are affected by noise levels from road traffic greater than 55 dB day-evening-night equivalent noise level (L_{den}), including more than 37 million exposed to noise levels above 65 dB L_{den}. Nearly 8 million and almost 3 million people exposed to rail traffic and aircraft noise above 55 dB L_{den}, respectively [2]. Noise had been associated with various health outcomes such as noise-induced hearing loss, myocardial infarction, ischaemic heart disease, stroke, annoyance, sleep disturbance and cognitive performance in children [3]. Several studies have found exposure-response relationships with annoyance due to increasing environmental noise mainly from road traffic, train and airplane movement [4,5].

Residential proximity to road traffic and railway lines can influence the noise exposure levels [6]. A two times higher proportion of annoyed and highly annoyed persons were observed in residential areas situated less than 50 m from major road compared to those live within 150 and more meters away from the road [7]. The maximum noise levels (L_{AFmax}) reported when trains pass by in study conducted by Lim et al. (2006) were varied between 91 and 100 dB, as 80% of the studied sites were situated within about 50 m of railway lines [8]. In addition, residents live closer to airport are also exposed to higher noise levels. Based on a noise study done in 12 homes near LaGuardia Airport, New York City, residents living near the airport were exposed to noise levels that were four times greater than those who live in a comparable quiet home [9]. Thus, high attenuation of outdoor noise to indoor can be influenced by distance between the residential dwellings and the noise source, window opening habits and sound insulation installed at the dwellings (e.g. single or double glazed windows).

Previous studies have, therefore, suggested that window characteristics should be considered when studying environmental noise effects on residents inside their homes as windows are generally the weakest point in the sound propagation path. Various window types can be found in homes including single thin panes within frames either with or without additional insulation and double or triple-pane windows within insulated frames. A sound reduction from outside to inside buildings of usually less than 24 dB has been estimated for the simplest types of façade, and more than 45 dB for the most elaborate facades (e.g. built to cope with cold climates) [10]. Building characteristics and window opening habits thereby lead to important differences in individual's exposure.

Generally, individuals spend approximately 90% of their time indoors and about 56-66% of time a day is spent at home [11]. Indoors, people are exposed to noise from both outdoor and indoor sources; indoor noise exposure is therefore a complex mixture of noise migrating from outdoor sources such as transport noise, together with noise generated by indoor sources [12] (such as inhabitants, children, and equipment including television and musical instruments) [13]. Most epidemiological studies have used models to assess outdoor long-term noise exposure accounting for traffic volume and sound propagation [14,15]. Other studies have measured noise outside residences to accurately reflect outdoor noise levels [16-18]. However, the variability of the relationship between ambient noise and indoor noise across a population is still unclear.

Few studies have measured indoor noise exposures in residential dwellings [19,20], mostly to investigate the effect of noise on sleep disturbance and cognitive impairment in children. Hence, the noise assessments were done either over a short period of time, only for night-time exposures or at school. A longer indoor and outdoor measurement at residential dwellings could provide more information on individual daily noise exposure levels, and provide further insight into the variability of the relationship of outdoor and indoor noise in different locations. This study aims to explore the relationship between outdoor and indoor noise a) to understand whether outdoor levels misclassify noise exposures for the time people spend indoors and whether this is different for day-time and night-time periods and b) inform future epidemiological studies of noise and health about the exposure misclassification and possible corrective measures.

METHODOLOGIES

We intend to investigate indoor and outdoor noise levels related to transport at 50 residential dwellings with repeat measures and completion of a time-activity diary. Selected study participants are residents who live within 300 m from a major road, within 200 m from railways and/or under a flight path in London. The study participants that have been recruited are Imperial College staff and students who were invited through email. Residents affected by aircraft from Heathrow and London City airports were also approached through contact with Heathrow Association for the Control of Aircraft Noise (HACAN). This study has obtained approval from the Imperial College Research Ethics Committee, Joint Research Compliance Office.

Measurements were conducted at participants' homes during winter (December 2016-January 2017). A survey was done at each of the participants' house before being selected for the study to evaluate the suitability of the location for the measurement and availability of a secure site to lock the outdoor noise monitor. Additionally, only residents who live at the same residential address within the study period (November 2016-February 2018) were included in the study.

The noise measurements were conducted simultaneously inside and outside residential dwellings for at least three consecutive days, covering the cold season to date. The cold season measurements are still ongoing and repeat measurements will be started in summer 2017. Noise levels were measured using an Optimus CR:171B class 1 sound level meter (SLM) with a CK:670 outdoor measurement kit for outdoor measurement. Outside, the SLM was placed in a bespoke weatherproof case with a cable extending from the case to a microphone on a tripod. Each SLM was sent to the manufacturer for annual calibration and then were checked onsite with an acoustic calibrator before each measurement. SLMs were located in the room with the most exposed façade to a main road and railway, with at least one window, and ideally unoccupied such as second bedroom. The SLMs were positioned at least 1 m from walls or other major reflecting surfaces, 1.2 to 1.5 m above the floor and 1.5 m from windows. Measurement outside residential dwellings were taken at a private garden or balcony, at least 1 m away from the façade of the building or any reflecting surfaces [21,22].

A building survey was conducted at each participant's dwelling to gather information related to building and household characteristics that may influence the level of indoor noise measured - source of transport noise, types of dwelling, number of occupants, types of window and room dimension. The participants were asked to identify the hours of the day in a diary when the occupants were absent from the home or asleep. The purpose of this diary was to identify the occurrence of indoor noise events and isolate those periods when indoor noise is predominantly a function of outdoor noise, to be able to study the mean and variance of the attenuation of outdoor noise in indoor microenvironments.

Noise data were processed using NoiseTools v1.6.4 software from Optimus SLM. Two time periods of each day were defined as follows: day (7:00-23:00) and night (23:00-7:00). Hourly L_{Aeq} was calculated for each day and night period. Descriptive statistics of measured noise levels, and dwelling and household characteristics are presented as mean and standard deviation or as percentage for categorical variables (dwelling characteristics). Indoor and outdoor noise levels from each dwelling were presented in box-and-whisker plots for day- and night-time. Pearson's correlation was used to test the association between the outdoor and indoor noise. Mann-Whitney U-test was used to find whether the noise levels varied by level of occupancy of the rooms used to locate the indoor noise monitor. Analyses were performed using Stata (v.13.0) package.

RESULTS AND DISCUSSION

So far, data have been collected at 18 dwellings. As shown in Table 1, most of those dwellings are terraced (a continuous row of houses with adjoining walls) houses (55.6%) and 33.3% of all dwellings are exposed to road traffic noise. Mean floor level is 1 and the number of room per dwelling ranges between 2 and 7 (not included are bathroom, kitchen and storage room). Number of occupants in each dwelling ranged from 1 to 6 persons. The types of window installed in the studied rooms were mainly double glazed (72.2%). Size of the studied rooms ranged from 6.9 m^2 to 24.8 m^2.

Table 1: Dwelling and household characteristics of the study sample

	n	**%**
Type of dwellings		
Terraced house	10	55.6
Semi-detached house	1	5.6
Medium-rise flat	2	11.1
High-rise flat	5	27.8
Sources of transport noise		
Aircraft	3	16.7
Road traffic	6	33.3
Aircraft and road traffic	5	27.8
Rail and road traffic	3	16.7
Aircraft, rail and road traffic	1	5.6
	Mean (SD)	**Range**
Number of inhabitants	2.8 (1.5)	1 - 6
Number of rooms	4.3 (1.8)	2 - 7
Floor	0.9 (2.3)	-1[a] - 9

[a]-1: basement floor and 0: ground floor

Table 2: Characteristics of the study room

	Mean (SD)	**Range**
Volume (m^3)	39.3 (14.3)	18.2 - 65.1
Area (m^2)	16.1 (5.5)	6.9 - 24.8
Type of window	**n**	**%**
Single glazed	4	22.2
Double glazed	13	72.2
Secondary glazed	1	5.6

Average noise levels reported during the winter measurement campaign (n=18) were 44.7±7.1 dBA $L_{eq,16h}$ indoors and 61.7±7.3 dBA outdoors and night-time exposures of 39.1±7.8 dBA L_{night} indoors and 55.9±7.6 dBA outdoors (Table 3). Highest mean noise levels were observed at dwellings with road traffic noise exposure for daytime indoors and outdoors and night-time outdoors. Similar daytime and night-time outdoor mean levels were recorded for dwellings with combine rail and road traffic noise exposures.

Table 3: Day- and night-time indoor and outdoor noise exposures

Source of noise	**Indoor noise (Mean±SD)**		**Outdoor noise (Mean±SD)**	
	L_{day} (dBA)	**L_{night} (dBA)**	**L_{day} (dBA)**	**L_{night} (dBA)**
Aircraft (n=3)	44.8±7.0	32.5±7.1	59.2±4.8	51.6±8.0
Road traffic (n=6)	48.5±6.4	38.9±6.3	64.4±8.6	59.7±10.0
Aircraft and road traffic (n=5)	45.0±7.7	35.4±6.5	61.2±6.2	54.2±6.2
Rail and road traffic (n=3)	44.3±10.3	38.7±8.6	64.2±11.5	57.8±12.2
Aircraft, rail and road traffic (n=1)	44.3±5.1	45.0±7.3	53.4±4.1	44.9±4.9
Average noise levels (n=18)	**44.7±7.1**	**39.1±7.8**	**61.7±7.3**	**55.9±7.6**

Figures 1 and 2 show the indoor-outdoor noise variation at each dwelling with more variability during the daytime than the night-time. Overall, the measured indoor noise is 10 to 30 dB lower than that measured outside. The variations of indoor and outdoor noise levels observed between dwellings (Figures 1 and 2) depended on distance from the house to the roadway and railway (for road and rail traffic noise), and number and height of aircrafts flying over the house (for aircraft noise). The highest indoor and outdoor L_{night} were found amongst dwellings located in close proximity to roads and railways especially roadside residences. Higher indoor $L_{Aeq,16}$ were found in occupied rooms and levels depended on the number of occupants and presence of children in the dwelling. Previous studies have identified dwelling characteristics, presence and activities of people in the dwelling, the number of children living in the dwelling and noisy event occurrences were some of the factors that influence noise variability within dwelling [13,20].The indoor noise levels that were measured in an occupied room had higher levels as the overall noise recorded was influenced by activities of the occupants. However, no significant differences were found between noise levels measured in occupied (n=10) and unoccupied (n=8) rooms (p=0.29) (Figure 3).

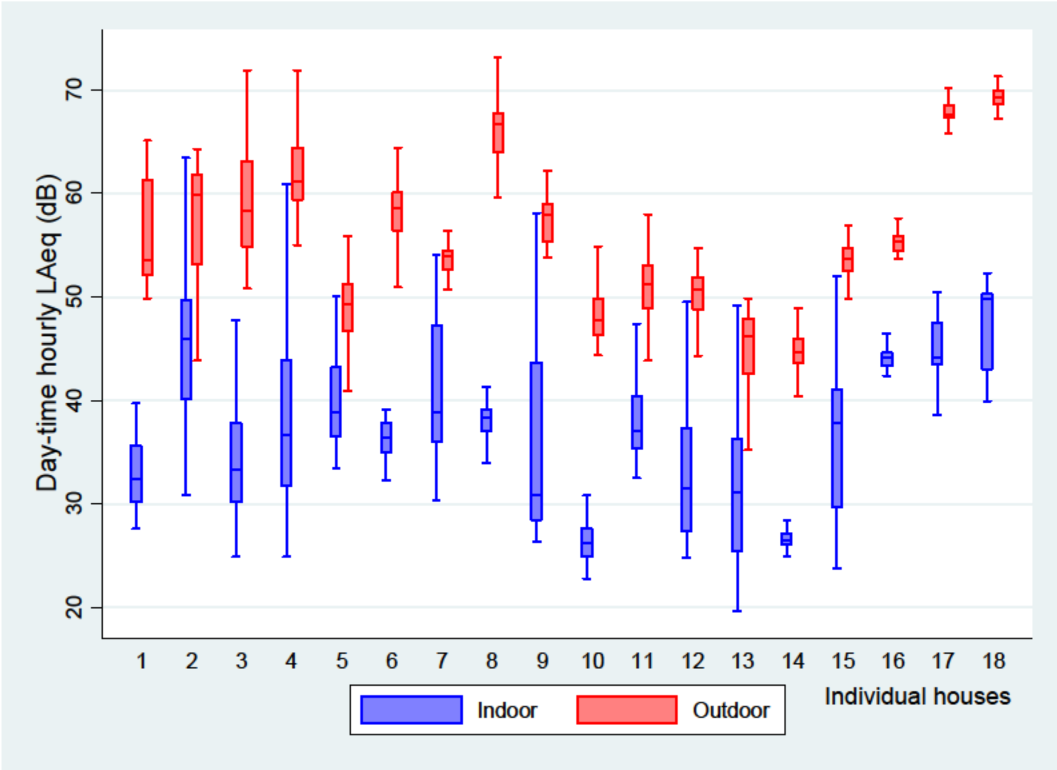

Figure 1: Boxplots of day-time noise levels (dB) indoors and outdoors for individual houses, n=18

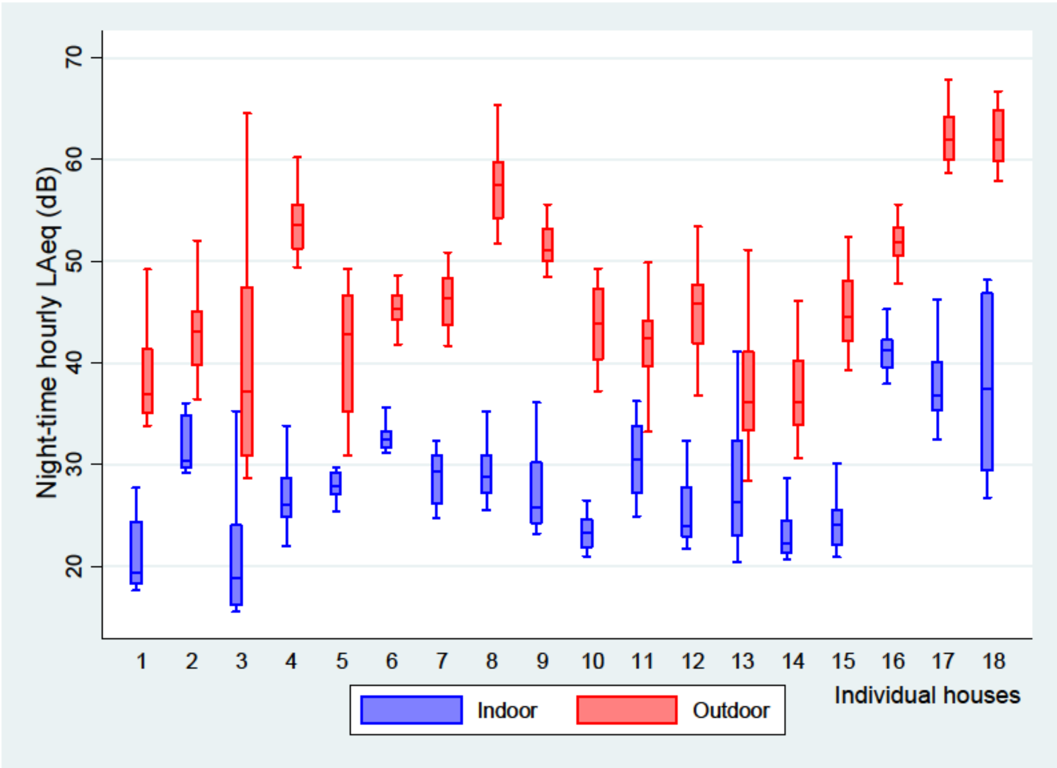

Figure 2: Boxplots of night-time noise levels (dB) indoors and outdoors for individual houses, n=18

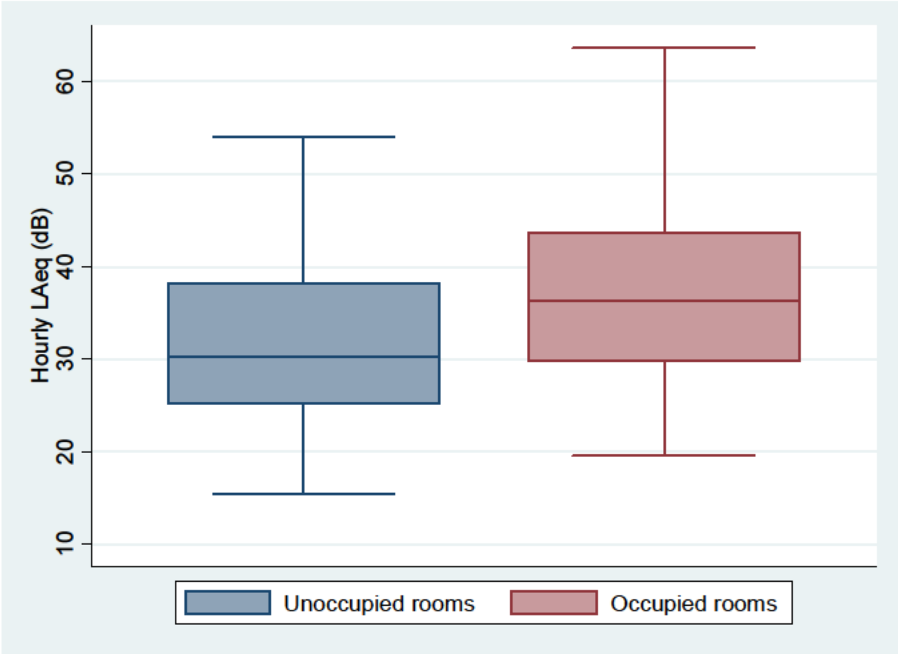

Figure 3: Difference of noise levels between unoccupied (n=8) and occupied (n=10) rooms

The indoor and outdoor noise levels were positively correlated during daytime (r=0.51, p<0.001) and night-time (r=0.69, p<0.001) as shown in Figures 4 and 5. This is consistent with previous findings but the study assessed the indoor-outdoor relationship only for night-time [23]. The coefficient of correlation value (r) between the indoor and outdoor data can be used as an indicator of the degree to which noise measured indoors is attributed to attenuation from outdoors [24]. This may applied to L_{night} as the r value obtained for the unoccupied room was higher than the occupied room (0.77 vs 0.47, p<0.001), but it was quite similar for the day-time (0.54 vs 0.40, p<0.001). These suggest that the outdoor noise is influencing the indoor noise in isolation of other sources. Indoor/outdoor (I/O) noise levels can vary largely due to multiple factors including locations of dwellings, building design and different activities [13,25]. I/O ratio is an indicator for evaluating the difference between indoor noise levels and the corresponding outdoor levels [24]. Mean I/O noise ratio calculated for each dwelling ranged from 0.56 to 0.91 (Table 4). All I/O ratios were lower than 1 but smaller for measurements in the unoccupied rooms. These lower I/O ratios indicate the higher outdoor noise levels. Higher I/O ratios for indoor measurement in the occupied room suggest that indoor noise is highly influenced by inside noise sources [20].

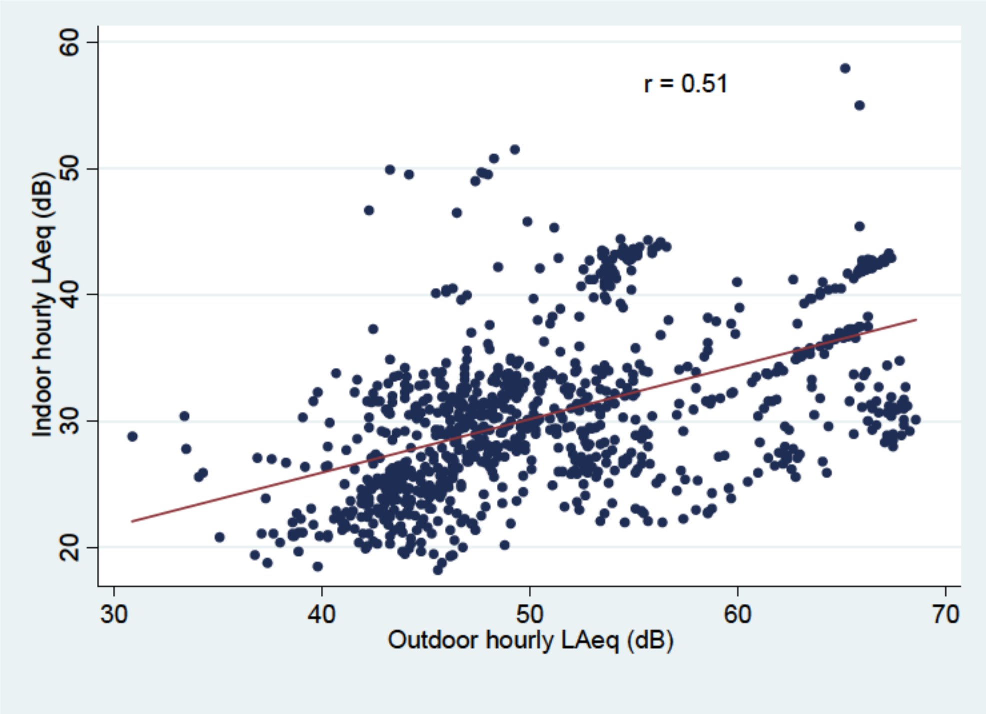

Figure 4: Correlation between indoor and outdoor noise levels in the day-time

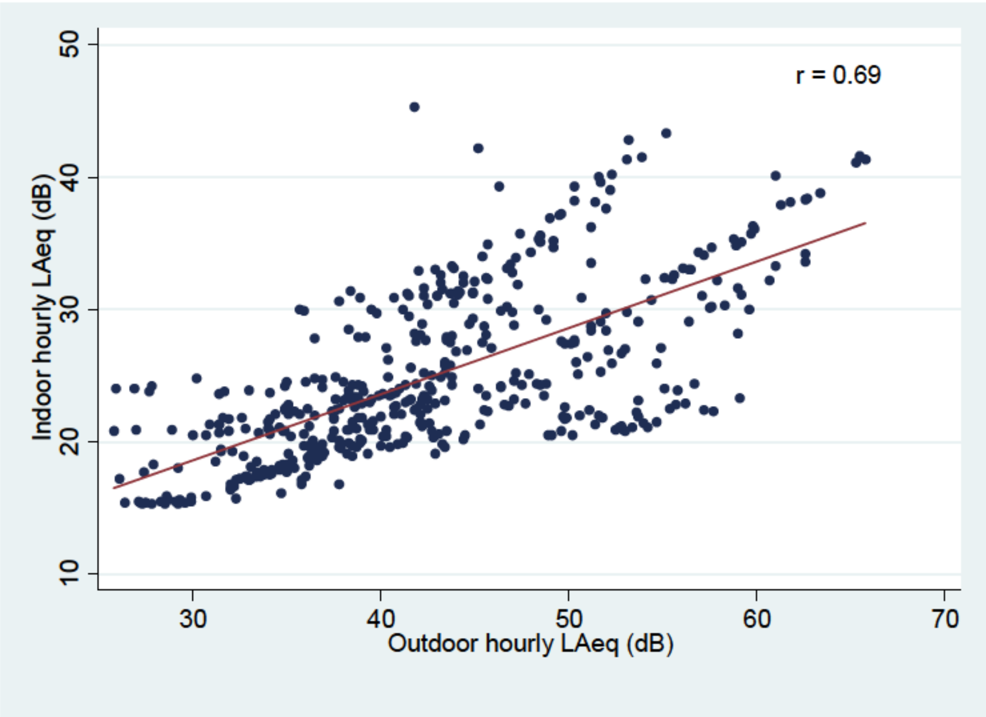

Figure 5: Correlation between indoor and outdoor noise levels in the night-time

Table 4: Summary of noise level results (hourly L_{Aeq} mean values)

Source of noise	Sample	Study room	Mean indoor (dB)	Mean outdoor (dB)	Mean I/O ratio
Aircraft	ID03	Unoccupied	33.9	57.7	0.59
	ID 05	Occupied	47.5	58.2	0.82
	ID 06	Unoccupied	33.9	57.3	0.59
Road traffic	ID 08	Occupied	42.8	49.1	0.87
	ID 10	Unoccupied	29.7	53.1	0.56
	ID 07	Unoccupied	43.9	52.7	0.83
	ID 14	Unoccupied	37.1	49.9	0.74
	ID 01	Unoccupied	43.4	54.6	0.79
Aircraft + road traffic	ID 19	Occupied	49.1	66.8	0.74
	ID 02	Occupied	46.7	62.2	0.75
	ID 09	Occupied	38.8	57.4	0.68
	ID 11	Unoccupied	36.6	65.7	0.56
	ID 12	Occupied	38.4	57.0	0.67
	ID 17	Occupied	47.9	52.7	0.91
Rail + road traffic	ID 15	Occupied	35.8	45.1	0.79
	ID 16	Unoccupied	31.0	44.1	0.70
	ID 20	Occupied	47.6	68.0	0.70
Aircraft + rail + road traffic	ID 13	Occupied	44.5	51.9	0.86

CONCLUSION

Preliminary results from a winter monitoring campaign suggest that majority of the residents from the 18 homes studied are exposed to noise levels that exceed the World Health Organisation outdoor recommended limits (55 dB at day-time [55.6%], 45 dB at night-time [72.2%]) and 50% exceed the indoor limit (30 dB at night-time). Outdoor noise levels are attenuated indoors up to 30 dB with slightly high correlation between outdoor and indoor noise during night-time. A total of 50 homes will be measured and repeat measurements taken in the summer period. A fuller analysis of the data will follow.

Acknowledgements

The work of the UK Small Area Health Statistics Unit is funded by Public Health England as part of the MRC-PHE Centre for Environment and Health, funded also by the UK Medical Research Council. This research was also funded by Ministry of Higher Education, Malaysia and Universiti Sains Malaysia. Our sincere gratitude to all volunteers who had helped and participated in this study.

REFERENCES

[1] Vos, P. D., & Beek, A. V. (2011). Environmental noise. In J. O. Nriagu, S. Kacew, T. Kawamoto, J. A. Patz, & D. M. Rennie, (Eds) Encyclopedia of environmental health (pp. 476-488). New York: Elsevier.

[2] European Environment Agency (EEA). (2014). Noise in Europe 2014 (EEA Report, No. 10/2014). Copenhagen: European Environment Agency.

[3] Basner, M., Babisch, W., Davis, A., Brink, M., Clark, C., Janssen, S., & Stansfeld, S. (2014) Auditory and non-auditory effects of noise on health. Lancet, 383(9925), 1325-1332.

[4] Miedema, H.M.E., & Oudshorn C.G.M. (2001). Annoyance from transportation noise: Relationships with exposure metrics DNL and DENL and their confidence intervals. Environ. Health Perspect, 109, 409-416.

[5] Ohrström, E., Barregård, L., Andersson, E., Skånberg, A., Svensson, H., & Angerheim, P. (2007). Annoyance due to single and combined sound exposure from railway and road traffic. The Journal of the Acoustical Society of America, 122(5), 2642–2652.

[6] Moudon, A. V. (2009). Real noise from the urban environment: How ambient community noise affects health and what can be done about it. American Journal of Preventive Medicine, 37(2),167-171.

[7] Ragettli, M. S., Goudreau, S., Plante, C., Perron, S., Fournier, M., & Smargiassi, A. (2016). Annoyance from road traffic, trains, airplanes and from total environmental noise levels. International Journal of Environmental Research and Public Health, 13(1), 90.

[8] Lim, C., Kim, J., Hong, J., & Lee S. (2006). The relationship between railway noise and community annoyance in Korea. J Acoust Soc Am, 120, 2037-2042.

[9] Cohen, B. S., & Bronzaft, A. L. (2011). Air transportation and human health. In J. O. Nriagu, S. Kacew, T. Kawamoto, J. A. Patz, & D. M. Rennie, (Eds) Encyclopedia of environmental health (pp. 53-63). New York: Elsevier.

[10] World Health Organisation (WHO). (2009). Night noise guidelines for Europe. WHO Regional Office for Europe.

[11] Schweizer, C., Edwards, R. D., Bayer-Oglesby, L., Gauderman, W. J., Ilacqua, V., Juhani Jantunen, M., Lai, H. K., Nieuwenhuijsen, M., & Künzli, N. (2006). Indoor time–microenvironment–activity patterns in seven regions of Europe. Journal of Exposure Science and Environmental Epidemiology, 17(2), 170-181.

[12] Le Cann, P., Bonvallot, N., Glorennec, P., Deguen, S., Goeury, C., & Le Bot, B. (2011). Indoor environment and children's health: Recent developments in chemical, biological, physical and social aspects. International Journal of Hygiene and Environmental Health. Elsevier GmbH, 215(1),1–18.

[13] Pujol, S., Berthillier, M., Defrance, J., Lardies, J., Levain, J. P., Petit, R., Houot, H., & Mauny, F. (2014). Indoor noise exposure at home: A field study in the family of urban schoolchildren. Indoor Air, 24(5), 511–520.

[14] Clark, C., Martin, R., van Kempen, E., Alfred, T., Head, J., Davies, H. W., Haines, M. M., Barrio, I. L., Matheson, M., & Stansfeld, S. A. (2006). Exposure-effect relations between aircraft and road traffic noise exposure at school and reading comprehension. The RANCH project. American Journal of Epidemiology, 163(1), 27-37.

[15] Murphy, E., King, E. A., & Rice, H. J. (2009). Estimating human exposure to transport noise in Central Dublin, Ireland. Environment International, 35(2), 298-302.

[16] Regecova, V., & Kellerova, E. (1995). Effects of urban noise pollution on blood pressure and heart rate in preschool children. Journal of Hypertension, 13(4), 405-412.

[17] Belojevic, G., Jakovljevic, B., Stojanov, V., Paunovic, K., & Ilic, J. (2008). Urban road-traffic and blood pressure and heart rate in preschool children. Environment International, 34(2), 226-231.

[18] Hong, J., Kim, J., Lim, C., Kim, K., & Lee, S. (2010). The effects of long-term exposure to railway and road traffic noise on subjective sleep disturbance. The Journal of the Acoustical Society of America, 128(5), 2829–2835.

[19] Graham, J. M. A., Janssen, S. A., Vos, H., & Miedema, H. M. E. (2009). Habitual traffic noise at home reduces cardiac parasympathetic tone during sleep. International Journal of Psychophysiology, 72(2), 179-186.

[20] Pujol, S., Berthillier, M., Defrance, J., Lardies, J., Petit, R., Houot, H., Levain, J-P., Masselot, C., & Mauny, F. (2012). Urban ambient outdoor and indoor noise exposure at home: A population-based study on schoolchildren. Applied Acoustics, 73(8), 741-750.

[21] British Standard Institution (BSI). (1991). Description and measurement of environmental noise - Part 2: Guide to the acquisition of data pertinent to land use (BS 7445-2:1991). London: British Standard Institution.

[22] Bruel & Kjaer, (1988). Measurements in building acoustics. [pdf] Available at: http://www.bksv.com/doc/br0178.pdf [Accessed 4 November 2016].

[23] Pirrera, S., De Valck, E., & Cluydts, R. (2014). Field study on the impact of nocturnal road traffic noise on sleep: The importance of in- and outdoor noise assessment, the bedroom location and nighttime noise disturbances. Science of the Total Environment, 500–501, 84–90.

[24] Massey, D., Masih, J., Kulshrestha, A., Habil, M., & Taneja, A. (2009). Indoor/outdoor relationship of fine particles less than 2.5 μm (PM2.5) in residential homes locations in central Indian region. Building and Environment, 44, 2037-2045.

[25] Pirrera, S., De Valck, E., & Cluydts, R. (2011). Nocturnal road traffic noise assessment and sleep research: The usefulness of different timeframes and in- and outdoor noise measurements. Applied Acoustics. Elsevier Ltd, 72(9), 677–683.