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DISTURBED SLEEP: ESTIMATING NIGHT-TIME SOUND ANNOYANCE AT A HOSPITAL WARD

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ABSTRACT

Hospital soundscapes are often associated with unhealthy sound levels and an overall perception of chaos and annoyance. Over the past four decades, concerns about the harmful effects of environmental noise on hospital stakeholders (patients, families, and healthcare professionals) were repeatedly raised by the scientific community. In this paper, the authors report a study they have conducted on the analysis of the acoustic environment of a multi-patient room in the Neurology unit in a Dutch hospital. The study employed sound source annotations by listeners to focus on what we claim is the most important emotional descriptor, namely annoyance. More than 9,000 sound events and their perceived annoyance were identified in over 400 night-time audio recordings. Analysis revealed that while patient-generated sounds such as snoring dominate the night-time soundscape and are identified as highly annoying, personnel-generated sounds such as speech might have an even higher accumulated annoyance when the duration of individual sound events is taken into account. This finding indicates the possibility of designerly approaches to improving the hospital ward environment by focussing on interventions to increase awareness of the impact of specific sound events on patient's sleep quality, and support actions to mitigate negative effects.

Keywords: *indoor soundscape, hospital ward, sleep disturbances, annoyance, sound-driven design.*

1. INTRODUCTION

Since humans subconsciously perceive and react to sound even while asleep, sound events are a significant environmental factor that can interfere with our regular sleep patterns. As an external stressor, sound has been shown to cause neurophysiological changes in the brain, particularly in regions of the prefrontal cortex, amygdala, and hippocampus, which are involved in cognitive and emotional processing [1]. The listener's directed attention reorientation reflex is activated by sudden foreground sounds, and chaotic soundscapes do not provide sufficient time between sound events for psychological mechanisms, preventing arousal from returning to a normal, relaxed state ([2] p. 7). Interruptions by sound during sleep increases physiological and cardiovascular activity, disturbing sleep and augmenting the risk of stress, exhaustion, or mental health issues [3]. The detrimental impact of sound on sleep is recognized as a significant factor affecting human health and wellbeing, especially in hospitalised patients [4][5][6]. The recent thesis work by de Meyer [7] focuses on snoring as a major cause for sleep disturbance. Of particular interest in the context of the present study is the notion that an undisturbed sleep is imperative for successful recuperation. A clinical review paper by Muzet [8] states that various factors, including the type of sound (e.g., continuous, impulsive, intermittent) and its frequency spectrum, affect a sleeper's sensitivity to sound. Therefore, considering sound level on its own, such as LAeq, may not be the most informative factor in the assessment of

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environmental sleep-friendliness. Crucially, it is necessary to investigate the way in which specific external sound sources might have a negative impact on sleep. In the present study, we determine sound events and their perceived annoyance quality through the evaluation of soundscape recordings. Sleep disturbance by sounds amongst patients is a frequently occurring problem in healthcare ranging from home care to general and intensive care in hospitals. One of the main causes of the problem is that hospitals offer shared acoustic spaces (i.e. acoustic biotopes) in which multiple actors (patients, visitors, and healthcare providers) and multiple objects (healthcare devices, medical tools) interact and contribute to the overall quality of the acoustic environment [9]. Such shared spaces also have different functions, which can change over the time of the day. For example, a patient room should be conducive to caregiving activities as well as resting and sleeping. Because of the ambiguity of its functions, it may be difficult to organise the acoustic environment or control the sound-producing events, especially because nurses are often unaware of the sonic consequences of their and others' actions [9]. Thus, mitigating the problem of sleep disruption by sound is an ongoing effort in the field of sound-driven design for healthcare [10] [11].

One major step towards improving patient experience at night-time would be to define what types of sounds cause sleep disruption. There are correlations between disruption and annoyance; that is being disrupted by (unwanted) sound causes sound annoyance [13]. We define an annoying sound event as a sound that has the potential to intrude and impede the listener's activity, in our case, sleeping [14]. In this study, we specifically investigate the annoyance caused by sound events occurring in a hospital ward during night hours (from 9.30 p.m. to 7.30 a.m.) and their association with disturbed sleep. As a following step, we will use data collected in the study to define a computational model of sound-induced sleep disturbances in hospital wards to inform nursing staff on the 'footprint' of specific sound events. Our overall aim is to be able to support design decisions for improved patient experience.

2. MATERIALS AND METHODS

Some of the authors of the present paper previously carried out an explorative study [15] in the Neurology department of a Dutch hospital, specifically, Reinier de Graaf hospital in Delft. Monophonic sound recordings were captured at night in different four-patient rooms for 14 nights. Health tracking bracelets worn by the patients monitored their sleep and allowed time stamping all the significant arousals (or awakenings) as transitions from either a deep or light sleep stage to awake. This decision was made because, when compared to polysomnography - the gold-standard scientific method for tracking sleep - Fitbit technology has been shown to be accurate at identifying transitions from deeper sleep stages to awake but largely ineffective at differentiating between deep and light sleep stages. The data contains a total of 474 arousals. More details on the experimental procedures can be found in [15].

The full set of sound recordings and time-stamped arousals is the starting point of the present work. A thirty-second excerpt corresponding to the sound recording immediately preceding each single arousal event was extracted. Out of the 474 sound excerpts, we excluded 45 that had short silent gaps in the recording due to technical requirements. The remaining 429 sound excerpts were used for the following experiment. Their total duration is 3 hours, 42 minutes, and 30 seconds.

2.1 Study procedure

The ratings task follows the procedure of sound source annotations developed by two of the authors of this paper [16] for the evaluation of the urban soundscape during the COVID lockdown. An individually randomised sample of sound files was given to each of the participating annotators (see further below). Each file was opened using the Audacity® software with settings as follows: spectrogram (80 - 8000 Hz Mel scale), grayscale, and full-width and -height display. The annotators wore headphones (Audio Technica ATH-M70X or similar closed-back monitor headphones). Firstly, listening to several recordings the second and third authors identified nine basic categories for sound events in the sample. Note that in this context, 'sound source' and 'sound event' are considered as equal. They were labelled as: beep, breath, clothes, cough, footstep, furniture, mechanical, snore, speech. In addition, a rest category was included as: 'other (specify)'. This step was necessary to be able to provide a standard set of labels for the participants to annotate and rate in the following steps.

Annotators were instructed to mark as many sound sources as they could (aiming at around 6 to 15 in each 30–second recording), focusing on "sounds that you think could disturb somebody's sleep". In the Audacity® interface, they would select the start and end points of the sound event in the corresponding spectrogram using the 'Label' function (see **Fig. 1**).

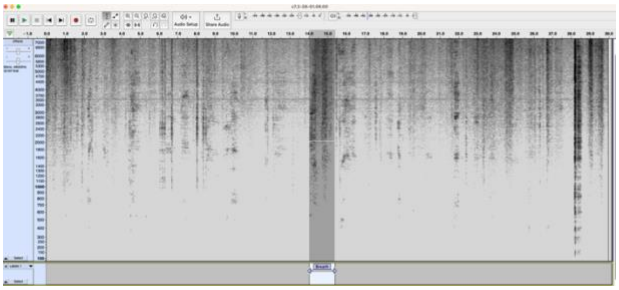

Figure 1. Spectrogram of a sound file with the selection and labelling process on Audacity®.

They were then asked to label each selected sound event using the nine categories provided (or the 'other'), and to rate the annoyance that each annotated sound source might cause. A three-step Likert scale was employed, with numerals 1, 2, and 3 referring to low, medium, and high perceived annoyance, respectively. We stress that annoyance was rated within the given category of sound and independently of loudness and duration. Hence, for example, 'breath 3' would indicate a highly annoying sound event, and more annoying than 'snore 2' even if the latter might very well be louder than the former; meanwhile, duration was captured by the label's end and start points. The three-step scale was adapted from the protocol developed by one of the authors in [17] to assess the Liking estimate (like/dislike) of sound sources in indoor (restaurant) soundscapes. Thus, annotators were instructed to add a number from 1 to 3 to the word label for each sound event in the Audacity® software and export all labels in text form.

2.2 Participants

Twenty-eight participants, here referred to as 'annotators,' were recruited to evaluate the 429 soundscape recordings. All confirmed being in normal health and having no hearing loss at the time of the task. In a first round, 18 participants were recruited by snowball sampling amongst undergraduate and research students currently in or having completed a sound-focused class. Their mean age was 26 years, with a range between 18 and 40, and consisted of 11 females and seven males. Their work lasted approximately 90 minutes. Two of them were excluded due to low consistency in performing the task. To assure high quality in ratings, we then recruited a second round of twelve annotators considered as expert raters (research students and assistants in the authors' labs, together with the authors themselves). Their mean age was 30 years, with a range between 24 and 55, and comprised 10 females and two males. The work took three to four hours. Taken under one, measures for the inter-rater agreement of the 28 annotators are reported further below.

3. RESULTS

In total, annotators identified 9296 sound events in the recordings. Raw annotations were tidied up (changing to lowercase, removing trailing blank spaces and non-letter symbols, correcting spelling mistakes, grouping by synonyms, e.g., snore-snoring or breath-breathing, and so forth) and allocated to the nine predetermined categories. In a small number of cases, the annotator had used the 'other' category. These were individually listened to by the researchers and interpreted in one of the predetermined nine categories or removed.
After this, the repartition amongst categories was as follows: 'snore' (47.0%), 'breath' (25.0%), 'furniture' (6.4%), 'mechanical' (5.9%), 'speech' (5.7%), 'clothes' (4.4%), 'footsteps' (2.3%), 'beep' (2.1%), and 'cough' (1.2%). In the next step, the nine sound types were allocated to two higher-level and non-overlapping categories (i.e., forming a taxonomic clade) following the procedure used in [15]. While the sounds 'breath', 'cough', and 'snore' entered a category for patient-generated sounds, the sound types 'beep', 'footstep', 'furniture', and 'speech' were considered as personnel-generated sounds. Sounds labelled as 'clothes' could have been generated either by personnel or patient movements and were not included in either. Finally, the personnel-generated sounds were subdivided based on whether they originated in behaviour ('footstep', 'speech') or the technical equipment that personnel use ('beep', 'furniture', 'mechanical'). This process yielded the classification illustrated in **Fig. 2**.

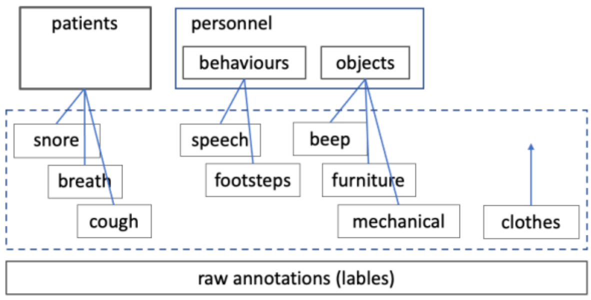

Figure 2. Schematic representation of a Taxonomy of Sound Sources in Hospital Wards.

To estimate inter-rater agreement among the annotators (N = 28), we extracted (for each annotator) the number of labels in each of the nine sound source categories relative to the total, as well as their cumulative duration relative to the total, as captured by the labels. Krippendorff's *alpha* (using the function DescTools::KrippAlpha in R, with interval scale) was 0.79 for label counts and 0.71 for label durations. While the evaluation of Krippendorff's alpha depends on context [18], we believe that the overall level of agreement among annotators in the present study can be considered as good. We also compared annotators by calculating Spearman's *rho* on the vectors pairwise. For the number of labels, the median correlation was 0.85 in a range [0.54, 0.90], and for durations, it was 0.80 in a range [0.37, 0.85]. These statistics support the decision to keep all the annotators for further analysis.

Recall that the annotators gave each labelled sound a value (1, 2, or 3) to indicate its level of annoyance (low, medium, or high) within that category of sound. In the following analysis, we treat the three levels as numerical values on a continuous scale. **Fig. 3** shows the distribution of annoyance for the nine predetermined sound categories.

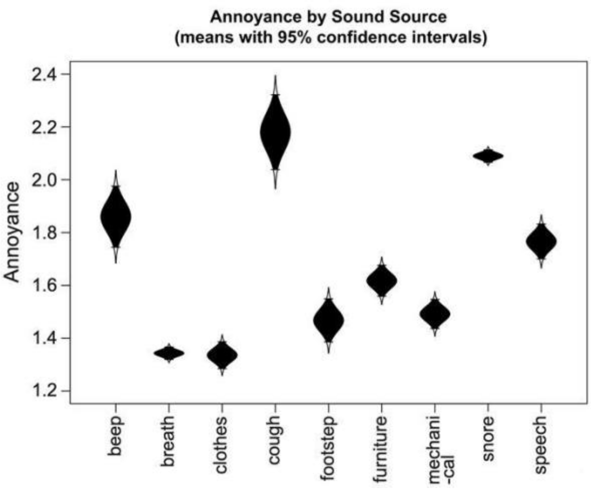

Figure 3. Violin plots of 'raw' annoyance ratings for sounds in nine categories.

Looking at the raw Annoyance values in **Tab. 1**, the highest scores were for 'cough' (2.8) and 'snore' (2.09). However, they were of different character: coughing appeared less frequently (1.2% of annotations) and were of shorter duration (1.42 seconds on average) than the very prevalent snoring (47%) that were typically longer (2.22 seconds). Slightly less annoying were 'beep' (alarms and other signals) and 'speech (almost exclusively communication amongst the nursing personnel). Similarly to the previous pair, their occurrence was different: beeps were less frequent and shorter than speech. The annoyance levels of sounds from furniture, footsteps, and mechanical were comparable, but the durations differed greatly. In fact, the category furniture included intermittent sounds such as the closing of doors, and mechanical included several occurrences of continuous background noise from air conditioners. Finally, the least annoying (yet still a potential cause for sleep disturbance) were sounds from breathing and the rustling of clothes, which were similar in terms of duration and frequency. These observations caused us to carefully consider the duration of potentially disturbing sound events. As mentioned, annoyance was rated for each sound event on a scale 1 to 3. Noting that the annotators used this scale slightly differently, we z-scaled the values within each annotator, putting the centre at 2 (corresponding to 'medium' annoyance) and giving the distribution a standard deviation of 1. Since the distribution of raw ratings within the annotator was always positively skewed, the variable scaled this way did not have a range of [1, 3] but instead [0.26, 10.9]; importantly, the interquartile range was [1.1, 2.9] which is indeed close to [1, 3]. We used this variable to operationally define two indices of the negative impact that sounds of different types might have on sleep. Firstly, *Integrated Annoyance* was calculated as the product of annoyance (scaled within each annotator) and the logarithm of the sound's duration. Secondly, *Cumulative Annoyance* was defined as the sum of Integrated Annoyance scores across its occurrences within a given time interval.

Table 1. Overall statistics for 9296 sound events labels in 429 night-time recordings. Integrated Annoyance is the product of Annoyance (scaled) and the logarithm of the sounds' duration; Cumulative Annoyance is Integrated Annoyance multiplied by Count, i.e., the total number of occurrences. The first nine rows are for the predetermined sound types, and the last three are for the higher categories, as defined in the text.

	Count	**Frequency (%)**	**Duration (seconds)**	**Annoyance (raw)**	**Annoyance (scaled)**	**Integrated Annoyance**	**Cumulative Annoyance**
beep	193	2.1	2.34	1.86	0.13	0.97	187
breath	2322	25	1.90	1.34	-0.43	0.56	1289
clothes	408	4.4	2.53	1.34	-0.49	0.92	375
cough	111	1.2	1.42	2.18	0.91	0.65	72

footstep	216	2.3	2.57	1.47	-0.32	0.94	203
furniture	599	6.4	1.46	1.62	-0.17	0.10	62
mechanical	551	5.9	8.21	1.49	-0.36	1.41	775
snore	4365	47	2.22	2.09	0.33	1.48	6442
speech	531	5.7	3.65	1.77	0.02	1.64	870
patients	6798	73.1	2.10	1.84	2.08	1.15	7804
behaviors	747	8.0	3.34	1.68	1.92	1.44	1073
objects	1343	14.4	4.35	1.60	1.80	0.76	1024

Tab. 1 shows the values of raw, scaled, Integrated, and Cumulative Annoyance for each sound category and the three higher-level categories (see **Fig. 2**) across the set of audio recordings. Human sounds (i.e., speech, cough, snore, and breath) were by far the most annoying sources (1.83 raw annoyance rate), followed by machine-related sounds (1.59). Sounds that refer to physical actions were characterised by intermittent and fairly loud events (such as a door closing, in the 'furniture' category) or repeated impulse sounds (such as footsteps), and were less annoying (1.50). Finally, breathing and clothing sounds, both typically with pink-noise characteristics and smooth dynamic envelopes, were perceived as the least annoying.

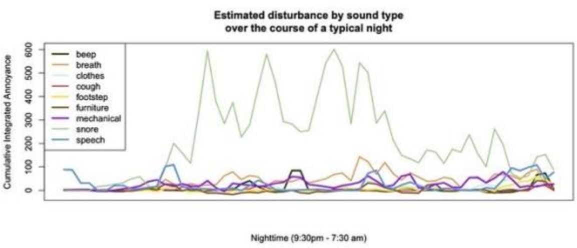

Figure 4a. Estimated disturbance of sounds in the nine categories during a typical night.

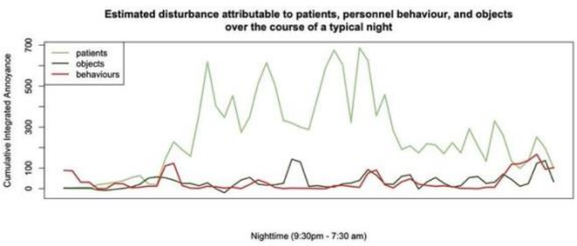

Figure 4b. Estimated disturbance of patient-generated sounds set against personnel-generated sounds (behaviours and objects) during a typical night. Values are accumulated Integrated Annoyance in time windows of 20 minutes with 50% overlap.

Fig. 4a illustrates how Cumulative Annoyance of different sound types developed over the course of a typical night (values accumulated in 30-minute windows), with snoring being by far the most annoying sound event, followed by breath, speech, and mechanical (**Fig. 4b**). The reader will recall that the sound samples analysed in this study immediately precede each single arousal as collected by the tracking bracelets. Therefore, the curves can be interpreted as an index of the probability that a given sound type caused a sleep disturbance at that point in time.

In an explorative time series analysis, we tested whether the present data might support the assumption that personnel-generated sounds cause patient-generated sounds (which, by extension, indicate disturbed sleep). Following the procedure outlined in [19] [20] the three curves in **Fig. 4b** were treated as time series. The series for patient-sounds was whitened to achieve 'weak stationarity', i.e., serial correlation was removed through ARIMA modelling with optimal coefficients. The residuals after fitting this series were then taken as the dependent variable in two successive Granger causality tests with the personnel-generated series for objects and behaviours, respectively, as the independent variable. Neither test was significant, so there is no evidence for causality among these variables in the current data. Further research might probe this matter more deeply.

4. DISCUSSION

In this study, we investigated sound-producing events and their relationship with perceived annoyance levels within a hospital ward during night-time. The primary goal of the study was to categorise sound events and understand how they relate to annoyance levels. We found that in a typical hospital ward at night, patients are likely to wake up to sounds from *patients* consisting of snoring, coughing, and breathing; and sounds from *nursing personnel,* either generated by them directly, as in talking and footsteps, or indirectly, as in medical alarms and other mechanical sounds (including air conditioning systems). They could also be awoken by sounds that come from the rustling of *clothes,* as in when patients move in their sleep, or when nurses are giving care (such as changing bed sheets). To model the differing likelihood that such sound events have for disrupting sleep, we focussed on their perceived annoyance level, duration, and frequency of occurrence.

Secondly, we gathered information on the distribution of annoying sounds to chart out a 'typical' night in order to identify sleep-disturbing sound sources. Estimates for annoyance were obtained for pre-determined sound categories and post-determined higher-level categories. The number of occurrences and duration of the annotated sounds, and their annoyance levels, were calculated to obtain Integrated and Cumulative Annoyance levels for each category as well as the three higher-level categories. Integrated Annoyance was then calculated in time windows over the nightly recordings (9:30 pm to 7:30 am) to obtain an estimation of sleep-disturbing sound events. Within the three higher-level categories, *personnel-generated behavioural sounds* have the highest level of Integrated Annoyance (1.44). Recall that Integrated Annoyance depends on the duration of sound events, as well as their perceived (Raw) Annoyance level (see **Tab.1**). This finding is critical in supporting design-driven interventions towards the improvement of patients' well-being in hospital wards. Sounds belonging to this category are, in fact, actively produced by nursing staff during their work routine (notably, speech and footsteps), and their potential to disrupt sleep increases as a function of their cumulative duration over time. As such, they can be actively mitigated to reduce their negative impact. Within the personnel-generated objects sounds, sounds generated by machines have a higher annoyance level. Even if sounds in this category occur less frequently than, for instance, furniture sounds, they tend to have a longer duration which is responsible for a higher Integrated Annoyance level. This might be due to the presence, within this category, of continuous sounds such as background noise generated by air conditioning and heating systems. Alarm ('beep') sounds, very often indicated as a critical source of discomfort for hospital patients and nursing staff [21], present low Cumulative annoyance. This is perhaps not surprising in the context of the ward under study, where alarms occur far less frequently than, for instance, intensive care units in which alarms represent a major health concern. In general, this is yet another evidence supporting the claim that the evaluation of the soundscape quality is highly context-dependent [22].

Preliminary experimental findings highlight an accumulation of snoring sounds rated with the highest Raw Annoyance level in the interval from 12:00 a.m. to 4:00 a.m. This might be due to contextual and environmental factors i.e., it is the time of the night when patients are in a deeper sleep state, and there is a very limited presence of other sound sources i.e., annotators might have tended to interpret as more annoying those sound sources that 'intruded' on the soundscape. This interpretation aligns with Lindborg's interpretation that noise sensitivity (a predictor of annoyance), as a self-report measure, captures an evaluative predisposition towards sounds rather than aspects of auditory processing or noise exposure *per se* [23]**.** To further validate this assumption, we will investigate the correlation between the level of annoyance by snoring sounds and loudness during the identified time slot, the annoyance level and loudness of co-occurring sounds, and other factors already identified in literature that characterise sounds that tend to disturb sleepers (e.g., continuous, impulsive, intermittent sound morphology and frequency spectrum [7, 8]). The highest sound annoyance is found between 3:00 am and 4:00 am. In this frame, a higher Integrated Annoyance for patients-generated sounds (breathing and snoring) corresponds to higher annoyance level for speech, which is a sound voluntarily generated by nursing personnel (**Fig. 4b**). This finding suggests a direct correlation between the increased occurrence of speech sounds and disturbance in patient sleep and as mentioned, its negative impact could be actively mitigated through behavioural-change interventions and training of nursing staff [24] [25], provided that nursing staff has access to information on the footprint of each sound category. Personnel-generated object sounds, such as furniture (e.g., doors opening and closing) can be addressed both as a medium-term behavioural change process. More interestingly, they can be addressed through medium-long term design strategies that need to engage the hospital management and industry stakeholders in defining broader guidelines that include the redesign of the architectural indoor space of hospital wards, the tools used by staff (such as delivery trolleys) and medical alarms.

Towards the end of our data collection timeframe, Cumulative Integrated Annoyance tends to grow for all the sound categories. Between 6:00 am and 7:00 am speech, furniture, beep, footsteps, and cough become more frequent and annoying (**Fig. 4**). This is most likely due to the progressive awakening of the ward's activity with the handover from the night shift, breakfast delivery to patients, cleaning, the start of the medical exams, all activities that will involve more communication and action-generated sounds. It confirms prior findings that hospital patients perceive their sleep to be inadequate mostly in the early morning [26].

5. CONCLUSIONS

The goal of this study was to gather empirical insights on the predominant sound sources in a hospital ward at night-time, their perceived annoyance level, and its correlation with disturbed patient sleep. The results will be used to inform the design and development of a computational model of annoyance by sound in hospital wards. The goal of the model is to provide nursing staff with increased awareness of the specific footprint of sound events in the context of hospital wards at night so that they can take action to mitigate the negative impact on patients' sleep. The main results highlighted that:

Cumulative Annoyance is highest for patients-generated sounds, such as snoring and breathing followed by speech sounds generated by nursing staff, which is an active, voluntarily produced sound source. According to the Cumulative Annoyance index, the snoring, breathing, and speech sounds have high annoyance levels, with snoring being by far the most annoying sound source. This is due to the higher number of occurrences, in our dataset, of snoring sounds. However, our analysis highlights that it is towards the reduction of nursing personnel behaviour-sounds, primarily speech, that a design-driven solution should focus, in order to sustain short- and medium-term mitigation strategies among the hospital staff.

Integrated Annoyance is highest for personnel behaviour sounds such as speech, patient sound such as snoring, followed by personnel object sounds such as mechanical. These findings fully confirm existing literature on the impact of speech and mechanical sounds on the hospital acoustic environment [24] [25] [27]. This is a key result since, while snoring is produced by patients in their sleep (and, as such, is emitted involuntarily), personnel-generated mechanical sounds are actively produced (mainly) by hospital professionals during their work. Previous research from some of the authors of this paper [10] [28] shows that hospital professionals are often unaware of their own contribution to the noisy sound environment and feel they have no control to change it. A novel technological solution that aims to increase the nurses' awareness of unwanted sounds (i.e., that can disrupt patients' sleep) will need to provide easy to understand information on what sounds are generated by nurses' behaviour that can be acted upon.

Speech (by nursing personnel) and snoring and breathing sounds (by patients) might be correlated, if personnel speaking causes patients to have a noisier sleep that is lighter and of lower quality. While these results confirm literature on sound-induced sleep disturbances [4] [29] [30], this assumption will have to be further explored by collecting new data within the specific timeframes and observations and interviews with the hospital's personnel.

Our findings on annoyance by sound during sleep will support a forthcoming phase of the study where we aim at designing an algorithm for the automatic detection of sleep-disturbing events in the context of multi-patients' hospital wards. The algorithm will integrate a comprehensive design-driven solution to increase awareness of the footprint of specific sound sources on patients' sleep quality and support actions to mitigate negative effects. We will also take a closer look at masking effects, such as when snoring (a broad-band noisy sound with a low-frequency centroid) masks breathing (which typically has a higher centroid).

6. ACKNOWLEDGMENTS

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