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Surveys on Noise in Some Hospital Wards and Self-Reported Reactions from Staff: A Case Study

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Abstract: Noise in hospital wards adversely affects the physiological processes of both patients and staff and it is a potential risk for communication breakdowns and errors, causing discomfort and problems regarding the healing of patients, as well as stress, fatigue, and annoyance for staff. Several noise sources are present in the wards, such as HVAC systems, alarms, paging, speech, calls, diagnostic equipment, medical devices, and so forth. This paper describes two surveys carried out at an Italian hospital in Rome to investigate the noise in some wards and to collect self-reported assessments from staff about their working environments, even if such assessments were not required for occupational noise exposure evaluation. Self-reported staff evaluations of the working environment quality and the effects of noise on their performances should be investigated. For this purpose, in this study, questionnaires were designed and submitted to staff members. In addition, noise measurements were taken from short-, medium-, and long-term audio recordings processed to determine psychoacoustic parameters, e.g., loudness, sharpness, roughness, and fluctuation strength. Their applications in enclosed spaces can provide additional information on some features of the noise observed in hospital wards, which may influence the perceptions and relevant extra-auditory effects. Even though the results cannot be generalized, they encourage the development of a methodology for noise surveys in hospital wards, including noise measurements and "ad hoc" questionnaires to collect self-reported reactions from exposed staff members.

Keywords: noise in hospital; extra-auditory effects; self-reported workplace quality

Citation: Lo Castro, F.; Iarossi, S.; Brambilla, G.; Mariconte, R.; Diano, M.; Bruzzaniti, V.; Strigari, L.; Raffaele, G.; Giliberti, C. Surveys on Noise in Some Hospital Wards and Self-Reported Reactions from Staff: A Case Study. *Buildings* **2022**, *12*, 2077. https://doi.org/10.3390/buildings12122077

Academic Editors: Simone Secchi, Nicoletta Setola and Luca Marzi

Received: 24 October 2022
Accepted: 21 November 2022
Published: 27 November 2022

1. Introduction

As stated by Florence Nightingale, the founder of modern nursing, "unnecessary noise, or noise that creates an expectation in the mind, is that which hurts a patient. It is rarely the loudness of the noise, the effect upon the organ of the ear itself, which appears to affect the sick [. . .]. Unnecessary noise, then, is the cruelest absence of care which can be inflicted either on sick or well" [1].

After more than 150 years, sonic environments inside hospitals are still often uncomfortable, attracting the attention of researchers [2] due to the negative impacts on patients and staff. The effects for patients include sleep disturbance, cardiovascular response, increased length of stay, and increased incidence of rehospitalization, while stressful working environments and performance reductions are the effects often observed in staff members.

The World Health Organization recommends that the average sound pressure levels measured over time not exceed 30 dB(A) in patient ward rooms and 35 dB(A) in patient treatment and observation rooms [3]. Hospital noises often do not comply with the limits issued by national regulations [4]. Moreover, impulsive or very loud noises, short events (e.g., doors slamming, metal-to-metal contact, alarms) occur very often and superimpose the background noises, formed by heating, ventilation, and air conditioning (HVAC) systems, medical devices, and anthropic sounds, such as conversation.

1.1. Noise Effects on Hospital Staff

Regarding a working environment, noise can have negative impacts on hospital staff, causing stress, performance reduction, alarm fatigue, speech intelligibility, and, in severe conditions, even hearing loss.

There is evidence in the literature that stresses that satisfaction and the psychosocial environment can be influenced by the sensory overload imposed by environmental factors, such as high noise levels. Occupational stress depends on workplace conditions and environmental loads. Noise, working hours, shift times, level of responsibility, and pace of work are a few examples of occupational stressors, which also relate to satisfaction and psychosocial environments [5].

Hospital buildings rely on mechanical systems to provide ventilation, heating, cooling, and water. However, these systems can also lead to noise and vibration issues. The sizes and placements of HVAC systems could create problems related to excessive noise if they work poorly or are badly designed/maintained. Indeed, HVAC systems could be relevant sources of vibration and low-frequency noises that can lead to sick building syndrome (SBS)–related stress [6].

Several studies have shown that noise can degrade mental activities, including sustained attention to multiple cues or complex analyses. The combination of noise and stressful mental activities can result in disturbed concentration, irritation, and annoyance. Studies linking noise and job performance are often based on self-report assessments by people who are exposed, rather than direct error observations. For instance, Bayo et al. [7] performed a survey on 295 staff members across a range of wards in a major university hospital with average noise levels ranging from 52 to 75 dB(A). Moreover, 15–20% of respondents noted that noise negatively affected their professional performances and quality of work. Another study by Ryherd et al. [8] found that 43% of neurologic intensive care unit (ICU) nurses felt that noise in their working environments caused concentration problems. A study of 51 medical-surgical ICU nurses by Persson Waine K. et al. [9] showed that noise annoyance was significantly related to self-reported mental fatigue (tiredness, headaches, concentration difficulties, irritation, etc.) and auditory fatigue (e.g., sound sensitivity, hearing fatigue, ringing in the ears).

The "overload hypothesis", proposed by Sundstrom et al. [10], suggests that humans have a finite capacity for processing stimuli and coping with overload by utilizing selective attention and ignoring low-priority inputs.

Alarm fatigue is the failure to recognize and respond to true alarms and it is due to the high occurrence of alarms that require bedside clinical intervention. This fatigue causes a limited capacity to identify and prioritize alarm signals, leading to delayed or failed alarm responses and deliberate alarm deactivations. Auditory warnings and alarms are used throughout medical environments and several studies describe the potentially negative impacts of the alarm environments. Creighton Graham et al. [11] studied 15 care units measuring a staggering 16,953 alarms over 18 days. The authors noted that this equates to an average of 942 alarms per day, or 1 alarm every 92 s. Alarms can be classified into:

- Actionable alarms, requiring a response to bedside and therapeutic interventions to avoid adverse events;
- False alarms, due to artifacts that produce false data;
- Non-actionable alarms—true alarms that do not require patient therapeutic intervention;
- Nuisance alarms, a high occurrence of clinically non-actionable alarms.

Medical electric devices must comply with the standard series of the IEC 60601-1-11: "Medical electrical equipment—Part 1–11: General requirements for basic safety and essential performance—Collateral standard: Requirements for medical electrical equipment and medical electrical systems" used in the home healthcare environment. Parts 1–8 deal with tests and guidance for alarm systems in medical electrical equipment and medical electrical systems.

Three issues of concern about alarm systems and management are:

- Masking of alarms by the overall background noise environment;
- Decreased detection because of staff hearing acuity;
- "Alarm fatigue", where staff tune out or silence/disable alarms because they are desensitized or exhausted by them.

Alarm–oral communication is a paramount issue for patient safety in hospitals. Miscommunication could potentially lead to medical errors, such as incorrect medication administration, although this topic has not been adequately investigated to date. Research has shown that both orthographic (spelling) and phonological (sound) similarities increase the probability of medication errors, regardless of the level of experience [12]. High background noise and bad acoustics (in particular, unsuitable reverberation time and poor noise insulation) emphasize trouble in speech communication and can hinder oral communication [13]. The need for good acoustic quality in the rooms addresses the importance of their adequate design and furnishings.

Hospitals are workplaces and, therefore, risk assessment and noise exposure must be evaluated in terms of the allowed daily noise dose according to occupational guidelines (Italian law T.U. 81/08 implementing the Directive 2003/10/EC of the European Parliament and the Council on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents–noise).

Although overall total noise exposure (dose) is generally acceptable, in some units, such as surgery and orthopedist, because of the use of noisy tools (drill, saw, etc.), there are brief periods of noise exposure exceeding the guideline levels or transient peaks leading to serious health hazards for surgeons.

1.2. Noise Effects on Patients

Several factors contribute to the detrimental effects and discomfort issues for ill patients, such as poor sleep. The nature of the illness, physical discomfort, the effects of medical treatments, and environmental factors can all have detrimental influences on sleep quality. Sleep deprivation is associated with cognitive impairment and impaired memory formation, which may in turn contribute to confusion. Lack of sleep is also associated with cardiovascular stress, impaired immune function, and catabolic metabolism. In ICU patients and healthy subjects, approximately 1/4 of all EEG-monitored arousals from sleep have been associated with peak sound levels [14]. The contribution of noise to sleep disruption is probably more important for patients in the recovery phase or with less severe illnesses, while encephalopathy, polypharmacy, intensive nursing, and ventilatory support may be less prevalent.

In addition, noise causes stress to patients. Among patients recovering from acute coronary syndrome, adverse coronary care acoustics were associated with increased markers of cardiovascular stress, as well as an increased readmission rate. Noise is also associated with greater requirements for sedation and analgesia among ICU patients [14].

Hearing loss associated with critical illness may be worsened by noise. In particular, in patients with hearing impairment, noise may significantly impede their communication and, hence, their understanding of the environment. This is especially the case for the elderly, whose speech-processing abilities are more sensitive to noise disruptions. Hearing impairment is associated with a greater prevalence of psychotic symptoms in both general and psychiatric populations. Moreover, the sound environment in an ICU can affect the odds of delirium incidence in patients, an acute and fluctuating disturbance of consciousness and cognition, which is a risk factor related to mortality in the hospital [15].

1.3. The Present Case Study

Taking into account the above-outlined framework, the present paper describes a case study where two surveys were carried out in a large Italian hospital in Rome, in order to investigate the sonic environments in some wards and to collect self-reported reactions from staff members. As a rule, occupational noise exposure evaluation does not include self-evaluation by the exposed staff. However, this issue deserves to be investigated by means of collecting the staff evaluations on different aspects of the working environment quality and the effects of noise on job performance. For this purpose, in the present investigation, specific questionnaires were submitted to a sample of hospital staff members. In addition, medium- and long-term noise measurements were taken, and short-term audio recordings were processed to determine psychoacoustic parameters, namely loudness, sharpness, roughness, and fluctuation strength, as well as whether noise annoyance was experienced at the workplace.

The psychoacoustic parameters, closely related to sound perception [16], are usually applied in product sound quality and, only recently, in studies on outdoor sonic environments and soundscapes. Their application in the present study, dealing with an indoor environment, was deemed interesting to investigate the potential of these parameters in describing acoustic comfort in enclosed spaces.

Loudness N is the subjective perception of the sound amplitude by the human ear. It is measured in sone, with 1 sone defined as equal to the subjective loudness of a 40 phon level.

Sharpness S is an attribute related to the high-frequency content in the sound and it is measured in acum. If the sound contains a lot of high frequencies, it is perceived as sharp and annoying. Sharpness increases for an increment from 30 to 90 dB by a factor of two. This means that the dependence on the level can be ignored as a first approximation, especially if the level differences are not very large. The sharpness calculation is based on specific loudness computations.

Roughness R is an important attribute in the subjective judgment of sound quality. An increase in roughness is perceived as more annoying. The sensation of roughness occurs during the existence of the time-varying envelops over a critical band when a tone varies in amplitude or frequency. When the frequency modulation is between 20 and 300 Hz, the sound is perceived as rough. The sensation of roughness is dependent on the center frequency, modulation frequency, and modulation depth. Roughness increases with the increasing modulation depth and decreases with very low or high modulation frequencies. Roughness is measured in asper, with 1 asper defined as a sine tone of 1 kHz with 60 dB, an amplitude modulated at a frequency of 70 Hz, and a unitary modulation depth.

The hearing sensation caused by very low-frequency modulations is called fluctuation strength F. The perception of fluctuations can be described as modulations in sounds, which occur slowly enough that human hearing can track the temporal changes in the level of the sound. Fluctuation strength is maximum at modulation frequencies of 4 Hz. The unit of fluctuation strength is vacil, with 1 vacil defined as a sine tone of 1 kHz with 60 dB, an amplitude modulated at a frequency of 4 Hz, and with unitary modulation depth.

A combination of the above four psychoacoustic metrics leads to the psychoacoustic annoyance PA, computed as follows [16,17], as a metric for sound quality evaluation:

$$PA = N_5\left(1 + \sqrt{\omega_S^2 + \omega_{FR}^2}\right), \tag{1}$$

with N_5 being the 5th percentile loudness in sone, acknowledged as an appropriate measure of the loudness of the time-varying sounds (as in the present case study), ω_S describes the effect of the sharpness S,

$$\omega_S = (S - 1.75) \cdot 0.25 \lg(N_5 + 10) \text{ for } S > 1.75\ acum, \tag{2}$$

and ω_{FR} describes the influence of the fluctuation strength F and roughness R

$$\omega_{FR} = \frac{2.18}{(N_5)^{0.4}}(0.4F + 0.6R). \quad (3)$$

2. Materials and Methods

Hospital environments are very particular regarding their features and functions. Noise zone schemes play a role in land planning and management; hospitals are often included in the most noise-sensitive class (e.g., with the lowest noise limits). For instance, in Italy, the equivalent continuous level L_{Aeq} of outdoor noise, measured 1 m away from the exposed building façade, must not exceed 50 dB(A) in the daytime (h 6–22) and 40 dB(A) at nighttime (h 22–6). Even when noise from the outdoors complies with the limits, indoor noise is often a cause of discomfort to patients and staff, often because of poor sound insulation of room partitions and/or excessive noise in the room.

Due to the important features and functions, any survey carried out inside a hospital should interfere as low as possible with the ongoing activities; therefore, this requirement leads to logistic and organizational constraints. Such practical limitations had large impacts on the noise surveys described in this paper, including recordings and measurements of the indoor sonic environment at a large hospital in Rome, Italy, together with responses collection given to questionnaires submitted to the hospital staff. For instance, a limitation deals with the microphone locations selected for the noise measurement in the surgical room. Locations have been selected on a case-by-case basis in order to minimize interference with staff activities.

Two surveys were carried out to investigate the sonic environments in 20 wards (Table 1) and to collect self-reported reactions from hospital staff.

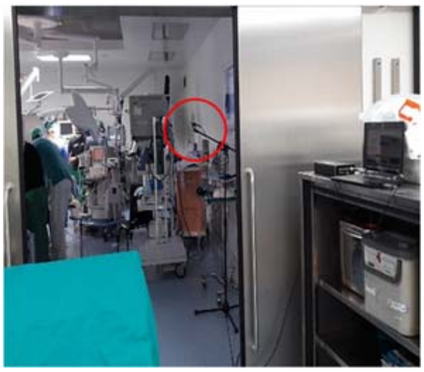
Table 1. Investigated wards in the two surveys.

Survey	Wards
S1	Surgical room, recovery room, intensive care unit (ICU), therapeutic radiology (control room CR)
S2	Intensive care unit (control room CR), surgical room (preparation prior to surgical operation), Single Photon Emission Computed Tomography (SPECT, control room CR), Scintigraphy Positron Emission Tomography (SPET, control room CR), Intensive Care Unit control room (ICU-CR), radiotherapy, radiotherapy (control room CR), magnetic resonance (MRI, control room CR), magnetic resonance (MRI), radiology (control room CR)

2.1. Acoustic Data

Medium- and long-term noise measurements, as well as short-term audio recordings, were collected to determine several acoustic data describing the indoor sonic environment (Table 2). For this purpose, the 1 s short L_{Aeq} time history of sound pressure level (SPL) detected in each measurement point was imported in a script developed in the "R" software [18] to compute the acoustic descriptors listed in Table 2. In addition, the audio recordings taken in survey 2 were post-processed via the ArtemiS software platform version n.10 to calculate psychoacoustic parameters, namely loudness, sharpness, roughness, and fluctuation strength. These parameters are not yet included in the standards and guidelines dealing with indoor noise in hospitals, even though they are meaningful for the evaluation of the sonic environment quality and its perception. Sound measurements were taken in locations that represented where staff members were exposed to noise, avoiding, at most, interfering with normal operating conditions (Figure 1).

(a)



(b)

Figure 1. Example of the microphone's location, highlighted by the red circle, selected for the noise measurement in the surgical room: (**a**) survey 1, (**b**) survey 2.

The importance of the sound spectrum in evaluating the indoor sonic environment was taken into account by the following parameters:

- The difference [dB] between the continuous equivalent level with *Z* (flat frequency response 10–20,000 Hz) and A frequency weightings; the higher this difference, the greater the sound energy at low frequencies;
- The average 1/3 octave band (12.5–20,000 Hz) spectrum and the corresponding center of gravity *G* [Hz].
- To evaluate the interference of the room sonic environment with speech communication, the *SIL* parameter, calculated according to the standard EN ISO 9921:2003 [19], was determined with the expected voice effort at 1 m at five levels (relaxed, normal, raised, loud, very loud).
- To assess the quality of the room sonic environment in terms of comfort perception, the methods of the room criterion *RC Mark II*, together with the quality assessment index (*QAI*) and the balanced noise criterion (*NCB*) curves were applied [20].

Moreover, the Harmonica index (*HRM*) was calculated [21,22] from the 1 *s* short L_{Aeq} time history of sound pressure level (*SPL*) detected at each measurement point. This index was developed for the outdoor sonic environment to take into account the two main components that influence its perception, namely the background noise (*BGN*) and the characteristics of noise peaks (*EVT*) that stand out from this background noise. The *EVT*/*BGN* ratio shows that the contribution of events (*EVT*) referred to the background noise (*BGN*). The higher this ratio, the higher the contribution of events. In this aspect, the ratio is always below 1 and changes from 0.1 to 0.8 (surgery and ICU control room).

The *HRM* value, on a scale from 0 to 10 (to avoid the use of a logarithmic scale that is too difficult to be understood by the public) was obtained for the measurement time *TM* by:

$$HRM = BGN + EVT, \quad (4)$$

where:

$$BGN = 0.2 \times (L_{A95eqTM} - 30) \quad [dB(A)], \quad (5)$$

$$EVT = 0.25 \times (L_{AeqTM} - L_{A95eqTM}) \quad [dB(A)], \quad (6)$$

with $L_{A95eqTM}$ being the continuous equivalent level of the series of percentile L_{A95} values determined by a mobile time window with width $w = TM/6$, a progressive sliding of 1 s, and L_{AeqTM} being the continuous equivalent level.

Even though the *HRM* index was proposed for evaluation of the outdoor sonic environment perception in terms of annoyance, its application to indoor room noise was deemed interesting to evaluate the potential of this index in describing acoustic comfort conditions.

Acoustic measurements were taken by class 1 compliant instrumentation, namely a 01 dB solo sound level meter with a 1/2″ MCE 212 microphone in survey 1 and a Sinus Apollo acoustic analyzer with a 1/2″ BSWA MP 201 microphone connected to a PC with SAMURAI version n. 2.6 software in survey 2. Audio recordings used to determine psychoacoustics parameters were collected at a 52 kHz sampling rate and 24-bit resolution.

Table 2. Collected acoustic data in the surveys.

Survey	Acoustic Parameters
S1	Continuous equivalent level L_{eq}, A [dB(A)] and Z [dB] frequency weighted Time weighting: Fast Linear repetitive average 1 s Percentile levels L_{A10}, L_{A90} [dB(A)] Average 1/3 octave band (12.5–20,000 Hz) spectrum [dB] Spectrum center of gravity G [Hz] Speech interference level of noise L_{SIL} [dB] Speech interference level L_{SIL} [dB] Vocal effort at 1 m from the measurement position Harmonica index (*HRM*) Room Criterion *RC Mark II* and Quality Assessment Index (*QAI*) Balanced Noise Criterion (*NCB*) curves
S2	All the above descriptors plus the following ones: Loudness average value N and 5th percentile N_5 [sone], determined according to standard DIN 45631/A1:2010-03 [23] Sharpness average value S [asper], determined according to standard DIN 45692:2009 [24] Roughness average value R [acum] Fluctuation strength average value F [vacil] Psychoacoustic annoyance *PA*

2.2. Subjective Assessment Data

For each survey, a specific questionnaire was designed; the first collected self-reported noise assessments at the workplace and the second investigated the perception of spectral and temporal noise features and associated them with noise metrics.

The two questionnaires were designed and submitted to the volunteer participants via Google Form®, which allows for collecting responses easily and efficiently via embedded controls, such as forcing participants to answer all questions in sequence according to their presentation order and saving data automatically for further analysis. This management method of the questionnaire allowed participants to fill out the forms without interfering with their work.

The first questionnaire, submitted to 60 staff members, collected responses from 10 items on a 5-level scale (not at all, a little, moderately, much, and very much), to obtain data on sound sources perceived in the hospital, attitudes toward noise, its effects, noise-induced physical–mental effects, interference with working performance, perceived quality of workplace environment, as well as personal details (gender, age, profession). Further information regarding exposure to noise in leisure time (attending dance clubs, concerts, or listening to loud music with earphones or headphones) was collected too.

In the second questionnaire, which was submitted to 28 out of 60 staff members, 10 items dealt with noise feature perceptions, collecting judgments on a 5-level scale (never, rarely, sometimes, often, and always) about the presence of intense and long-lasting, intermittent, persistent, short and very intense, low-frequency, and high-frequency sounds/noises at the workplace, with intensities that vary very slowly and very quickly over time, in order to investigate respondents' perceptions of the psychoacoustic features. For each feature, the questions listed in Table 3 were asked.

Table 3. Questions in survey 2 for each psychoacoustic feature.

Psychoacoustic Feature	Question
Loudness N	Do you perceive loud and long-lasting sounds/noises at your workplace?
Sharpness S	Do you perceive high frequencies in the sounds/noises at your workplace (e.g., ringing of a telephone or whistle)?
Roughness R	Are the perceived sounds/noises at your workplace characterized by a quick intensity variation over time (e.g., the sound of a ringtone)?
Fluctuation strength F	Are the perceived sounds/noises at your workplace characterized by a slow intensity variation over time (e.g., such as the sound of a siren or the ding-dong of a doorbell)?
Annoyance	Do you consider sounds/noises at your workplace annoying?

3. Results and Discussion

This section reports the main results obtained from the analysis of the collected acoustic data and responses given by hospital staff to the submitted questionnaires in the two surveys. Note that the staff activity was often unpredictable in terms of location and time of exposure, being linked to the needs and emergencies. This makes the association between the acoustic parameters, detected in fixed sites with the subjective assessments of the working environment, difficult.

3.1. Acoustic Data

Table 4 summarizes the values obtained for some of the acoustic and psychoacoustic metrics.

Table 4. Results of some acoustic metrics obtained by the developed R script.

Survey	Ward	L_{Aeq} [dB(A)]	L_{Zeq}-L_{Aeq} [dB]	L_{A10}–L_{A90} [dB(A)]	L_{SIL} [dB]	*EVT/BGN*	*HRM*	*RC MarkII*	*QAI*	*NCB*
1	ICU_day1	57.8	24.1	8.7	50.9	0.3	5.83	53	10	51
	ICU_day2	58.6	23.7	9.7	51.7	0.3	6.01	54	11	52
	Recovery	64.8	16.0	13.1	58.0	0.5	7.47	60	24	58
	Surgery	66.3	17.0	18.5	59.7	0.8	7.96	61	21	60
	Radiotherapy_CR	65.0	14.1	11.1	57.8	0.4	7.42	60	24	58
2	ICU_CR	59.0	10.7	11.2	51.6	0.4	6.17	54	15	52
	Surgery	64.4	6.7	10.7	57.8	0.5	7.34	59	22	58
	SPECT_CR	59.0	8.6	3.4	51.9	0.1	5.89	54	18	52
	SPE_CR	63.9	6.1	4.9	56.6	0.1	6.94	59	20	57
	ICU_CR	64.9	6.7	14.3	58.7	0.8	7.64	59	23	59
	Radiotherapy3_CR	58.8	7.8	9.3	52.2	0.3	6.05	54	20	52
	Radiotherapy3_RR	65.1	3.2	6.5	58.3	0.1	7.11	60	31	58
	Radiotherapy2_CR	57.5	7.0	8.7	50.5	0.3	5.73	52	22	51
	Radiotherapy1_CR	55.0	9.2	4.8	48.2	0.2	5.15	50	20	48
	Radiotherapy_cyberknife_RR	52.9	8.8	3.9	43.6	0.2	4.73	47	15	44
	Radiotherapy_cyberknife_CR	59.6	10.3	11.5	51.8	0.5	6.32	54	16	52
	Radiotherapy_TAC2_CR	59.8	12.3	6.6	52.4	0.2	6.19	54	14	52
	RMN_3TESLA_CR	61.9	14.7	12.9	54.7	0.4	6.73	57	11	55
	RMN_1.5TESLA_CR	57.4	10.8	7.2	50.2	0.3	5.72	52	15	50
	Radiology_TAC2_CR	61.2	10.7	8.2	54.6	0.2	6.50	56	17	55
	Radiology_3_04_CR	62.9	10.8	11.4	54.3	0.4	6.98	57	14	54

Figure 2 reports the box plots of the L_{AeqTM} and L_{SIL} levels; the L_{SIL} is computed as the arithmetic averages of the octave band mean levels centered at 500, 1000, 2000, and 4000 Hz. These L_{SIL} levels compared with the dB(A) vocal effort levels of a male speaker at a distance of 1 m to the listener led to increased and loud efforts in 57.1% and 30.0% of cases respectively, confirming that speech intelligibility is critical in most of the wards surveyed, considering the possibility of misunderstandings in important communications, most likely even worse when the staff members wear sanitary masks. Figure 2 shows the distribution of the percentile L_{A95}, often considered representative of the background noise, which is always above 50 dB(A).

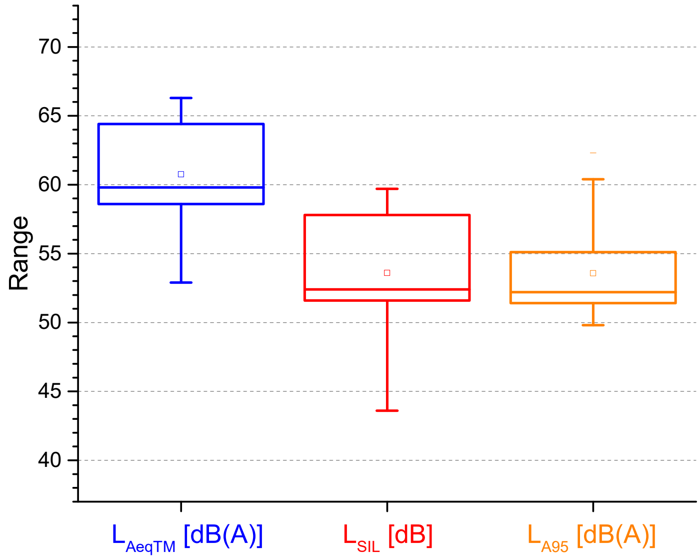


Figure 2. Box plots of the L_{AeqTM}, L_{SIL}, and L_{A95} values in the wards surveyed.

The range of the mean octave band spectrum observed in the wards is given in Figure 3, showing that the sound energy, as expected, decreases with increasing frequency except in the range of 125–500 Hz. This pattern is also responsible for the high values obtained for the applied room criteria *RC Mark II* (from 47 to 61) and *NCB* (from 44 to 60) given in Table 4. The methods detected unbalanced spectra with "hissy" components, as reported by the quality assessment index (*QAI*), as always greater than 5, a value corresponding to a presumed neutral spectrum. The observed range of *QAI* (from 10 to 31) is due to the spectrum unbalance at mid-frequencies.

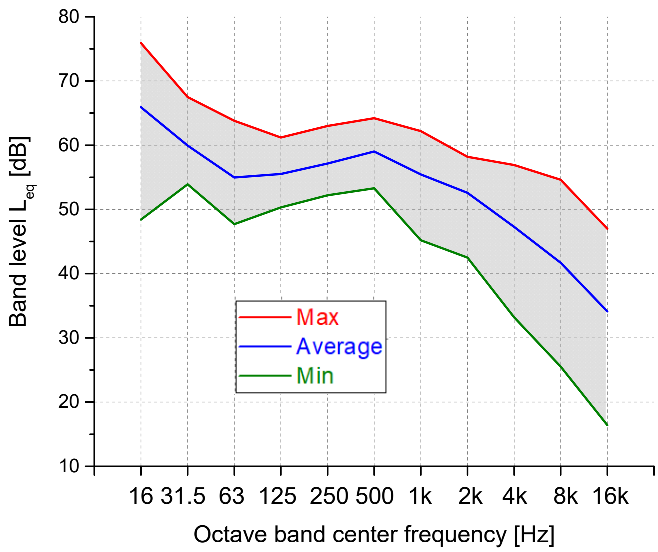


Figure 3. Range (grey area) of the mean octave band spectrum observed in the wards.

The time variability of the sound level can be evaluated by the noise climate, computed to the difference L_{A10}–L_{A90}. Moreover, for this metric, a large variability was observed, from 3.4 to 18.5 dB(A) across the wards, with a maximum value in the surgery room.

The box plots in Figure 4 show the large variability of the psychoacoustic metrics observed in the wards.

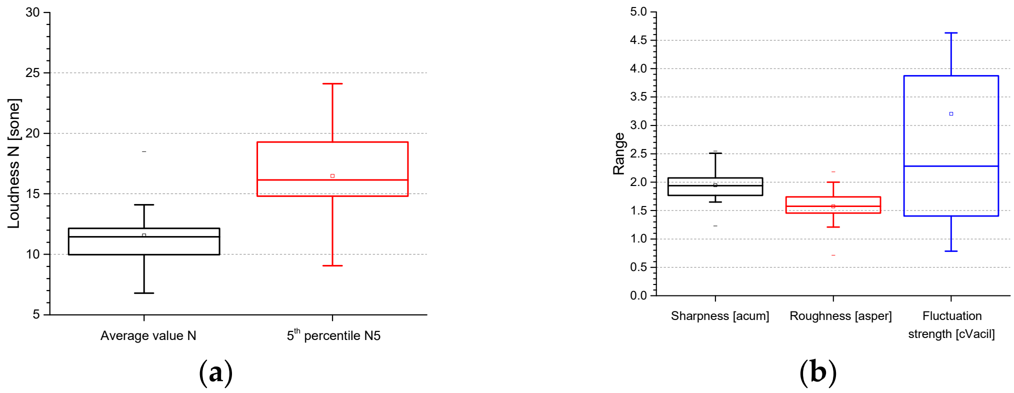


Figure 4. Range of the psychoacoustic metrics observed in the wards: (**a**) average value and 5th percentile of loudness; (**b**) average values of sharpness, roughness, and fluctuation strength.

Noise annoyance is a critical factor in increasing stress and reducing work performance. Harmonica (*HRM*) and perceived annoyance (*PA*) (the former factor was developed for outdoor noise and the latter was computed as a combination of the four psychoacoustic descriptors (see equations 1, 2 and 3) were considered to take into account the potential annoyance. They are correlated (r = 0.75) and seem suitable to characterize indoor sonic environments in terms of the potential evoked annoyance. The observed values are given in the scatter plot in Figure 5, together with the regression line. Again, the *HRM* highest value was observed in the surgery room and the minimum value was 4.7 above the *HRM* value = 4 proposed in [22] to classify the sonic environment as "noisy". Moreover, the presence of noise events is an additional factor in deteriorating acoustic comfort. Such a presence can be evaluated by the *EVT* component of the Harmonica index or, even better, by its ratio with the background noise *BGN*. The greater this ratio, the larger the presence of noise events. The results obtained for *EVT*/*BGN* (from 7.1 to 78.5%) show that in 12 out of 21 cases, the *EVT* component was below 33% of the *BGN* value.

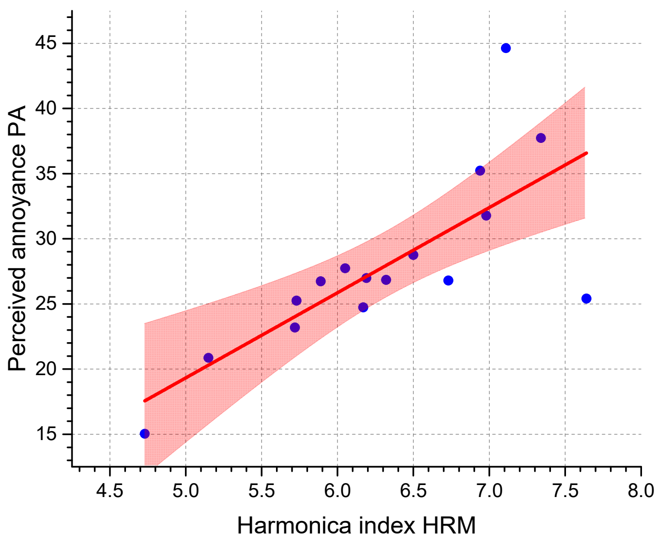


Figure 5. Harmonica index *HRM* and perceived annoyance *PA* determined to evaluate the potential annoyance in the wards. The colored area around the regression line corresponds to the 95% confidence interval.

A further analysis was aimed to determine the correlation among the acoustic metrics, as reported by Pearson's correlation matrix in Figure 6, where cells with × correspond to the non-significant r-value at the 95% confidence level.

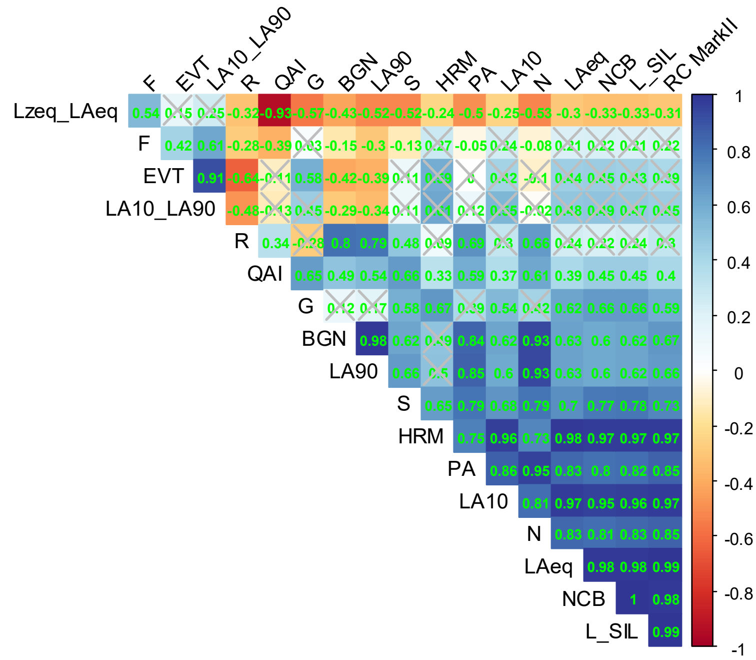


Figure 6. Pearson's correlation matrix of the noise metrics. Cells with × correspond to the non-significant r-value at the 95% confidence level.

The presence of large sound level fluctuations over time detected by the noise climate (L_{A10}–L_{A90}) is well correlated (r = 0.91) with the event component *EVT* of the Harmonica index *HRM*. Furthermore, *HRM* has a good correlation with the room criteria (r = 0.97), L_{Aeq} level (r = 0.98), and loudness *N* (r = 0.73). Thus, this index appears to be adequate to describe the indoor sonic environment in terms of time variability and evoked annoyance. Roughness *R* is in good accordance with L_{A90} (r = 0.79) and, therefore, with the background component *BGN* of *HRM* (r = 0.80), because of the slow amplitude modulation acoustic emissions from electromechanical systems. Sharpness *S* is correlated (r = 0.79) with loudness *N* and perceived annoyance *PA*, most likely due to the sound energy content in the middle-high frequencies. For this reason, a good correlation (r = 0.73) is also observed between *S* and room criteria. As expected, roughness *R* and sharpness *S* are positively correlated with loudness *N* (r = 0.66 and 0.79, respectively). The results show that psychoacoustic parameters can provide additional information on some features of the noise observed in the hospital wards, which may influence their perceptions and the relevant extra-auditory effects.

3.2. Subjective Assessment Data

The first questionnaire was submitted to 60 workers (45% female *F* and 55% male *M*), grouped as physicians (43%), technicians (22%), operators (12%), nurses (15%), and others (8%). Physicians had almost the same gender distribution (46% *M* and 54% *F*) as operators (57% *M* and 43% *F*). Larger differences were observed in the remaining groups: technicians (85% *M* and 15% *F*), nurses (33% *M* and 67% *F*), and others (60% *M* and 40% *F*).

Two age groups were selected: up to 50 years (42% of the sample, mainly nurses and others) and over 50 years (58%, especially physicians, operators, and technicians).

Responses given in Table 5 showed that the working environment was largely reported as "noisy" by nurses (89%), technicians (77%), and physicians (69%). This feature is positively correlated with the concentration loss (Spearman's rank order correlation ρ = 0.684) reported by all categories, except the operator (Table 6).

Table 5. Percentage of responses to the question: "Usually how noisy is your working environment?".

Category	Not At All	A Little	Moderately	Much	Very Much	Moderately + Much + Very Much
Physician	0	31	38	27	4	69
Operator	14	57	29	0	0	29
Technician	0	23	54	15	8	77
Nurse	0	11	67	22	0	89
Others	20	60	0	20	0	20

Table 6. Percentage of responses to the question: "How much does the noise affect your concentration?".

Category	Not At All	A Little	Moderately	Much	Very Much	Moderately + Much + Very Much
Physician	0	35	38	12	15	65
Operator	0	71	0	29	0	29
Technician	0	31	46	23	0	69
Nurse	11	22	33	33	0	67
Others	0	40	20	40	0	60

Even speech intelligibility was affected by noise, as reported mainly by physicians (69%), technicians (62%), nurses (60%), and 57% of the interviewees overall. This outcome confirms the critical situation in most of the wards surveyed, where the observed L_{SIL} levels led to raised and loud efforts in the majority of wards.

Noises from the instrumentation categories (multiparametric monitors, HVAC systems, and electrocautery, particularly in surgery rooms) and related to the colleagues' activities were perceived as the most annoying.

Experienced stress at work (57% of operators, 77% of physicians and technicians, 89% of nurses, and 70% of the interviewees overall) was positively correlated with the perceived noise (Spearman's rank order correlation ρ = 0.705), as well as concentration loss (ρ = 0.442). It should be noted that work tasks in hospitals are affected by noise and the consequences of the effects depend on the specific responsibility and workload, from ordinary activities to particularly delicate ones, such as those carried out by physicians and nurses. Unconscious "adaptation" strategies can be implemented, which in certain cases determine "alarm fatigue" with a negative influence on concentration (55%) and work performance (36%), mainly associated with the medical and nursing staff.

Regarding technicians, 75% of operators complained of alterations in their concentrations and performances and about 50% in the ability to complete their work efficiently, due to the noise in the healthcare facility.

For a general view of the interactions between the perceived noise and its extra-auditory effects reported by the staff members, Figure 7 shows the occurrence percentage of responses [%] given by physicians/nurses and technicians. Percentages below 25% are colored in green, between 25% and 50% in yellow, and above 50% in red.

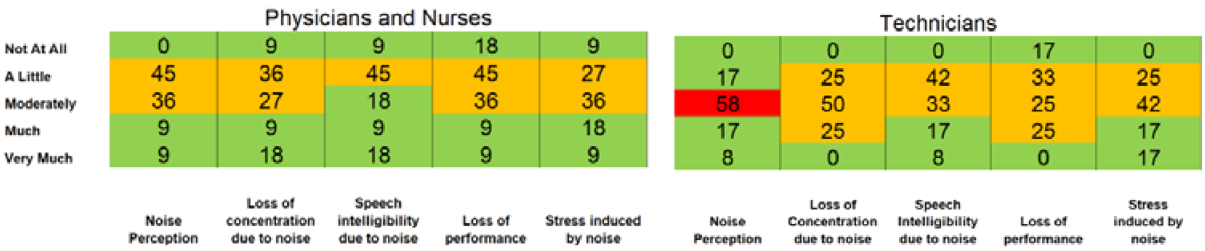


Figure 7. Interactions between the perceived noise and its extra-auditory effects reported by the staff members (occurrence percentage of responses [%]).

Table 7 shows the perceptions of some spectral and temporal noise features reported by the interviewees, as outlined in Table 3.

Table 7. Occurrence percentages of responses [%] to questions asked in survey 2 for each psychoacoustic feature.

Psychoacoustic Feature	Never (N)	Rarely (R)	Sometimes (S)	Often (O)	Always (A)	(N + R)	(S + O + A)
Loudness *N*	21	36	29	7	7	57	43
Sharpness *S*	7	29	46	14	4	36	64
Roughness *R*	25	43	21	7	4	68	32
Fluctuation strength *F*	21	47	21	11	0	68	32
Annoyance	4	50	31	11	4	54	46

Loud, long-lasting sounds and annoyance were "often" and "always" perceived by 14% and 15% of respondents, respectively, while "never" and "rarely" by 57% and 54% of respondents. This appears to contrast with the values obtained for the Harmonica index *HRM*, all above *HRM* = 4 corresponding to a "noisy" environment, unless the occurrence percentages of "often" and "always" annoyed may be reasonably associated with the extent of being "highly annoyed".

Regarding sharpness, 18% of participants reported the presence of high-frequency sounds "often" and "always", whereas a large part of them (46%) experienced this feature as "sometime". This outcome is in agreement with the applied room criteria *RC Mark II* and *NCB* that detected unbalanced spectra with "hissy" components, as also reported by the quality assessment index (*QAI*) values due to the spectrum unbalance at mid-frequencies.

Most of the respondents (68%) "never" and "rarely" reported sound perceptions relevant to roughness (perception of rapid amplitude modulation of noise) and fluctuation strength (perception of slower amplitude modulation of noise).

These reactions are consistent with the values of the roughness variable from 0.71 (ICU control room) to 2.18 asper (radiotherapy 3 RR), and fluctuation strength varying from 0.79 (SPECT control room) to 15.40 cvacil (RMN3Tesla control room).

4. Conclusions

Among the several types and uses of buildings, the hospital environment is very particular regarding its features and functions. Even when noise from outdoors complies with the limits, indoor noise is often a cause of discomfort to patients and staff, frequently because of poor sound insulation of room partitions and/or excessive noise in the room.

Researchers are increasingly becoming interested in noise inside hospital wards, due to its harmful effects on patients and staff members. The present investigation, carried out in 20 wards in a hospital in Rome, is a case study on the above topic. However, even though the results cannot be generalized, the outcomes of the described surveys address some issues that could be interesting (in methodological terms) for further studies, namely:

- The use of structured questionnaires submitted to workers to collect their assessments on the working environment quality and effects of noise on their job performances and well-being;
- Submission of questionnaires via the web to increase the efficiency of their management and to interact with the staff without interfering too much during their course of work;
- Supplement L_{Aeq} level with other acoustic parameters, including psychoacoustic descriptors, which are more related to human perceptions, to figure out the complex features and the on-time and frequency domains of the sonic environment in the hospital rooms;
- Applying the Harmonica index *HRM*, which takes into account the sound energy and its fluctuation over time due to the presence of sound events, to evaluate the potential

annoyances producing harmful effects and discomfort in working environments, as well as the psychoacoustic annoyance *PA*, a metric developed for sound quality evaluation and obtained by a combination of the four psychoacoustic parameters—loudness *N*, sharpness *S*, roughness *R*, and fluctuation strength *F*.
- The outcome of this study provides hints on the methodological issues that would be useful and encourages further investigations into such a critical indoor environment. The obtained results confirm the need to increase acoustic comfort and, therefore, contribute to reducing the recovery time for patients and preserving the work performances and safety of staff members by reducing stress, at least caused by noise, at the workplace.

Author Contributions: Conceptualization, F.L.C., R.M. and C.G.; data curation, F.L.C., G.B. and R.M.; formal analysis, F.L.C., G.B., M.D. and C.G.; investigation, F.L.C., S.I., R.M., V.B., L.S. and G.R.; methodology, F.L.C., G.B., R.M. and C.G.; resources, F.L.C., S.I., R.M., V.B., L.S. and G.R.; visualization, F.L.C., G.B. and M.D.; writing—original draft, F.L.C., G.B., M.D. and C.G.; writing—review and editing, F.L.C., S.I., G.B., R.M., M.D., V.B., L.S., G.R. and C.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and the protocol was approved by the Ethics Committee of IRCCS Lazio (Protocol code: ifo_058.IFO_AOO.REGISTRO UFFICIALE.U.0011112.25-08-2022, date of approval 2022-08-04, Minutes extract n. 8 date 2022/08/04, Survey Notification: "Noise in closed working environments" - Experimental Register No. 1745/22.

Informed Consent Statement: There is not a revised Ethical Statement.

Data Availability Statement: Not applicable.

Acknowledgments: The authors thank the hospital staff and all participants in the surveys for their cooperation.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Nightingale, F. Noise. In *Notes on Nursing. What It Is, and What It Is Not*; Cambridge University Press: Cambridge, UK, 1869.
2. de Lima Andrade, E.; Collins da Cunha e Silva, D.; Augusta de Lima, E.; Angrizani de Oliveira, R.; Trombetta Zannin, P.H.; Germano Martins, A.C. Environmental noise in hospitals: A systematic review. *Environ. Sci. Pollut. Res.* **2021**, *28*, 19629–19642. [CrossRef] [PubMed]
3. World Health Organization. *Environmental Noise Guidelines for the European Region*; WHO Regional Office for Europe: UN City, Copenhagen, Denmark, 2018.
4. Konkani, A.; Oakley, B. Noise in hospital intensive care units—A critical review of a critical topic. *J. Crit. Care* **2012**, *27*, 522. [CrossRef] [PubMed]
5. Gagnon, M.; Hanna, T.; Mello, B.; Pinette, W. Increasing the Quality of Patient Care by Reducing Noise Levels in the Healing Environment. Bachelor's Thesis, Faculty of Worcester Polytechnic Institute, Worcester, MA, USA, 2012.
6. Schwartz, S. Linking Noise and Vibration to Sick Building Syndrome in Office Buildings. *Air Waste Manag. Assoc.* **2008**, 26–28.
7. Bayo, M.V.; Garcia, A.M.; Garcia, A. Noise levels in an urban hospital and workers' subjective responses. *Arch. Environ. Health* **1995**, *50*, 247–251. [CrossRef] [PubMed]
8. Ryherd, E.E.; Persson Waye, K.; Ljungkvist, L. Characterizing noise and perceived work environment in a neurological intensive care unit. *J. Acoust. Soc. Am.* **2008**, *123*, 747–756. [CrossRef] [PubMed]
9. Persson Waye, K.; Ryherd, E.E.; Hsu, T.; Lindahl, B.; Bergbom, I. Personnel response in intensive care units. In Proceedings of the Internoise 2010, Lisbon, Portugal, 13–16 June 2010.
10. Sundstrom, E.; Bell, P.A.; Busby, P.L.; Asmus, C. Environmental psychology: 1989–1994. *Annu. Rev. Psychol.* **1996**, *47*, 485–512. [CrossRef] [PubMed]
11. Creighton, G.K.; Cvach, M. Monitor alarm fatigue: Standardizing use of physiological monitors and decreasing nuisance alarms. *Am. J. Crit. Care* **2010**, *19*, 28–34. [CrossRef]
12. Lambert, B.; Chang, K.; Lin, S. Effect of orthographic and phonological similarity on false recognition of drug names. *Soc. Sci. Med.* **2001**, *52*, 1843–1857. [CrossRef] [PubMed]

13. Masullo, M.; Maffei, L. Il rumore negli uffici. In Proceedings of the Atti 39° Convegno Nazionale Associazione Italiana di Acustica, Roma, Italy, 4–6 July 2012. (In Italian).
14. Pugh, R.J.; Jones, C.; Griffiths, R.D. The Impact of Noise in the Intensive Care Unit. In *Intensive Care Medicine. Yearbook of Intensive Care and Emergency Medicine*; Springer: Berlin/Heidelberg, Germany, 2007.
15. Sangari, A.; Emhardt, E.A.; Salas, B.; Avery, A.; Freundlich, R.E.; Fabbri, D.; Shotwell, M.S.; Schlesinger, J.J. Delirium Variability is Influenced by the Sound Environment (DEVISE Study): How Changes in the Intensive Care Unit soundscape affect delirium incidence. *J. Med. Syst.* **2021**, *45*, 76. [CrossRef] [PubMed]
16. Fastl, H.; Zwicker, E. *Psychoacoustics: Facts and Models*, 3rd ed.; Springer: Berlin/Heidelberg, Germany, 2007. [CrossRef]
17. Kaczmarek, T.; Preis, A. Annoyance of Time-Varying Road-Traffic Noise. *Arch. Acoust.* **2010**, *35*, 383–393. [CrossRef]
18. R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2020.
19. *EN ISO 9921:2003*; Ergonomics—Assessment of speech communication. International Organization for Standardization: Geneva, Switzerland, 2003.
20. Tocci, G.C. Room Noise Criteria-The State of the Art in the Year 2000. *Noise News Int.* **2000**, *3*, 106–119. [CrossRef]
21. Vincent, B.; Gissinger, V.; Vallet, J.; Mietlicky, F.; Champelovier, P.; Carra, S. How to characterize environmental noise closer to people's expectations. In Proceedings of the InterNoise 2013, Innsbruck, Austria, 15–18 September 2013.
22. Mietlicki, C.; Mietlicki, F.; Ribeiro, C.; Gaudibert, P.; Vincent, B. The HARMONICA project, new tools to assess environmental noise and better inform the public. In Proceedings of the Forum Acusticum, Kraków, Poland, 7–12 September 2014.
23. *DIN 45631/A1:2010-03*; Calculation of Loudness Level and Loudness from the Sound Spectrum—Zwicker Method—Amendment 1: Calculation of the Loudness of Time-Variant Sound. Deutsches Institut für Normung: Berlin, Germany, 2010.
24. *DIN 45692:2009*; Measurement Technique for the Simulation of the Auditory Sensation of Sharpness. Deutsches Institut für Normung: Berlin, Germany, 2009.