# Assessment of residential exposure to aircraft, road traffic and railway noise in London: Relationship of indoor and outdoor noise

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**Summary**
Most epidemiological studies investigating the association between noise exposure and health use modelled outdoor noise estimates as an exposure proxy. This could potentially lead to misclassification of exposure. This study aims to explore the variability of the relationship between indoor and outdoor noise at residential dwellings in London. Measurements were done at 49 homes mostly in the winter and spring seasons when windows are most likely to be closed. Continuous noise measurements were made simultaneously 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, railways, under an aircraft flight path or a combination of these. Building surveys and time-activity diaries of the occupants were also collected. The relationship of daytime and night-time indoor and outdoor levels was investigated using linear regression and mixed-effects models with random intercepts and slopes on dwelling. The ability of the model to predict indoor noise was investigated. Based on 49 homes measured, mean noise levels recorded were 38.4 dB indoors and 57.7 dB outdoors for $L_{Aeq,16h}$ and 30.2 dB indoors and 52.1 outdoors for $L_{night}$. The mean outdoor noise levels were attenuated indoors up to 21.9 dB, with weak correlation between indoor and outdoor noise ($L_{Aeq,16h}$: r=0.34, p=0.02; $L_{night}$: r=0.32, p=0.03). From linear regression analysis, significant associations were found between indoor and outdoor noise: $L_{Aeq,16h}$ (β=0.41, 95% Confidence Interval (CI): 0.08-0.74, p=0.02) and $L_{night}$ (β=0.33, 95% CI: 0.04-0.62, p=0.03). Based on mixed-effects model, $L_{night}$ has better explanatory power than $L_{Aeq,16h}$ which the model predicted 87% of variability in indoor noise. For application in epidemiological studies, this suggests using the $L_{night}$ will provide a less biased measure of exposure than daytime noise.

## 1. Introduction

Most epidemiological studies investigating the health effects of noise use modelled outdoor noise estimates as exposure proxy. These models, however, do not consider factors such as sound insulation of buildings or window opening habits if they were used as indicator of indoor exposure. As the majority of people spend most of their time indoors, indoor noise estimates are needed to represent individual noise exposures inside buildings, to reduce exposure misclassification. Since individual indoor noise measurements are difficult to collect for a large sample, most studies use either modelled [1,2] or measured [3,4] outdoor noise to assess long term noise exposure. However, very little information is available on the difference between indoor and outdoor noise levels and the consequent exposure error introduced to epidemiological analyses [5]. A reliable approach of estimating indoor noise is needed but there are challenges associated with deriving indoor noise from outdoor estimates.

People tend to close their windows or have special sound insulation such as secondary glazing to reduce the noisy effects from outdoor sources, especially those who live next to busy road or railway or under the aircraft flight path. This will lead to overestimation of indoor exposure levels due to outdoor sources as the modelled and measured outdoor noise levels will not take into account the sound insulation factors. Multiple studies that have taken measurements under closed window conditions showed that sound insulation is mainly influenced by façade type [6,7]. Window and room size are also factors that need to be taken into account in noise propagation [8-10]. Locher et al. found a mean indoor-outdoor difference of 27.8 dB for 76 residential dwellings measured in Switzerland under closed window conditions [5]. Several studies have also investigated indoor and outdoor noise levels at schools suggesting different sound levels of more than 10 dB(A) [11,12]. Various methods have been used to estimate the indoor-outdoor differences at residential dwellings and schools, and suggested a range of mean or median values to be applied as a correction factor to estimate the indoor noise. However, detailed information on dwelling characteristics is difficult to acquire for large populations including information on window insulation and type and opening habits, dwelling volume and type of dwelling. Therefore, generalised indoor noise model is needed that can be used in future epidemiological studies to predict indoor noise exposure for a large number of people based on modelled outdoor noise.

In studies that have investigated indoor noise exposures in residential dwellings, the noise assessments were done either over a short period of time [5,13] or only for night-time exposures [14-16] or at school [17-19] where building layout and exposure level might be different. A longer indoor and outdoor measurement period at residential dwellings could provide more information on individual daily noise exposure level and for day- and night-time differences. This study aims to explore the relationship between indoor and outdoor noise and develop a model to predict indoor noise using the outdoor and indoor measured data.

## 2. Methods

### 2.1 Study area and population

Assessment of transport-related indoor and outdoor noise levels at 49 residential dwellings and collection of time-activity diary of inhabitants were done. Selected study participants were residents in Greater London who lived close to a major road, railway and/or under an aircraft flight path(s) related to Heathrow or London City airports or any combination of these. The study participants that were recruited were Imperial College London staff and students who were invited to participate in the study through email. Some of the participants were also approached through existing contacts with Heathrow Association for the Control of Aircraft Noise (HACAN). This study obtained approval from the Imperial College Research Ethics Committee, Joint Research Compliance Office (ICREC Reference: 16IC3545).

### 2.2 Noise measurements

Noise measurements were conducted at participants' homes from December 2016 to August 2017. Most of the measurements were done during the winter season. A survey was conducted 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. The measurements were conducted inside and outside dwellings simultaneously for at least three consecutive days, mainly in cold season. Noise levels were measured using Optimus CR:171B class 1 sound level meter (SLM) with a CK:670 outdoor measurement kit for outdoor measurement. The outdoor 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 an acoustic calibrator was used on site before each measurement. The indoor SLM was located in a room with at least one window and being at the most expose façade if road traffic or railway was the main source of noise, and ideally unoccupied such as a second bedroom. The SLMs were mounted on a tripod at least 1 m from walls or other major reflecting surfaces, 1.2 - 1.5 m above the floor and 1.5 m from windows. The outdoor SLM was located either at a private garden or balcony, at least 1 m away from the façade of the building or any reflecting surfaces [20,21].

## 2.3 Dwelling and household characteristics information

A building survey was conducted at each participant's homes to gather information related to dwelling and household characteristics that may influence the level of indoor noise measured including source of transport noise, types of dwelling, types of window and window and room dimensions. A time-activity diary was also collected to gather information on the number of occupants and hours of the day 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 was predominantly a function of outdoor noise.

## 2.4 Data processing

Noise data were processed using NoiseTool ver.1.8.2 from Optimus SLM. Equivalent continuous sound pressure level ($L_{Aeq}$) were categorised into two time periods of each day as follows: daytime $L_{Aeq,16h}$ (07:00-23:00) and night-time $L_{night}$ (23:00-07:00). Hourly $L_{Aeq}$ were calculated for each time period.

## 2.5 Statistical analysis

Descriptive statistics of measured noise levels, and dwelling and household characteristics were presented as mean and standard deviation or as frequency and 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 correlation and linear regression were used to test the association between the indoor and outdoor noise. Independent t-test was used to explore differences of indoor noise levels between occupied and unoccupied rooms. One-way anova was used to compare indoor noise levels based on number of occupant at each dwelling. Mixed-effect model was used to predict the indoor noise using the outdoor noise as the predictor and dwelling and hour of the day as factors. Analyses were performed using Stata v.13.0 package.

# 3. Results

## 3.1 Descriptive data

The 49 dwellings sampled were located mostly in the West and East of London which includes the area affected by Heathrow aircraft noise. Based on Table I, the majority of the study participants lived in terraced (a continuous row of houses with adjoining walls) houses (44.9%). 36.7% of all dwellings were exposed to combined sources of aircraft and road traffic noise. The number of occupants in each dwelling ranged from 0 to 6 persons. The volume of the studied rooms and the whole dwellings ranged from 9.9 $m^3$ to 70.7 $m^3$ and 92.2 $m^3$ to 1,050.0 $m^3$, respectively. The types of window installed in the studied rooms were mainly double glazed (75.5%). More than half of the rooms studied were unoccupied (59.2%). Most of the measurements were conducted in winter (51.0%).

Table I. Dwelling, household and study room characteristics of the study sample (n=49).

| | *n* | *%* |
|---|---|---|
| **Type of dwelling** | | |
| Terraced house | 22 | 44.9 |
| Semi-detached house | 5 | 10.2 |
| Detached house | 6 | 12.2 |
| Medium-rise flat | 7 | 14.3 |
| High-rise flat | 9 | 18.4 |
| **Source of transport** | | |
| Aircraft | 12 | 24.5 |
| Road traffic | 7 | 14.3 |
| Aircraft & road traffic | 18 | 36.7 |
| Rail & road traffic | 8 | 16.3 |
| Aircraft, rail & road traffic | 4 | 8.2 |
| **Type of window** | | |
| Single glazed | 9 | 18.4 |
| Double glazed | 37 | 75.5 |
| Secondary glazed | 3 | 6.1 |
| **Type of room** | | |
| Occupied | 20 | 40.8 |
| Unoccupied | 29 | 59.2 |
| **Season of measurement** | | |
| Winter | 25 | 51.0 |
| Spring | 15 | 30.6 |
| Summer | 4 | 8.2 |
| Autumn | 5 | 10.2 |
| | *Mean (SD)* | *Range* |
| Number of occupants | 2.4 (1.3) | 0-6 |
| Dwelling volume ($m^3$) | 288.3 (194.8) | 92.2-1050.0 |
| Room volume ($m^3$) | 32.8 (13.7) | 9.9-70.7 |

## 3.2 Average indoor and outdoor noise levels for day- and night-time

Average noise levels with standard deviations recorded at 49 homes were 38.4±7.5 dB $L_{Aeq,16h}$ indoors and 57.7±6.2 dB outdoors and night-time exposures of 30.2±6.9 dB $L_{night}$ indoors and 52.1±6.6 dB outdoors (Table II). Highest mean noise levels were observed at dwellings with road traffic noise exposure for daytime indoors and rail and road traffic noise exposure for night-time indoors. All combined noise sources (aircraft, rail and road traffic) showed the highest mean for daytime and night-time outdoors.

Table II. Day- and night-time indoor (IN) and outdoor noise (ON) exposures.

| *Source of noise* | *$L_{Aeq,16h}$ (dB) Mean(SD)* | | *$L_{night}$ (dB) Mean(SD)* | |
|---|---|---|---|---|
| | *IN* | *ON* | *IN* | *ON* |
| Aircraft | 33.9 (5.3) | 57.3 (4.2) | 25.8 (4.7) | 50.9 (4.4) |
| Road traffic | 44.2 (8.9) | 55.0 (6.4) | 33.1 (7.4) | 50.1 (6.6) |
| Aircraft & road traffic | 38.3 (7.4) | 58.2 (5.2) | 28.9 (6.0) | 52.8 (5.6) |
| Rail & road traffic | 41.7 (6.3) | 58.7 (10.3) | 36.1 (6.2) | 53.1 (10.4) |
| Aircraft, rail & road traffic | 35.7 (6.1) | 59.4 (6.6) | 32.1 (8.9) | 54.4 (8.9) |
| *Average noise levels* | *38.4 (7.5)* | *57.7 (6.2)* | *30.2 (6.9)* | *52.1 (6.6)* |

## 3.3 Mean indoor/outdoor ratios in occupied and unoccupied rooms

From independent t-test, significant difference of mean noise levels were found between occupied and unoccupied rooms ($p<0.001$). Figure 1 and 2 show indoor/outdoor (I/O) ratios for each dwelling. Mean I/O ratio calculated for each dwelling ranged from 0.45 to 0.98 for $L_{Aeq,16h}$ and from 0.40 to 1.00 for $L_{night}$ but was smaller for measurements in the unoccupied rooms. Overall, the I/O ratio showed the variability between unoccupied rooms was smaller than occupied rooms. One-way anova confirmed no significant differences between indoor noise based on number of occupant at each dwelling ($L_{Aeq,16h}$:p=0.36, $L_{night}$: p=0.28).

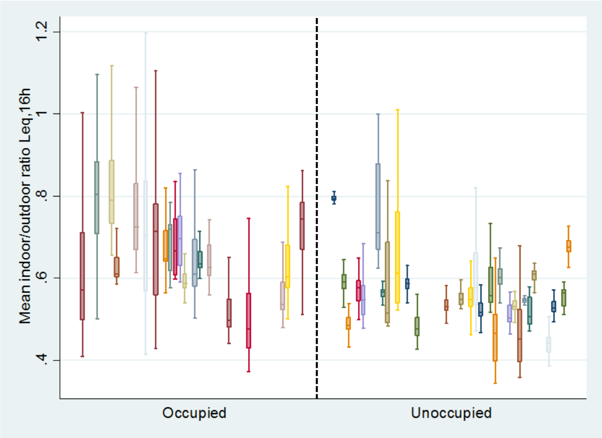


Figure 1. Mean I/O ratio for $L_{Aeq,16h}$ by room type and dwelling.

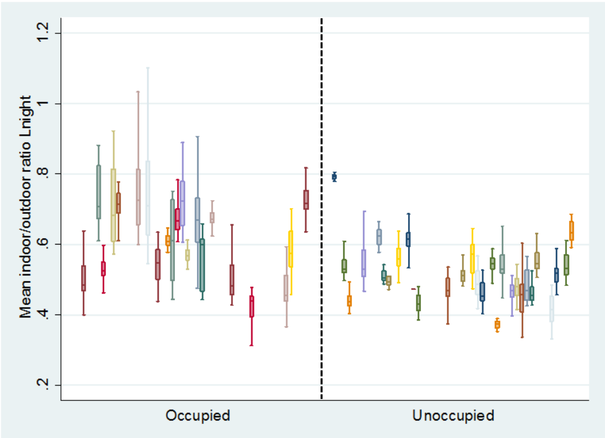


Figure 2. Mean I/O ratio for $L_{night}$ by room type and dwelling.

## 3.4 Variability of the relationship between indoor and outdoor noise

Weak to very strong correlations of indoor and outdoor noise were found for 86% of the dwellings, mostly strong and very strong positive correlations for unoccupied rooms in night-time (Table III). Based on scatterplots with linear fit for indoor versus outdoor noise, variable intercept and slope were observed at individual dwellings and varied between day- and night-time. Some dwellings had higher indoor noise levels compared to outdoor during the day, mostly in the occupied rooms. Based on hourly $L_{Aeq}$, both day- and night-time noise levels had moderate correlations between indoors and outdoors with slightly higher correlations for $L_{night}$ (0.62) than $L_{Aeq,16h}$ (0.46) (Figure 3). However, for all dwellings (n=49), both $L_{Aeq,16h}$ and $L_{night}$ were weakly correlated (r=0.34, p=0.02 and r=0.32, p=0.03) (Figure 4). From linear regression analysis, only 12% of measured outdoor noise (x) explain the variance in measured indoor noise (y) for $L_{Aeq,16h}$ (β=0.41, 95% Confidence Interval (CI): 0.08-0.74, p=0.02; y=0.41x+14.58) and 10% for $L_{night}$ (β=0.33, 95% CI: 0.04-0.62, p=0.03; y=0.33x+12.88). But these models were not adjusted with other indoor factors that might influence the relationship between indoor and outdoor noise such as window type, room size and occupancy.

Table III. Number of dwellings based on the correlation coefficient (r) between indoor and outdoor noise for day- and night-time by room type.

| *r* | *Occupied (n)* | | *Unoccupied (n)* | |
|---|---|---|---|---|
| | $L_{Aeq,16h}$ | $L_{night}$ | $L_{Aeq,16h}$ | $L_{night}$ |
| *Weak (0.20-0.39)* | 2 | 1 | 4 | - |
| *Moderate (0.40-0.59)* | 3 | 5 | 5 | 1 |
| *Strong (0.60-0.79)* | - | 3 | 5 | 10 |
| *Very strong (0.80-1.00)* | - | 3 | 6 | 16 |

*Significant correlation at p<0.05, Pearson correlation test.*

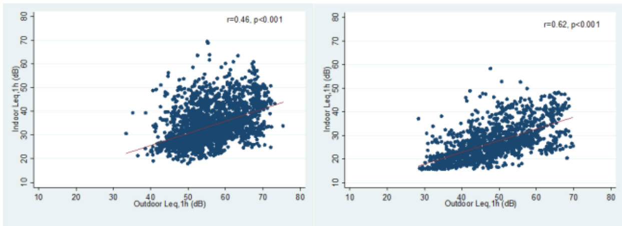


Figure 3. Correlation between indoor and outdoor noise for day- and night-time $L_{Aeq,1h}$ at 49 homes.

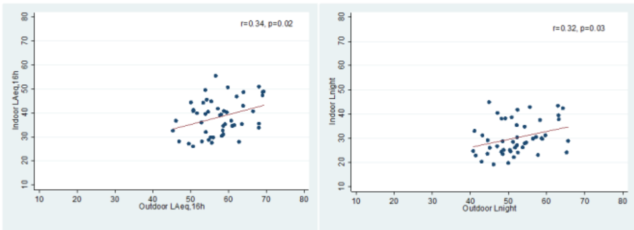


Figure 4. Correlation between indoor and outdoor noise for $L_{Aeq,16h}$ and $L_{night}$ at 49 homes.

## 3.5 Model testing and selection

Graphical inspection of the scatterplots of indoor vs outdoor noise for each dwellings informed choice of regression model to predict indoor noise. A mixed-effects model with random intercept and slope was used with dwelling number and hour of the day as random factors. In this model, outdoor noise (x) was the predictor and indoor noise the outcome (y). Significant associations were found between indoor and outdoor noise and fairly good correlation was found between the measured and predicted indoor noise for $L_{night}$ ($r^2$=0.87) compared to $L_{Aeq,16h}$ ($r^2$=0.57) (Figure 5 and 6).

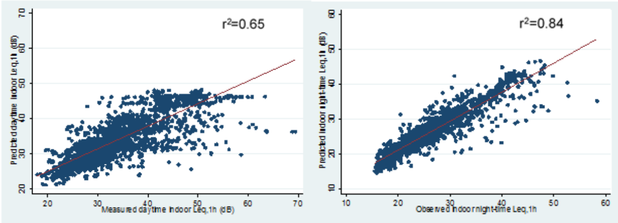


Figure 5. Predicted vs observed indoor day- and night-time $L_{Aeq,1h}$ at 49 dwellings.

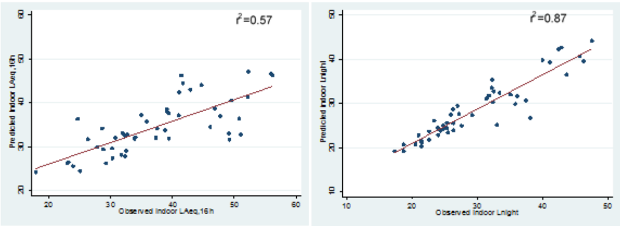


Figure 6. Predicted vs observed indoor $L_{Aeq,16h}$ and $L_{night}$ at 49 dwellings.

## 4. Discussion

In our analysis of 49 dwellings in London, mean indoor noise was lower than the outdoor noise and lower for night-time compared to daytime. As most of the measurements were conducted in unoccupied rooms, the indoor levels were largely not influenced by inside activities. Additionally, based on the completed time-activity diaries, the majority of dwellings had two occupants and most of the occupants were absent from home during working hours. Based on the mean I/O for each dwelling, occupied rooms have smaller difference between indoor and outdoor noise compared to unoccupied rooms. I/O is used as an indicator for evaluating the difference between indoor noise levels and the corresponding outdoor levels [22]. In this study, presence of occupants in the rooms increased the level of noise measured indoors and, for some dwellings the levels were higher than the outdoors. This observation occurred mainly during the day period when the occupants were awake and active around the dwelling. I/O noise levels can vary largely due to multiple factors including locations of dwellings, building design and different activities [16,23]. Individuals as well as household items in the dwelling can be considered to be indoor sound sources and can help to explain a majority part of the noise level and the variability of the indoor noise [24]. Number of occupants observed were almost equal between dwellings which is between 1 and 3 persons per dwelling. So, in this study, the indoor noise levels measured could be unlikely influenced by the number of occupants.

A weak correlation between indoor and outdoor noise (Figure 4) might be due to closed window conditions. Locher et al. found no clear outdoor-indoor correlation in measurements with closed window [5]. Some dwellings were not significantly correlated which indicate the noise measured inside has not totally captured the levels that were measured outside. This could possibly be due to unavailability of ideal locations for indoor and outdoor SLMs at some dwellings as these were depended on the availability of unoccupied room to place the indoor sensor and also availability of secure site for the outdoor sensor. But, when taking into account the hour of the day for each dwelling measured, the correlation becomes moderate and slightly higher for $L_{night}$. This is consistent with a previous study that also assessed the relationship of indoor and outdoor for night-time [25]. The coefficient correlation value (r) between the measured indoor and outdoor levels can be used as an indicator of the degree to which noise measured indoors is attributed to attenuation from outdoors [22].

The unadjusted regression model showed low regression coefficients for both $L_{Aeq,16h}$ and $L_{night}$ (Figure 4) due to high variability of measured indoor and outdoor noise. However, the slopes indicate that the outdoor noise has significant linear relationship with indoor noise. In an attempt to develop a model that can be used in epidemiological studies, we aimed to produce an indoor noise model that is generalizable. The indoor noise was predicted fairly well based on mixed-effects model for $L_{night}$. In future analysis, the model will be adjusted with potential indoor factors. This could show the maximum achievable explained variability and to test whether the slopes and intercepts change in the model with indoor factors. If the intercepts and slopes are not changed, this would add more strength of this generalised approach. World Health Organisation suggested insulation value for $L_{night}$ to estimate the indoor noise exposure based on window opening, however the issue is complicated by the fact that closing behaviour is, to certain extent dependent on noise level [26]. Although it is very well having models with open and closed windows and other indoor factors but this is not easy to apply to individuals in large population.

## 5. Conclusions

The present study findings indicate a potential relationship between indoor and outdoor noise despite the variability of the measured data within and between dwellings. Representative levels of indoor and outdoor noise differences in residential dwellings for $L_{Aeq,16h}$ and $L_{night}$ have been obtained through simultaneous inside and outside measurements of transportation noise. Preliminary results showed good correlation of indoor-outdoor noise using mixed-effect model mainly for $L_{night}$ and regression fit lines could be used in epidemiological studies where a generalizable model is needed.

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