Impacts of Low Frequency Noise Exposure on Well-Being: A Case-Study From Portugal

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Abstract

Introduction: The aim of this article is to assess the impacts of low frequency noise, emitted by high-voltage lines and power poles, on the perception of discomfort, comparing two different groups of inhabitants (exposed and unexposed groups) in two areas in the Northwest of Portugal. It proposes a new oriented methodology to assess discomfort due to the low frequency noise. Materials and Methods: Two predominantly urban areas were used to test the methodology: an “exposed” area with a high presence of the source under study and an “unexposed” area without records of power transmission lines. The research developed included measuring sound levels (in frequency bands from 10 to 160 Hz) with the help of a sound level meter in the two selected urban areas. Results: The real sound coming from the source was recorded and reproduced in an audiometric testing booth to determine the hearing threshold and discomfort of the volunteers. Using the criteria curve developed by DEFRA (Department for Environment, Food & Rural Affairs/University of Salford) in 2011, the results reveal that the sound levels recorded for the “exposed” group were higher than that for the “unexposed” group. The first recording showed an average of 68.9 dB and the second 64.6 dB, resulting in a significant difference of 4.3 dB between the two groups. After an attempt to isolate the source, the difference was 5.6 dB. Regarding the adapted audiometric tests, the real sound was used, which was collected 5 m between the receiver and the source. Conclusion: These results provide support that at this distance the noise was considered annoying.

Keywords: audiometric testing, human well-being, noise discomfort, noise pollution, power poles and power lines

INTRODUCTION

There is a relatively large body of literature concerning the impacts on health regarding exposure to environmental noise.[1-5] However, there are still few studies focusing exclusively on health impacts and discomfort due to low frequency noise. One of the main reasons is low sensitivity of the human auditory system to low frequencies. This type of noise presents very particular characteristics and causes much more discomfort and nonauditory effects in the long term. The range of frequency of low frequency noise is not perfectly clear. Sound up to 250 Hz is sometimes referred to as low-frequency noise.[6] This research considered sound below 160 Hz as the upper limit of low-frequency. Taking this into consideration, this research aims to help assess noise discomfort by measuring sound levels and comparing them with criterion curves, as well as performing adapted audiometric tests.

Taking this into account, the present research focuses on the impact of exposure to low frequency noise on the perception of discomfort, based on an “exposed” and “unexposed” study conducted between 2013 and 2017 in Serzedelo (southwest of the municipality of Guimarães) and in Abação (São Tomé) (southeast of the same municipality) in the Northwest of Portugal. It focuses on the evaluation of low frequency noise from an area with a large number of power poles and power lines and compares it with another area where there is no concentration of this type of elements. The noise emitted from high-voltage lines is caused by the discharge of energy that occurs when the electrical field strength on the conductor surface is greater than the “breakdown strength” of the air surrounding the conductor. The degree or intensity of the corona discharge and the resulting audible noise are affected...
by the air condition (e.g., humidity, wind and water, drizzle, and fog).[7]

In the present study, due to inconsistencies in the available data, the weather conditions were not considered. Weather data were collected from the nearest automatic weather station. Due to maintenance problems, this station did not have data on the velocity and direction of wind. On the other hand, given the location of the weather station (located more than 7 km from the areas under analysis), the data were not considered representative.

The sound levels were measured from 2014 to 2015 and compared with a criterion curve from a methodology developed by DEFRA (Department for Environment, Food & Rural Affairs/University of Salford), created in 2011[8] and tested in some studies[1-3] to analyze the discomfort in the population, resulting from the indoor annoyance of low-frequency noise.

In a survey conducted in 2015, from the 1022 dwellings located in the village of Serzedelo, only 98 are 250 m (or more) away from high-voltage lines, that is, 9.6% are very close to these elements (up to 250 m).[1] This causes a conflict regarding the use of space. The study presented here follows the conclusions found in the previous approach,[1] where according to the DEFRA methodology, noise data were collected inside dwellings. To increase the sample, it was decided to make a large number of measurements outside the dwellings, for shorter representative periods, guaranteeing a greater spatial coverage. An analysis was made of the “exposed” and “unexposed” groups. Thus, two similar territories were used: one having high-voltage lines; and the other in the same municipality without this type of elements. In addition, in 2016 and 2017, audiometric tests adapted to the low frequencies were conducted with the “exposed” and “unexposed” volunteers to determine the hearing threshold for pure sounds and for the real sound recorded.

The investigation attempts to answer the following questions: (a) Do power poles and power lines cause noise? (b) Do power poles and power lines cause discomfort due to noise? and (c) Is it suitable to use the A-weighting filter to analyze discomfort due to the noise from power poles and power lines?

This research is part of a broader research project developed by a team of researchers from the University of Minho, who are evaluating the impact of low-frequency noise pollution on the health and well-being of the population.[1] The results found by this team of researchers, obtained only in the village of Serzedelo, showed that regardless of the distance from the source, “near the source” (up to 50 m) and “away from the source” (more than 250 m), the noise levels exceeded the reference values of the methodology developed by DEFRA.[8] According to these authors, two possible explanations may be presented to explain this result. First, the low-frequency noise measured for the “away from the source” group may come from other sources. Second, the need to redefine group limits, that is, what is being considered as “away from the source” may be classified as “near the source.” The authors recommend choosing a territory where individuals are not under the influence of power poles and power lines and other sources of low-frequency noise emission.[1]

**Exposure to low frequency noise and the impacts on human health**

Many studies have shown the relationship between noise and the development of cardiovascular diseases,[9-13] agitation and distraction[14-17] and sleep disturbance.[4,5,18]

Emotional changes have also been documented: agitation, distraction, disappointment and psychological disorders, such as depression, stress, and irritability.[14,17,19,20]

Concerning “nonauditory effects,” discomfort has been reported as the most frequent impact of exposure to low frequency noise in humans.[6,17,21,22]

Different from “auditory effects,” “nonauditory effects” are the most difficult to prove as they result exclusively from exposure to noise. Assessing noise discomfort is generally centered on medium and high frequencies.[1,22]

By convention, a frequency A-weighting filter is used in these evaluations because the human auditory system is not very sensitive to low frequencies. However, is an A-weighting filter more suitable to assess discomfort due to low-frequency noise? Some studies indicate that the A-weighting filter is not suitable for assessing the discomfort of low-frequency noise.[21-24] In the authors’ opinion, this evaluation should be made using an appropriate filter or in linear mode.

**Methodologies for assessing discomfort due to low frequency noise**

Some guidelines for low frequency noise control in residential areas, adopted in some European countries such as Germany and the United Kingdom,[9,25] are based on a 1/3 octave analysis of sound pressure levels (SPLs) measured and compared with criterion curves. However, in the case of some methods, corrections are applied, such as the A-weighting filter.

Using this filter leads to a significant reduction in the sound levels emitted, often contributing to the resulting values remaining below the levels considered as annoying or harmful, when compared with criterion curves used in various countries [Figure 1].

Figure 1 presents reference curves used in various criterion concerning environmental exposure (at dwellings) and Swedish recommendations for workplaces.

It can be observed that the existing methods are based on quantitative parameters to analyze discomfort due to low frequency noise, while discomfort is essentially a subjective parameter, which can vary from individual to individual.
These methods consider a limited frequency range, and generally span the frequency range between 25 and 200 Hz.

The current legislation for ambient noise adopted in Portugal, which falls within the scope of the NP ISO 1996 standard, establishes that noise assessment should use frequency A-weighting, with fast integration time and frequency bands of 1/3 octave to vary between 50 and 10,000 Hz.\textsuperscript{[26,27]}

In the study of discomfort due to low-frequency noise, there is a need to lower the minimum threshold of assessment, that is, below 50 Hz. In this respect, the methodology developed by DEFRA in 2011 is worth mentioning as it covers a broad frequency range from 10 to 160 Hz and also because it recommends conducting surveys as a complement to analyzing noise discomfort.

**MATERIAL AND METHODS**

This research comprises an “exposed” and “unexposed” study, conducted in two predominantly urban areas of the municipality of Guimarães. The “exposed” area was defined due to a high presence of power poles and power lines. Considering this, the village of Serzedelo was selected, whose area has more than 80% of this type of infrastructure and which includes in its vicinity a substation with the highest installed power at national level called Riba d’Ave Substation\textsuperscript{[1]} and the choice of territory free of the passage of these infrastructures and without the presence of other sources of emission of low-frequency noise. Considering these aspects, the village of Abaçção (São Tomé) was chosen, classified as “unexposed.”

The adopted methodology was divided into two dimensions performed in the “exposed” and “unexposed” groups. The objective dimension included measuring noise levels in 2015 and comparing them with the criterion curve of the DEFRA methodology.\textsuperscript{[8]} The subjective and complementary dimension focusing on the audiometric tests adapted to low frequencies was conducted with the volunteers in 2016 and 2017.

**Methodology developed by DEFRA (NANR45)**

Among the various methods to analyze the discomfort due to low frequency noise is a procedure developed by the DEFRA Acoustics Research Center at the University of Salford called proposed criteria for the assessment of low frequency noise disturbance (NANR45).\textsuperscript{[8]} The procedure proposes the measurement of noise levels for 72 h (3 days) and comprises the night time, from 02:00 to 04:00, in 1/3 octave bands from 10 to 160 Hz. The measured values in $L_{eq}$ are compared with a criterion curve, which corresponds to a threshold of discomfort per frequency band. If the $L_{eq}$ values exceed the reference values, it is an indication that the noise source may cause discomfort.\textsuperscript{[8]} Additionally, according to the DEFRA methodology,\textsuperscript{[2]} when the $L_{10} - L_{90}$ difference exceeds 4 dB, the sound fluctuates and a penalty should be imposed. This methodology suggests that 5 dB relaxation
may be applied for steady sounds, rather than introducing a penalty for fluctuating sounds. Furthermore, it states that a fluctuating sound with an average level of 5 dB below the threshold would be audible, whereas a steady sound would not. Because the curve values at low-frequency are set at 5 dB below the threshold, this is again consistent with allowing relaxation for steady sounds.[1,8]

**Assessment of noise levels**

Considering the results obtained in Alves et al.,[1] it was decided to adapt the DEFRA methodology, that is, to take a larger number of measurements for representative, but shorter periods of 15 min each and measured outside the housing. Taking this into account, a greater spatial coverage was guaranteed at several points located in the two selected areas. Therefore, in the village of the “exposed” group, 32 measurements were performed [Figure 2] in November, 2015 (autumn).

In the village of the “unexposed” group, 30 measurements were performed in December, 2015 (autumn) [Figure 3].

The sound levels in $L_{eq}$ (dB) were measured and compared with the values of the criterion curve proposed by the DEFRA methodology.[8] A sound level meter class 1 was used with third octave filters from 10 to 160 Hz, a tripod and a field calibrator. The height of the measurements was 1.2 m, and it was measured at a distance more than 4 m away from the nearest facade. The fluctuating characteristics of the noise were evaluated by calculating the difference between $L_{10}$ and $L_{90}$ to evaluate the discomfort due to this type of noise.

It is important to refer the complexity of the analysis in this type of investigation due, among other aspects, to the interference from sources other than the source under study, such as road traffic (heavy vehicles). For this reason, it was decided to make an isolated analysis of a set of points without road traffic interference, mainly of the heavy vehicles.

**Discomfort analysis using adapted audiometric tests to the low frequencies — methodological proposal**

The audiometric tests were taken as a complement of analysis for the measurements performed in loco and comprised the perception of the discomfort due to noise, orienting exclusively for the low frequencies. It was observed that, although the noise was perceptible, the “exposed” individuals seemed to be accustomed to it.[1] Considering this, the audiometric tests were used to remove individuals from their habitual place of residence and to introduce, within the audiometric booth, the same acoustic stimulus to which they are exposed to in their daily lives.

It should be noted that in the literature on the subject, there is no methodology for audiometric evaluation oriented to low frequencies and, due to this aspect, the protocols developed were adapted based on ISO 8253-1/2010,[28] which can be confirmed in the Supplementary Material of this paper.

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Figure 2: Location of the measured points in the village of the “exposed” group in relation to the distance from the power poles and power lines.
The tests consisted of three stages: the hearing threshold, the assessment of discomfort due to noise and the cognitive test performance [mini mental state examination (MMSE)].

The test procedure has a duration of approximately 25 min. Due to limitations of the audiometer, not allowing them to operate with the desired frequencies (below 50 Hz), it was decided to use the VLC media player in the computer to reproduce the sound source. The audiometer was used only to vary the intensity of the signal. Thus, the following circuit was established: computer – audiometer – audiometric booth.

To determine the hearing threshold of pure sound, it was reproduced by frequency bands, from 18 to 90 Hz (18 Hz; 21 Hz; 24 Hz; 30 Hz; 39 Hz; 51 Hz; 60 Hz; 80 Hz; 90 Hz) with a variation in the signal intensity. The hearing threshold was also determined for the recorded sound composed from the real sound, with varying signal intensity. The hearing threshold was also determined for the recorded sound (real sound) with varying signal intensity. The real sound was recorded at 5 m from the projected horizontal distance from the nearest source (power pole 400 kV). The characteristics of the recorded sound are listed in Table 1.

The recorded sound (real sound) is variable, consisting of background noise from different and varied sources in addition to the main source. The hearing threshold was evaluated in the total frequency of the real sound. For this reason, the participant’s response to the signal was considered, and the values reported in more than 50% of the responses were determined as the hearing threshold.

The participants, after being exposed to the reproduction of pure sounds and recorded sounds, responded to a small three-question survey.

The subjective and complementary dimension to determine the hearing threshold consisted of conducting a small discomfort survey (using a Likert scale) before exposure to noise in the audiometric booth, as well as doing a cognitive test performed after the audiometric tests.

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**Table 1: Characteristics of the recorded sound – exposed area**

| Group     | Proximity of the source (m) | $L_{eq}$ (dB) | $L_{min}$ (dB) | $L_{max}$ (dB) | Exceeded range (Hz) | Environmental area                                                                 |
|-----------|-----------------------------|---------------|----------------|----------------|---------------------|-----------------------------------------------------------------------------------|
| “Exposed” | 5                           | 54.5          | 48.4           | 62.9           | 25–160              | Located near the high voltage power pole (400 kV). Weather conditions: humid, cloudy and rainy. Sound recording lasted 15 min (between 2:15 PM and 2:31 PM) |
The tests were conducted in an audiometric booth Optac – Aumec Horprufkabine brand, and two acoustic stimuli were introduced: pure sounds (tracks from a high-fidelity CD of the brand Nordost – System Set-Up & Tuning Disc) and the sounds previously recorded at the place of exposure.

The sound was reproduced inside the audiometric booth through headphones with good response at low frequencies of the model (HE400S – Hifiman). Connections were made to allow the passage and control of the signal by the AD28–Interacoustics audiometer.

The pure sounds were played by Windows Media Player, and the recorded sound was played by software dBTrait. According to the mentioned methodology, audiometric tests were performed with eight volunteers from the “exposed” group and six volunteers from the “unexposed” group. It is important to highlight the difficulty of recruiting volunteers to participate in the audiometric tests, because the audiometric booth used is in the Laboratory of Ergonomics at the University of Minho. In fact, after several attempts by telephone, and even when the team offered transport to the individuals invited to participate in the audiometric tests, few accepted to participate.

**Main Results**

In this section, we describe the results of the sound levels measured in the two predominantly urban areas, as well as the results obtained with the performance of the adapted audiometric tests.

**The measured sound levels**

For both the “exposed” and “unexposed” groups, the measured sound levels ($n = 62$) exceeded the reference values when compared to the DEFRA criterion curve in different bands of frequency. The mean exceeded recorded was obtained by averaging the values of pressure sound levels obtained at each measurement point. For the “exposed” group, it was 68.9 dB, and for the “unexposed” group it was 64.6 dB. The difference of the average of exceedance was of 4.3 dB, which reveals a considerable difference between the two evaluated situations.

Another aspect that deserves attention is related to the percentage of time in which fluctuating characteristics were registered. In fact, in $L_{10} – L_{90} \geq 4$, for the “unexposed” group, the occurrence frequencies tended to be lower than those recorded for the “exposed” group.

The exceeded SPL, referred to in Tables 2 and 3, corresponded to the sum of the noise exceedances in relation to the DEFRA curve criteria of the exceeded frequency bands.

**Isolated approach without road traffic interference**

**Sound levels – “exposed” group**

For this group, 26 points ($n = 32$) were isolated with none or negligible register in terms of road traffic interference (mainly of heavy vehicles), measured in the exposed area [Figure 4].

The “exposed” group, without interference from road sources, exceeded for all points measured between the bands of 50 and 160 Hz. The mean exceeded recorded in this group was 55.7 dB [Figure 4 and Table 2].

Higher noise levels could be justified due to the distance from the source (near and very close to the source), the presence of high power poles and power lines (e.g., 400 kV) and the nearby space characteristics, which can potentiate sound levels at very low frequencies.

**Sound levels – “unexposed” group**

For this group, 21 points ($n = 30$) were isolated with no or negligible interference from car traffic (mainly from heavy vehicles) [Figure 5 and Table 3].

The “unexposed” group exceeded for all measurement points between 50 and 80 Hz bands. The mean exceeded recorded in this group was 50.1 dB [Figure 5].

The sound levels could be justified due to surrounding space characteristics (e.g., cultivated areas), influence of other sources and climatic conditions, which may have influenced the sound levels measured, especially at low frequencies.

**Audiometric tests and discomfort evaluation due to the low frequency noise (LFN)**

Audiometric tests were performed with eight volunteers from the “exposed” group aged between 24 and 68 years, with a distinct professional profile (students, various occupations in the textile industry and an administrative assistant). In the “unexposed” group, audiometric tests were performed with six volunteers, aged between 44 and 60 years and a differentiated occupational profile (unemployed, drivers and construction workers).

Regarding pure sounds, in both the “exposed” [Figure 6 and Table 4] and “unexposed” groups [Figure 7 and Table 4] in all the frequency bands, the hearing threshold was evaluated and presented different sonorous intensities, varying from individual to individual.

The average hearing threshold of the recorded sound of the eight volunteers tested from the “exposed” group was 51.3 dB, ranging from 40 to 65 dB, while the average hearing threshold of the six volunteers tested from the “unexposed” group was 24.1 dB, ranging from 20 to 30 dB.

The perception of discomfort due to noise was assessed using a survey (with 10 questions) with a five-level Likert scale, ranging from “strongly disagree” to “strongly agree” [Figure 8a–j].

“Exposed” and “unexposed” volunteers answered three questions to assess the perception of the noise reproduction within the audiometric booth [Figure 9a–c].
Table 2: Characteristics of measurement points of the “exposed” group – sound levels with interference reduction

| Point | Proximity to the source (m) | Exceeded Range (Hz) | SPL (dB) | Environmental area |
|-------|-----------------------------|---------------------|----------|--------------------|
| 1     | 1                           | 40–160              | +63.8    | Predominantly soil: unpaved ground. Located near the high voltage power pole (400kV) |
| 3     | 10                          | 31.5–160            | +104.7   | Predominantly soil between sound level meter and the source: granite cube. Passage of vehicles during measurement: one heavy vehicle and 11 light vehicles |
| 5     | 25–50                       | 31.5–160            | +121.4   | Predominantly soil: granite cube. Passage of vehicles: two light vehicles. About 10 km away from the Riba d’Ave Substation |
| 7     | 5                           | 50–160              | +21.4    | Predominantly soil: granite cube. Passage of vehicles: one heavy vehicle. Located near the urban gardens with power poles and power lines. Noise perceived: continuous noise from the power pole |
| 8     | 5                           | 31.5–160            | +36.7    | Predominantly soil: unpaved ground. Predominant soil: granite cube. The noise of the power pole and power line is highway perceptible |
| 9     | 5                           | 40–160              | +39.2    | Predominantly soil: asphalt pavement. Located near the urban garden. Passage of one heavy vehicle |
| 10    | 10                          | 40–160              | +32.3    | Predominantly soil: asphalt pavement. Passage of two light vehicles. Noise perceived: continuous noise from the power pole |
| 11    | 8                           | 40–125              | +37.4    | Predominantly soil: grassy. Noise perceived: continuous noise from the power pole and road traffic |
| 12    | 50–75                       | 50–160              | +39.8    | Predominantly soil: grassy and asphalt pavement. Passage of vehicles: one light vehicle and one heavy vehicle |
| 13    | 10                          | 40–160              | +71.3    | Predominantly soil: asphalt. Noise perceived: continuous noise from the road traffic. Passage of vehicles: one light vehicle |
| 14    | 10                          | 50–160              | +33.6    | Predominantly soil: granite cube. Noise perceived: continuous noise from the power pole and road traffic |
| 15    | 20                          | 50–160              | +13.7    | Predominantly soil: unpaved ground. Passage of vehicles: one light vehicle. Reports: noise discomfort from the power pole and some health problems. Noise perceived: continuous noise from the power pole |
| 16    | 50–75                       | 50–160              | +16.5    | Predominantly soil: unpaved ground. Nearest highway pavement: granite cube. Located near the urban gardens with power poles and power lines. Noise perceived: continuous noise from the power pole |
| 17    | 8                           | 50–160              | +28.3    | Predominantly soil: granite cube. High density of 150kV voltage power poles and power lines |
| 19    | 50                          | 40–160              | +45.4    | High density of 150 and 400kV voltage power poles and power lines. Predominantly soil: granite cube |
| 20    | 10                          | 40–160              | +49.3    | Predominantly soil: granite cube. Noise perceived: continuous noise from the power pole. Passage of vehicles: one light vehicle |
| 21    | 20                          | 40–160              | +87      | The receiver was positioned 12 m away from the façade of a textile industry in the village. Passage of vehicles: one light vehicle |
| 22    | 30                          | 31.5–160            | +109.5   | Predominantly soil: granite cube. Passage of vehicles: three light vehicles and two heavy vehicles. Located near extensive cultivation areas (urban garden) |
| 24    | 10                          | 40–63 and 125–160   | +9.5     | Predominantly soil: granite cube. High density of power poles and power lines |
| 25    | 10                          | 50–160              | +31      | Predominantly soil: granite cube. High density of power poles and power lines. Presence of boulders |
| 26    | 5                           | 31.5–160            | +103     | Predominantly soil: granite cube. Passage of vehicle: one light vehicle. Noise perceived: continuous noise from road traffic |
| 27    | 50                          | 50–160              | +33.7    | Predominantly soil: granite cube. Passage of vehicle: one light vehicle. Noise perceived: continuous noise from road traffic |
| 28    | 50                          | 40–160              | +81.6    | Surrounded by vegetation. Noise perceived: continuous noise from power poles and power lines and noise from road traffic |
| 29    | 25                          | 31.5–160            | +87.8    | Predominantly soil: granite cube. High density of power poles and power lines. Passage of vehicles: five light vehicles |
| 30    | 50                          | 40–160              | +50.7    | Predominantly soil: unpaved ground and vegetation. Passage of one light vehicle. Located near the Riba d’Ave Substation |
| 32    | 1                           | 31.5–160            | 62.7     | Predominantly soil: grassy. Noise perceived: continuous noise from power poles and power lines and noise from road traffic |
In the case of the “unexposed” group, for most participants (67%), the noise reproduced within the audiometric booth corresponds to a “humming” noise. Volunteers typified the noise in some differentiated types as “continuous noise,” “sea waves,” and, finally “annoying and discomfort.” Regarding “discomfort,” four participants responded, “not bothered,” one respondent felt “sleepiness,” and another volunteer felt “annoyed.”

After exposition inside the audiometric booth, the MMSE was conducted to evaluate the cognitive status of the volunteers. The procedure involved two categories of response: verbal and nonverbal. The first category measured the spatial-temporal orientation, immediate memory, evocation, and memory of procedure, attention, and language. The second category, nonverbal, was responsible for measuring perceptual-motor coordination and comprehension of instructions. The maximum score of MMSE is 30 points, and the interpretation of the test results is shown in Table 5.

Tables 6 and 7 present social and educational characteristics of the volunteers and the score reached by each one during the cognitive tests.

**DISCUSSION**

**Objective dimension — measured sound levels**

Regardless of the group analyzed (“exposed” and “unexposed”), the recorded sound levels exceeded the criterion curve of the DEFRA, having been registered for the points measured in the group of “exposed” higher sound levels. One of the possible explanations for this exceeded value could be the contribution of noise not only from the source under study, but also from other sources with low-frequency characteristics, such as road traffic noise (heavy vehicles). Due to the above-mentioned interferences, the isolated sound level analysis was performed, which included the study of a set of points that did not register the passage of heavy vehicles.

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**Table 3: Characteristics of measuring points of the “unexposed” group — sound levels with interference reduction**

| Point | Range (Hz) | SPL (dB) | Environmental area |
|-------|------------|----------|---------------------|
| 2     | 50–160     | +23.5    | Predominantly soil: granite cube. Noise perceived: continuous noise from road traffic |
| 3     | 40–160     | +89.4    | Predominantly soil: granite cube. Noise perceived: continuous noise from road traffic |
| 4     | 40–160     | +74.7    | Predominantly soil: asphalt. Passage of vehicles: one light and one heavy vehicle |
| 5     | 31.5–160   | +89.8    | Predominantly soil: granite cube. Noise perceived: continuous noise from road traffic. Passage of vehicles: one light and one heavy vehicle. Located near extensive cultivation areas (urban garden) |
| 6     | 40–160     | +49.9    | Predominantly soil: granite cube. Noise perceived: continuous noise from road traffic |
| 7     | 40–160     | +50.4    | Predominantly soil: granite cube. Passage of one light vehicle. Noise perceived: continuous noise from road traffic (about 25 m from the measurement point) |
| 8     | 50–160     | +16.7    | Predominantly soil: granite cube. Noise perceived: continuous noise from road traffic. Located near the houses and extensive cultivation areas (urban garden) |
| 9     | 50–160     | +25.2    | Noise perceived: continuous noise from road traffic. Predominantly soil: granite cube. Located near the extensive cultivation areas |
| 10    | 50–160     | +27.2    | Receiver positioned on the granite cube pavement, approximately 3 m from the asphalt road. Located near the residential area. Noise perceived: continuous noise from road traffic |
| 11    | 40–160     | +21.5    | Predominantly soil: granite cube. Passage of one light vehicle. Located near the houses and the primary school |
| 12    | 31.5–160   | +82.4    | Predominantly soil: granite cube (the receiver was positioned on the unpaved ground). Noise perceived: noise from road traffic (José Manuel Street) |
| 13    | 50–160     | +31.4    | The receiver was positioned on the concrete pavement. Located near the asphalt residential area |
| 14    | 40–160     | +49.2    | Predominantly soil: granite cube. Noise perceived: noise from the road traffic |
| 15    | 40–160     | +51.4    | Predominantly soil: asphalt. Passage of one light vehicle. Located near the residential area and urban gardens. Noise perceived: noise from road traffic (São Tomé Street) |
| 16    | 40–160     | +51.8    | Noise perceived: noise from road traffic |
| 17    | 50–80 and 160 | +12.4 | Predominantly soil: granite cube and vegetation. Noise perceived from road traffic |
| 18    | 40–160     | +68.9    | Passage of six light vehicles and one heavy vehicle. Located near urban gardens. Note: measurement performed without the microphone sponge |
| 19    | 40–160     | +78.9    | Located near urban gardens. Predominantly soil: asphalt |
| 20    | 40–160     | +32.7    | Predominantly soil: asphalt. Located near the Vaga Bond industry and the residential area |
| 21    | 40–160     | +48.7    | Predominantly soil: asphalt and granite cube. Passage of three light vehicles and one heavy vehicle. Noise perceived from road traffic |
| 22    | 50–160     | +57.6    | Predominantly soil: asphalt. Passage of one light vehicle. Located near the industry and residential area. Receiver positioned on the granite cube pavement |
After source isolation, with the minimization of interference due to heavy traffic, the average of the “unexposed” group exceeded 50.1 dB, while the average of the “exposed” group was 55.7 dB. Under these conditions, it was found that the low-frequency sound levels recorded for the “exposed” group were higher than for the “unexposed.” This means that if the studied source is the predominant contribution to measured low frequency noise, the “exposed” source more than doubles in comparison with the “unexposed” one [Figure 10].

Considering this, the increase of 5.6 dB can be considered significant. In this analysis, we can say that the village of the “exposed” presented, on average, higher levels due to the presence of power poles and power lines that occupy more than 80% of the area of this village. Taking this into account, the study source played an important role in the recorded sound levels.

The A-weighting filter was applied, having as a reference point 5 (Table 2—“exposed” group), which recorded the highest noise levels and point 20 (Table 3—“unexposed” group), which recorded the lowest noise levels. As illustrated in Figure 11, using the A-weighting filter considerably penalizes the sound levels measured and

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**Figure 4:** Isolated analysis of the “exposed” group sound levels — analysis in $L_{eq}$ (dB)

**Figure 5:** Isolated analysis of the “unexposed” group sound levels — analysis in $L_{eq}$ (dB)
disguises the objective parameters of evaluating discomfort due to low frequency noise.

Based on Portuguese legislation on ambient noise (DL 9/2007), 50 Hz was considered the minimum limit of evaluation, for this reason the A-weighting filter was applied only between frequencies from 50 to 160 Hz [Figure 11].

Subjective dimension — adapted audiometric tests
The registered differences in the hearing threshold for the “exposed” and “unexposed” groups, for pure sounds and real sound recorded (in locals without interference from other sources of noise) were significant [Table 4].

Concerning pure sound, the differences between the averages of the hearing threshold were 33.9 dB for the 18 Hz; 41.2 dB for the frequency of 21 Hz; 38.9 dB for the 24 Hz frequency; 40.6 dB for 30 Hz; 16.4 dB for the frequency of 39 Hz; 5.0 dB for the frequency of 51 Hz; 2.5 dB for 60 Hz; −1.3 dB for the frequency of 80 Hz; and 1.4 dB for 90 Hz [Table 4].

Relating the real sound recorded at the field, the difference between the average of the hearing threshold of the two groups corresponded to 27.2 dB. These data reveal that the “exposed” group is less sensitive to low frequencies and corroborates with the results illustrated in Figures 6 and 7, which clearly show the low sensitivity of the “exposed” group below 39 Hz, when compared to the “unexposed” group.

The audiometric tests contributed to assessing the discomfort due to real sound recorded and to demonstrating that the low-frequency pure sounds were audible [Table 8].

Finally, the performed tests revealed that the noise collected in the field (the real sound recorded) was audible at sound levels above 40 dB for the “exposed” group and 20 dB for the “unexposed” group.

Regarding the perception of discomfort due to noise of the two study groups [Figure 8]:

1) The perception of hearing tended to be higher for the “unexposed” group when compared to the “exposed” group;

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Table 4: Hearing threshold for pure sound from “exposed” and “unexposed” groups

| Group      | Hearing threshold (dB) | 18 | 21 | 24 | 30 | 39 | 51 | 60 | 80 | 90 |
|------------|------------------------|----|----|----|----|----|----|----|----|----|
| “Exposed”  | Minimum                | 75.0| 75.0| 75.0| 75.0| 25.0| 25.0| 20.0| 15.0| 15.0|
|            | Maximum                | 100.0| 100.0| 90.0| 90.0| 55.0| 50.0| 35.0| 30.0| 35.0|
|            | Average                | 85.6| 88.7| 85.6| 80.6| 50.6| 35.0| 30.0| 23.7| 23.1|
| “Unexposed”| Minimum                | 45.0| 40.0| 40.0| 35.0| 20.0| 25.0| 20.0| 20.0| 15.0|
|            | Maximum                | 65.0| 60.0| 60.0| 55.0| 50.0| 45.0| 40.0| 35.0| 30.0|
|            | Average                | 51.7| 47.5| 46.7| 40.0| 34.2| 30.0| 27.5| 25.0| 21.7|
| Δ “exposed” and “unexposed” | 33.9| 41.2| 38.9| 40.6| 16.4| 5.0| 2.5| −1.3| 1.4 |
The perception of day-to-day noise discomfort was similar for the two study groups, that is, most volunteers responded not feeling discomfort; only volunteers in the “exposed” group responded that noise has affected their lives. Although four of the eight volunteers from the same group “disagreed” with this statement; regarding the statement “I awake easily with the minimum noise,” the group’s perception of the “exposed” responses were not unanimous (three “disagreed,” one “undecided,” and four “agreed” or “strongly agreed”). In the “unexposed” group, most volunteers (n = 4) “agreed” or “strongly agreed;” In the statement “I can easily get used to most of the noise,” most volunteers from the “unexposed” group (n = 4) “agreed” or “strongly agreed” with this statement; about the statement “I feel annoyed with the noise,” in both groups, most volunteers “agreed” or “strongly agreed” with this statement; regarding the statement, “I feel discomfort with the noise coming from outside my home,” four volunteers “agreed” or “strongly agreed,” while in the case of the “unexposed” most volunteers (n = 5) “disagreed” or “strongly disagreed;” for the statement, “I have difficulty concentrating in noisy environments,” as far as the “unexposed” group is concerned, most volunteers (n = 4) “disagreed” or “strongly disagreed.” In the “unexposed” group, most volunteers (n = 6) “agreed” or “strongly agreed;” when confronted with the statement “I have difficulty in relaxing in noisy environments,” most volunteers (n = 6) from the “exposed” group “agreed” or
a. What kind of noise did you hear? (e.g., humming, sound, sparks)  

b. Can you describe the kind of discomfort this noise causes? 

c. How would you describe the type of noise you just heard?

(10) Finally, regarding the statement “I am aware of the impact of noise on my health,” in both groups, most “exposed” (n = 6) and “unexposed” (n = 4) volunteers “agreed” or “strongly agreed” with this statement.

Regarding the evaluation of the real sound reproduced in the audiometric booth, the groups were evaluated.

Concerning the evaluation of discomfort due to noise reproduced in the audiometric booth, the “exposed” group showed that they felt more uncomfortable with this type of noise than the “unexposed” group [Figure 9].

From the performance of the cognitive tests, in the “exposed” group [Table 6], only one participant reached 22 points, which may reveal a cognitive deficit. One of the participants reached 25 points, which represents a nonsuggestive change in deficit. For the remaining participants, three reached 26 points and the other three participants 27 points, which corresponds to a preserved cognitive function [Table 5]. Participant 5 (male, 68 years old and with 4 years of schooling), who had a cognitive deficit had been a textile carder for 44 years and retired 14 years ago.

Although this participant revealed that he “strongly agreed” with the statement “I usually hear well” and that the noise had little impact on his quality of life, the participant’s hearing threshold for pure sounds was above average for low frequencies. For the real sound recorded, the hearing

Figure 9: Evaluation of real sound recorded reproduced in the audiometric booth of the “exposed” and “unexposed” groups

Table 5: Interpretation of results of the mini mental state examination

| Score | Preserved cognitive function | Nonsuggestive change in deficit | Cognitive deficit |
|-------|-----------------------------|---------------------------------|------------------|
| 30–26 points | 26–24 points | 23 points or less |
| Data source: Adapted from Agência Portuguesa do Ambiente.[27] |

Table 6: Profile of volunteers from the “exposed” group

| Test | Age (years) | Sex | Occupation | Time | Previous occupation | Time (years) | Education | Score MMSE |
|------|-------------|-----|------------|------|----------------------|--------------|-----------|------------|
| 1    | 24          | M   | Student    | –    | –                    | –            | Master    | 27         |
| 2    | 56          | M   | Unemployed | 6 months | Textile operator | 45           | Year 9    | 27         |
| 3    | 58          | M   | Weaving    | 42 years | –                   | –            | Year 4    | 25         |
| 4    | 62          | M   | Unemployed | 6 months | Garage manager    | 16           | Year 4    | 26         |
| 5    | 68          | M   | Retired    | 13 years | Textile carder     | 44           | Year 4    | 22         |
| 6    | 49          | M   | Administrative assistant | 26 years | –                   | –            | University degree | 26         |
| 7    | 63          | M   | Retired    | 4 years | Textile Stamper    | 44           | Year 3    | 26         |
| 8    | 50          | M   | Operations assistant | 26 years | Textile operator | 26           | Year 11   | 27         |

“strongly agreed.” In the case of the “unexposed” group, the perception was divided into three who “agreed” and three who “disagreed” or “strongly disagreed.”

From the performance of the cognitive tests, in the “exposed” group [Table 6], only one participant reached 22 points, which may reveal a cognitive deficit. One of the participants reached 25 points, which represents a nonsuggestive change in deficit. For the remaining participants, three reached 26 points and the other three participants 27 points, which corresponds to a preserved cognitive function [Table 5]. Participant 5 (male, 68 years old and with 4 years of schooling), who had a cognitive deficit had been a textile carder for 44 years and retired 14 years ago.

Although this participant revealed that he “strongly agreed” with the statement “I usually hear well” and that the noise had little impact on his quality of life, the participant’s hearing threshold for pure sounds was above average for low frequencies. For the real sound recorded, the hearing
### Table 7: Profile of volunteers from the “unexposed” group

| Test | Age (years) | Sex | Occupation          | Time | Previous occupation | Time (years) | Education | Score MMSE |
|------|-------------|-----|---------------------|------|---------------------|--------------|-----------|------------|
| 1    | 45          | M   | Construction workers| 9 years | Locksmith           | 15           | Year 4    | 29         |
| 2    | 44          | M   | Unemployed          | 10 years | Construction workers| 5           | Year 2    | 17         |
| 3    | 49          | M   | Unemployed          | 10 years | Textile            | 20           | Year 6    | 30         |
| 4    | 60          | F   | Housewife           | Since always | Textile (operator)| 22           | Year 4    | 26         |
| 5    | 45          | M   | Driver              | 10 years | Textile (operator) | 10           | Year 9    | 26         |
| 6    | 47          | M   | Driver              | 7 years | Automotive electrician | 20    | Year 9    | 29         |

**Figure 10:** Isolated analysis of the “exposed” and the “unexposed” group sound levels – dB, average

**Figure 11:** Isolated analysis of the “exposed” (point 5) and the “unexposed” (point 20) group sound levels – $L_{eq}$ dB(Lin) and $L_{eq}$ dB(A)
threshold of this participant was 60 dB (8.7 dB above the average of this group).

For the “unexposed” group [Table 7], participant number 2 (male, 44 years old and 2 years of schooling) reached 17 points, which reveals a cognitive deficit. This participant worked in civil construction for 5 years and has been unemployed for 10 years. The hearing threshold was 30 dB (5.8 dB above the mean of this group).

**Conclusion**

Due to the fact that it is a difficult study and has never been conducted in Portugal, one of the most important limitations in this type of study was the difficulty in isolating the main source under study and in the analysis of the results. The sound levels measured and the real sound recorded correspond to external ambient noise resulting from various contributions in the place. When measuring and recording the noise, other sources of low-frequency noise were captured in addition to the main source (e.g., heavy vehicle noise).

The recorded sound was audible by volunteers during audiometric tests; the hearing threshold average for recorded sound was 51.3 dB and ranged from 40 to 65 dB. For the “unexposed” group, the hearing threshold average was 24.1 dB and ranged from 20 to 30 dB. These data reveal that the “exposed” group is less sensitive to low frequencies and corroborates with the results found, which clearly show the low sensitivity that the “exposed” group presents, below 39 Hz, when compared to the “unexposed” group. According to the findings, the “exposed” group feels more uncomfortable with this type of noise than the “unexposed” group. It is important to note that age could be an important factor that can contribute to the loss of sensitivity to low frequencies observed. In the case of the “exposed” group, the average age of the volunteers was 53.8 years old, while to the “unexposed” group it was 48.3 years old [Table 6].

Regardless of the various existing methodologies for the assessment of environmental noise, namely in areas with low-frequency noise sources, we propose to reduce the lower limit of frequency range, which is 50 Hz, considering the contributions of sources that emit noise below 50 Hz such as power poles and power lines. In addition, it is worth noting the use of the A filter that considerably penalizes the sound levels measured and disguises the objective parameters of evaluating discomfort due to low frequency noise. Thus, measurement and assessment of discomfort due to low-frequency noise should be made with an appropriate filter or without any filter applied, that is, in linear mode.

The methodology developed and presented here was appropriate for the intended purpose, as it enabled us to evaluate the perception of low frequency noise, as well as alert us about the necessity of extending the minimum interval of frequency in the evaluation of the impact of this type of noise in the population. It is a simple methodology, involving few steps, inexpensive and exclusively oriented towards low frequencies.

The distance between the receiver and source may interfere with the degree of discomfort experienced by individuals. For the presented results, the real sound was measured at 5 m of distance, between the receiver and source. It was observed that at this distance, noise is uncomfortable and presents levels of sound pressure above those considered safe for human health. According to some authors, low frequency noise could propagate over large distances and is not absorbed by most materials. As well as this factor, it is important to remember that this type of noise often has tonal characteristics, which is why it is more annoying. It is expected that in future research, this type of evaluation can be explored by varying the distance between the receiver and the source. This may provide important information on the definition of the limits for installation of power poles and power lines in residential areas, based not only on the objective component (measurement of sound levels and setting the minimum limit of evaluation below the usual 50 Hz), but considering also the subjective component, that is, the perception of discomfort reported by the exposed population. The authors believe that the relationship between low frequency noise levels and weather conditions exist and should be studied to complement this type of analysis.

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**Conflicts of interest**

There are no conflicts of interest.

**References**

1. Alves JA, Silva LT, Remoaldo PC. The influence of low-frequency noise pollution on the quality of life and place in sustainable cities: A
case study from Northern Portugal. Sustainability 2015;7:13920-46. doi: 10.3390/su71013920
2. Pawlaczyk-Luszczynska M, Szymczak W, Dudarewicz A, Sliwińska-Kowalska M. Proposed criteria for assessing low frequency noise annoyance in occupational settings. Int J Occup Med Environ Health 2006;19:185-97.
3. Pawlaczyk-Luszczynska M, Szymczak W, Dudarewicz A, Sliwińska-Kowalska M. Evaluation of annoyance from low frequency noise under laboratory conditions. Noise Health 2010;12:166-81.
4. Eysel-Gosepath K, Daut T, Pinger A, Lehmacher W, Erren T. Effects of noise in primary schools on health facets in German teachers. Noise Health 2012;58:129-34.
5. Vianna KM, Cardoso MR, Rodrigues RM. Noise pollution and annoyance: An urban soundscapes study. Noise Health 2015;6:125-33.
6. Berglund B, Hassmén P, Job RF. Sources and effects of low-frequency noise. J Acoust Soc Am 1996;5:2985-3002.
7. Dent R. What Causes the Noise Emitted From High-Voltage Power Lines – Is It Static Discharge, Vibration From the 60-Cycle Field or Something Else Entirely? Scientific American. Available from: https://www.scientificamerican.com/article/what-causes-the-noise-emi/#. [Last accessed on 2017 Oct 27].
8. Moorhouse A, Waddington D, Adams M. Procedure for the Assessment of Low-Frequency Noise Complaints; 2011. Available from: https://core.ac.uk/download/pdf/1655460.pdf. [Last accessed on 2017 Oct 15].
9. Babisch W. Traffic noise and cardiovascular disease: Epidemiological review and synthesis. Noise Health 2000;8:9-32.
10. Passchier-Vermeer W, Passchier WF. Noise exposure and public health. Environ Health Perspect 2000;1:123-31.
11. Lercher P, Botteldooren D, Widmann U, Ulmer U, Kammeringer E. Cardiovascular effects of environmental noise: Research in Austria. Noise Health 2011;5:234-50.
12. Stansfeld S, Crombie R. Cardiovascular effects of environmental noise: Research in the United Kingdom. Noise Health 2011;52:229-33.
13. Van Kempen E. Cardiovascular effects of environmental noise: Research in The Netherlands. Noise Health 2011;52:221-8.
14. Karpova NI, Alekseev SV, Erokhin VN, Kadyshkina EN, Reutov OV. Early response of the organism to low-frequency acoustical oscillations. Noise Vib Bull 1970;65:100-3.
15. Brown JE, Thompson RN, Folk ED. Certain non-auditory physiological responses to noise. Am Ind Hyg Assoc J 1975;36:285-91.
16. Job R. The role of psychological factors in community reaction to noise. In: Vallet M, editor. Noise as a Public Health Problem, vol. 3. Arcueil Cedex, France: INRETS; 1993. p. 47-79.
17. Pawlaczyk-Luszczynska M, Dudarewicz A, Szymczak W, Waszowska M, Sliwińska-Kowalska M. The impact of low frequency noise on human mental performance. Int J Occup Med Environ Health 2005;2:185-98.
18. Ising H, Kruppa B. Health effects caused by noise: Evidence in the literature from the past 25 years. Noise Health 2004;22:5-13.
19. Castelo-Branco N, Alves-Pereira M. Vibroacoustic disease. Noise Health 2004;23:3-20.
20. Eysel-Gosepath K, Daut T, Pinger A, Lehmacher W, Erren T. Sound levels and their effects on children in a German primary school. Eur Arch Otorhinolaryngol 2012;12:2475-83.
21. Waye KP. On the effects of environmental low frequency noise. Dissertation thesis. Gothenburg, Sweden: Gothenburg University; 1995.
22. Alves JA, Silva LT, Remoalco PC, Arezes P, Neto Paiva FM. Proposta metodológica para avaliação audiométrica e da incomodidade ao ruído de baixa frequência. 9ª Iberian Congress and the 47th Spanish Congress on Acoustics TECNIACUSTICA®; 2016. p. 175-6.
23. Kjellberg A, Goldstein M. Loudness assessment of band noise of varying bandwidth and spectral shape. An evaluation of various frequency weighting networks. J Low Freq Noise Vib 1985;4:12-26.
24. Leventhall G. Low frequency noise and annoyance. Noise Health 2004;6:59-72.
25. DIN: 45680. Measurement and Assessment of Low-frequency noise immissions in the neighbourhood [in German]. Berlin: Deutches Institut für Normung; 1997.
26. Silva LT. Avaliação da qualidade ambiental urbana. Portugal: Universidade do Minho (Tese de Doutoramento em Engenharia Civil); 2007.
27. Agência Portuguesa do Ambiente. Directrizes para elaboração de mapas de ruído. Portugal: APA; 2011.
28. ISO 8253–1. Audiometric Test Methods, Part 1: Pure-Tone Air and Bone Conduction Threshold Audiometry. Geneva, Switzerland: International Organization for Standardization; 2010.
29. Folstein M, Folstein S, McHugh P. Mini-mental state: A practical method for grading the cognitive state of patients for the clinician. J Psychiatr Res 1975;3:189-98.
30. HIFIMAN. Headphone HE400S: Characteristics. Available from: http://hifiman.com/products/detail/238. [Last accessed on 2018 Mar 22].
31. DOC1081. Dbrain Software User Manual. France: ACOEM Smart monitoring, diagnosis & solutions; 2013.