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Quieter and calmer than before: Sound level measurement and experience in the Intensive Care Unit at Erasmus Medical Center

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ABSTRACT

Intensive care units (ICUs) are the ultimate socio-technological environments known for their loud sound levels. Alarms, noise produced by patient support devices, loud conversations, physical interactions with tools and the environment in general contribute collectively to a sound quality generally perceived as low. This paper reports the results from a study conducted inside the old and new ICUs at Erasmus Medical Center, Rotterdam, the Netherlands. Sound level measurements have been collected continuously for three weeks in several matching rooms inside the old and new ICUs at full operational level at a one-year distance from one another. The results support the idea that changes in architectural layout, procedures, and culture have contributed to a significant decrease of the measured sound levels across all daily shifts, both inside patient rooms and in the nurse stations. We further discuss the results in light of a series of contextual considerations that emerged from interviews with healthcare providers (i.e., nurses and intensivists) who actively worked in both the old and the new ICU.

1. INTRODUCTION

Amongst socio-technological environments known for their loud soundscapes, intensive care units (ICUs) are often described as hostile as the sonic impact of healthcare technologies contradicts the healing function of its environment. Especially alarms, the noise of patient support devices, loud conversations, physical interactions with tools, equipment and the environment in general contribute to the cacophony in addition to the overall background noise

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from the air conditioning and weather conditions [1]. As a result, alleviating excessive noise in the ICU has become a mission for regulatory agencies, hospital management, and healthcare device manufacturers [2–4].

The noise problem in the ICU is well acknowledged worldwide thanks to advanced sound measurement tools that vary from professional SPL measurement tools to smartwatches and smartphones [5–7]. The long history of measurements of sound levels in the ICU motivates a common goal to observe sound reduction and it has been made aware that sound levels vary between different shifts (day, evening/late and night) carrying contextual information. Some measurements reflect the effect of an intervention and therefore compare the measurements before and after the introduction of a new protocol, an educational program, a technological intervention, change in staff behaviour, and even structural reconstruction [8, 9]. For example, Krueger and colleagues [10] describe structural changes such as reorganising the architectural layouts, and how they affected the sound levels. In a recent study, Carvalhais and colleagues [11] used a questionnaire to extract the causes of changes and measured the perceived quality of the sound environment by healthcare professionals discovering a major difference between before and after the structural intervention and layout changes.

In their seminal systematic review paper, Konkani and Oakley [1] conclude that the effect of sound and noise on staff performance or patient wellbeing is equally important to triangulate sound measurement, source identification, and psychological effect. Yet, identifying sound sources remains a main issue in this area [12, 13]. As a solution, researchers rely on recording the sound environment and having it retrospectively annotated by listeners (e.g., [14]) which is an arduous process and difficult to achieve in ICUs due to patient privacy concerns. In a rare human annotation study, Park and colleagues [15] revealed that more than half of the sound producing events (excluding the patient-involved sounds) were attributed to healthcare providers (57%) followed by alarms (30%) and the operational noise of life-supporting devices (13%). Amongst these, human-induced sounds contributed to the highest peaks in loudness.

Our own review of the future needs for sound measurement tools [16, 17] revealed that for effective noise mitigation, contextual sound source detection is required for two reasons. First, in order to determine the psychological effect of sound events, the conditions in which sound events occur need to be clear. Secondly, to prevent unwanted sounds on the work floor through behaviour change, healthcare professionals need actionable information regarding the appropriateness of the sound to the context. Therefore, we propose that in order to introduce sound-driven solutions that are listener-centric and have a positive effect on the acoustic environment (sound reduction or sound quality improvement), we need to gain insights into how sound and sound producing events in a functional environment affect healthcare professionals and their workflows [18].

In this study we aim to highlight the importance of contextual information regarding ICUs (function of healthcare professionals, shifts, time of day, caregiving activities and protocols, architectural layouts, medical devices, etc.) and accordingly demonstrate the use of a method that relies on listeners' account to interpret the acoustic, psychological, and social consequences of structural change on intensive care workflows.

Based in Rotterdam, Erasmus Medical Center (EMC) hosts one of the largest adult intensive care units in the Netherlands with 36 beds allocated to four sub-units. In 2018, the entire EMC moved to a new hospital which was designed to respond to the needs of modern medicine and caregiving standards. Figure 1 depicts how the ICUs looked before and after. In this paper, we present a before-and-after study by which we measured the sound levels in the old ICU and repeated the measurements a year later in the new ICU. Our research objective is to discover first whether there would be a drop in sound levels due to any changes in the new hospital (acoustic measurements) and secondly, if so, what contextual factors may have caused it (in-depth expert interviews). Thus, we used a mixed method approach as sound level measurements are not self-explanatory in identifying sound sources and events. As a follow-up, we relied on a human account on extracting from experts (nurses and intensivists) what sound producing events and activities changed between the two hospitals.

(a) Old ICU.

(b) New ICU.

Figure 1: Photos of the old and new ICU architectural elements. From left to right: nurse station, corridor, and patient room. The photos are property of the Critical Alarms Lab.

2. STUDY 1 - SOUND PRESSURE LEVEL MEASUREMENTS

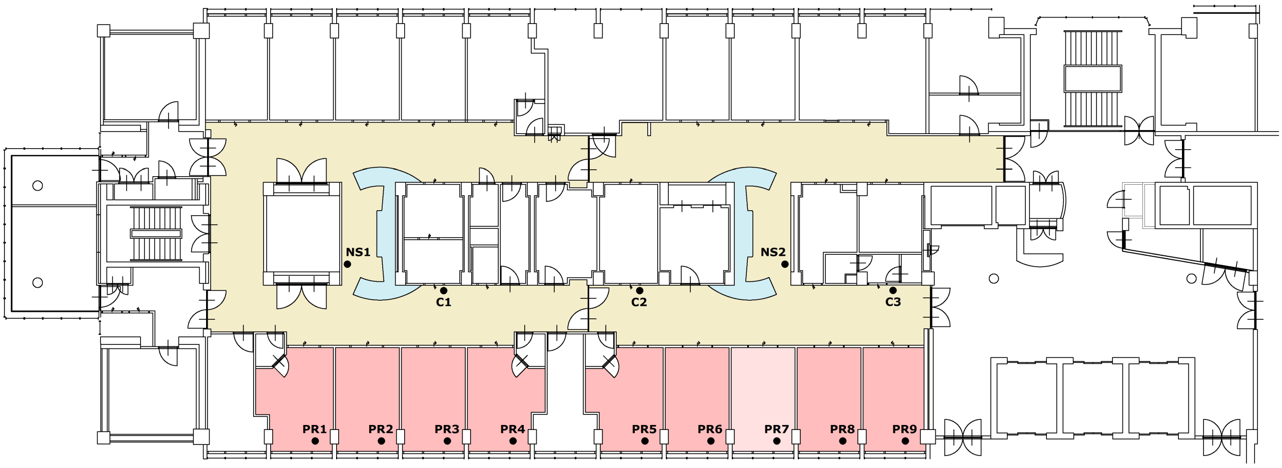
2.1. Measurement apparatus

Sound pressure levels inside the ICU have been measured with the help of the Quietyme system [19], a sensor system specifically designed for healthcare and communal settings. The Quietyme system comes with 16 identical sensor units to be directly plugged into standard power outlets, as well as a coordinator hub (a Raspberry Pi micro computer running the Linux operating system) that collects data from the sensor units via the Zigbee protocol at a rate of 1 kHz, and transmits them to the Quietyme servers via the Internet through an Ethernet port.

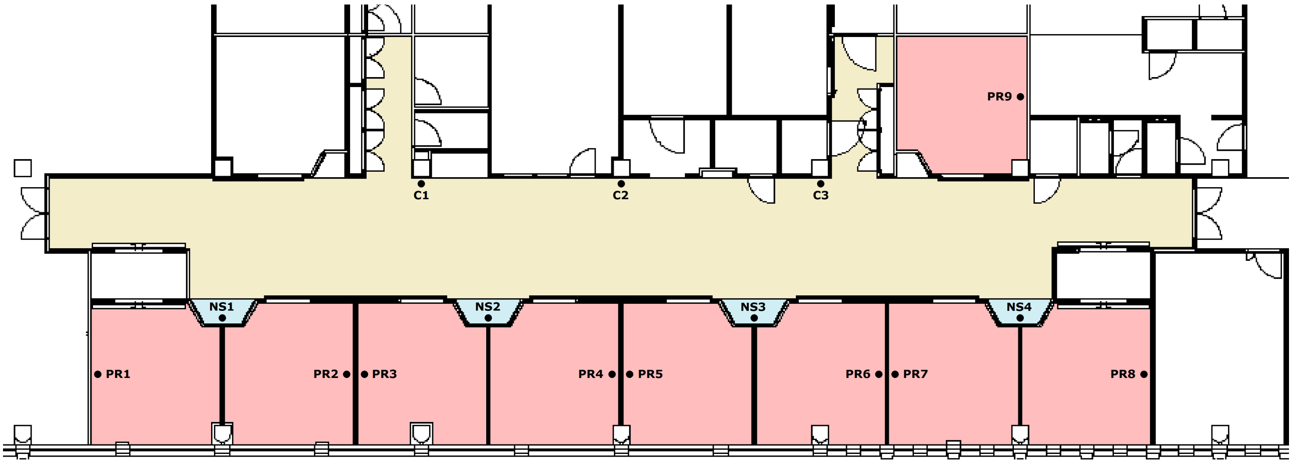
Each individual sensor unit includes sound level, light, temperature, and humidity sensors. For our study, we only considered data from the sound level sensors. According to the technical specifications from Quietyme, each sound level sensor outputs one Z-weighted peak dB value per second (hereinafter referred to as *SPL* value).

2.2. Measurement procedure

The 16 sensor units were installed in one of the units of the old ICU between the months of April and May 2018. Nine sensor units were placed in the patient rooms (one per room) and connected to power plugs just behind the patient beds. Two more sensor units were placed in each of the two nurse stations, and the remainder were placed in the corridor (3 sensors) and other rooms (2 sensors). The same setup was adopted in one of the units of the new ICU one year later between the months of April and May 2019, with the only difference that four sensor units were placed in each of the four nurse stations, leaving no sensors for rooms other than the nine patient rooms, nurse stations, and the corridor. In the remainder of this paper, only data from these three room types will be analysed. Figure 2 illustrates the exact placement of the sensor units on the planimetries of both the old and the new ICU.



(a) Old ICU.



(b) New ICU.

Figure 2: Planimetries of the old and new ICUs. Points mark the locations of sensor units installed in each of the three room types: NS = nurse stations (blue background), PR = patient rooms (red background), C = corridor (yellow background).

The sensor units collected SPL data continuously for three full weeks, from April 21, 2018 at 00:00:00 CET to May 11, 2018 at 23:59:59 CET (old ICU), and from April 20, 2019 at 00:00:00 CET to May 10, 2019 at 23:59:59 CET (new ICU). Patient rooms were at regular occupancy and nurse teams were kept the same both in the old and the new ICU.

2.3. Data preprocessing

Following an accurate inspection of the collected data, it was found that some had not been sent to the Quietyme servers due to unforeseen technical failures and temporary disconnections. These included (1) full data from a single patient room (PR7) in the old ICU; (2) data for part of week 2 and week 3 from two of the three sensors in the corridor in the old ICU; (3) data for two single shifts from a single patient room in the new ICU. While (2) and (3) have simply been considered as missing data in our following analysis, (1) implied that only eight patient rooms from the old ICU could be considered, as opposed to nine patient rooms in the new ICU.

For the sake of analysis, raw SPL data—collected every second from each sensor—were aggregated to yield minutely averages ($L_{eq,M}$), as well as averages by daily shift ($L_{eq,S}$). The three considered shifts are the night shift (22:45:00–07:29:59), the day shift (07:30:00–14:59:59), and the late shift (15:00:00–22:44:59). Since the raw data directly came in dB units, all averages were computed as log mean (rather than linear mean) values. In total, we were able to collect 1,740 $L_{eq,S}$ data points and 828,620 $L_{eq,M}$ data points.

2.4. Results

Figure 3 shows the distributions of $L_{eq,S}$ by ICU, room type, and daily shift. Each individual $L_{eq,S}$ data point refers to the equivalent SPL of an entire shift within a single room of that ICU and type. The number of available points for each different condition are reported in Table 1.

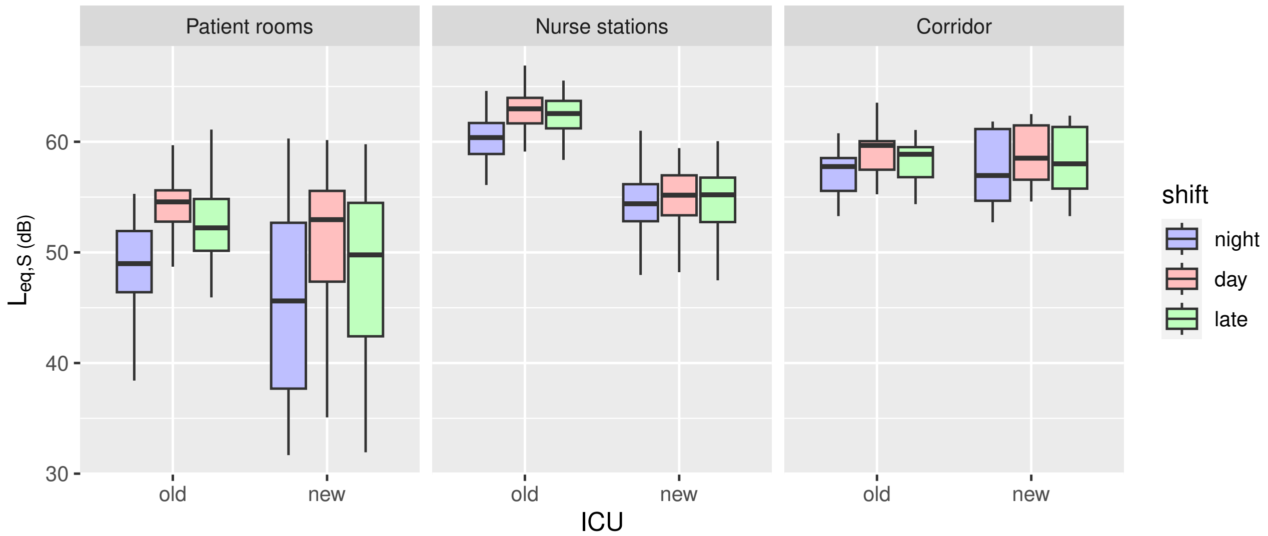


Figure 3: Boxplot of $L_{eq,S}$ by daily shift in the patient rooms, nurse stations, and corridor of the old and new ICU.

Table 1: Available $L_{eq,S}$ data points by ICU, room type, and shift (N=night, D=day, L=late).

ICU	Old									New								
Room type	Patient rooms			Nurse stations			Corridor			Patient rooms			Nurse stations			Corridor		
Shift	N	D	L	N	D	L	N	D	L	N	D	L	N	D	L	N	D	L
# points	168	168	168	42	42	42	34	36	34	189	188	188	84	84	84	63	63	63

In order to test for the effect of ICU (old/new) and daily shift on $L_{eq,S}$ for each of the three room types, we conducted three separate statistical tests. Since the data do not follow a normal distribution in any of the factor combinations, we chose to apply the Scheirer-Ray-Hare test, i.e., the non-parametric equivalent of a two-way ANOVA with replication [20]. For patient rooms, we found a strongly significant effect of ICU ($H = 36.83$, $p < .001$) and shift ($H = 140.7$, $p < .001$), with a non-significant effect of their interaction ($H = 4.48$, $p = .11$). Pairwise comparisons using Dunn's test with Bonferroni adjustment indicated that $L_{eq,S}$ values were significantly different between each pair of shifts (all $p < .001$). The test on nurse station data yielded similar results on the effect of ICU ($H = 229.45$, $p < .001$) and a lower yet significant effect of shift ($H = 6.07$, $p = .048$), with again a non-significant effect of their interaction ($H = .94$, $p = .63$). Pairwise comparisons indicated that $L_{eq,S}$ values were slightly different between night and day shifts ($p = .052$), with no other statistically significant differences. On the other hand, only the effect of shift ($H = 14.37$, $p < .001$) was found to be statistically significant for corridors, the effects of ICU ($H = .001$, $p = .97$) and the interaction ($H = 1.62$, $p = .44$) being non-significant. Pairwise comparisons indicated significant differences only between night and day shifts ($p < .001$).

Figure 4 shows the average $L_{eq,M}$ by time of day for patient rooms and nurse stations in the old and new ICU. Here, each individual $L_{eq,M}$ data point refers to the equivalent SPL of a single minute within a single room of that ICU and type. The figure reveals generally similar trends between the two hospitals, with a consistent average decrease in SPL in the new ICU compared to the old ICU at most times of day, aside from a few notable exceptions—see, for instance, the small peak at 19:00 in the nurse stations of the old ICU compared to a valley at the same time in the new ICU. In nurse stations, major peaks are found in correspondence of shift changes. The same peaks also appear in corridors (hereby not shown because of their low significance), where they represent the only notable feature. In patient rooms, higher levels are found during the day shift, with smaller peaks recurring approximately every two hours during the day and late shifts. These trends and differences are thoroughly analysed in the following section.

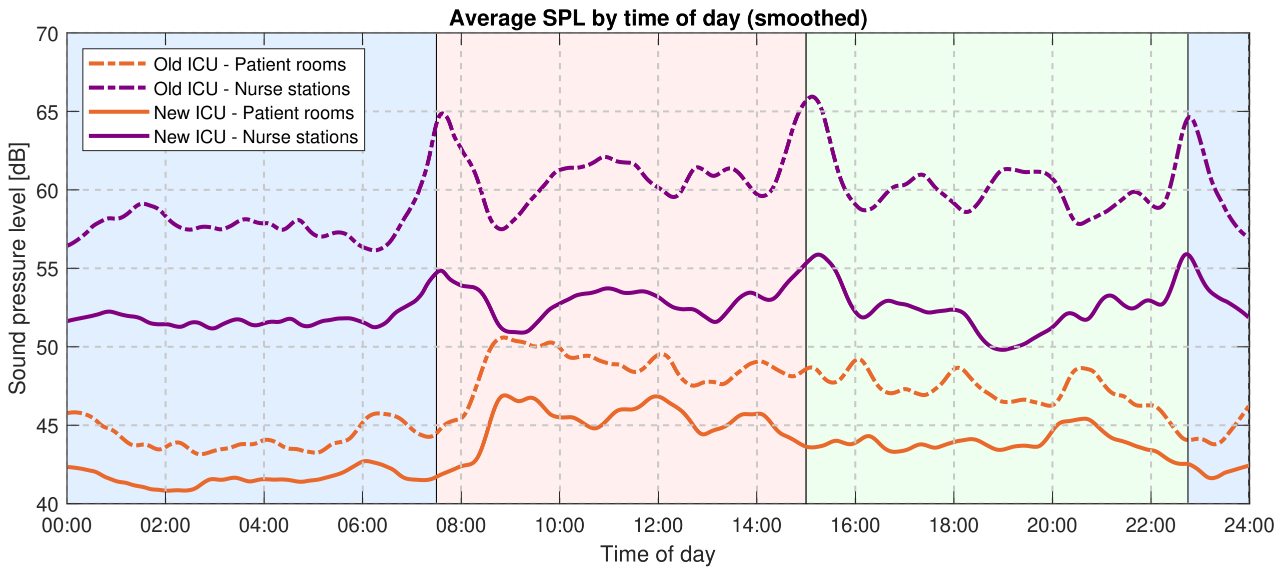


Figure 4: Average $L_{eq,M}$ by time of day in the patient rooms and nurse stations of the old and new ICU. For better readability, SPL curves have been smoothed with local regression using weighted linear least squares and a 2nd degree polynomial model. Background colours represent daily shifts: blue = night shift; red = day shift; green: late shift.

3. STUDY 2 - EXPERIENCE OF ICU SOUNDS

3.1. Expert interviews

The measured sound levels fail to clarify the sound experience inside the ICU. Therefore, we referred to the healthcare professionals of the Adult ICU (nurses and intensivists, i.e., doctors who specialise in intensive care) to explain from their account what might have caused the measured differences in sound levels. ICU nurses and intensivists are both familiar with the daily routine of the ICU and its physical environment and they can vouch for activities taking place in the unit.

We approached five healthcare professionals based on their professional background. Three interviewees were nurses and two were intensivists. The three ICU nurses had professional experience of 10, 12, 42 years and the two intensivists had professional experience of 13 and 15 years in the Adult ICU department of Erasmus MC. All participants had experienced both the old and the new ICU setups. The interviews took place between July and September 2022. This three-year delay with respect to Study 1 was due to the COVID-19 pandemic. All healthcare professionals had had 3> years of experience in the new ICU at the time of the interview.

The interviewees were instructed to reflect on Figure 4 by focusing on the differences in the sound level measurements taken in patient rooms and nurse stations. They were prompted by the interviewer if they were not able to spot the differences. Our research objective was explained to them as "we would like to understand the reduction in sound levels from the human perspective". They were asked to answer the main open-ended question "what may have contributed to the drop in the sound levels in your daily experience of the old and the new ICU?" by remembering how the daily activities were like in the old hospital and make a comparison with the new hospital. Their reflections started with the patient rooms followed by nurse stations. The interviewees were free to choose to start from any shift they preferred. The interviews lasted between 17 min and 35 minutes. All interviewees gave consent to participate in the study.

3.2. Data collection and analysis

Data was collected via in-person interviews at Erasmus Medical Center Rotterdam in a quiet office room. The interviews were recorded on the online meeting platform Zoom. Audio files were then transferred to the Microsoft 365 Word Online platform for its voice-to-text function. After extracting the transcribed verbatim text, we cleaned up the transcribed interviews of interjections, repeated words, and grammar as spoken English language was at times incomplete.

Then, we identified the main aspects the interviewees deemed important from their own perspective. These findings are collected and presented in Figure 5. Our aim was to be able to annotate Figure 4 with input from healthcare professionals; thus, we only used the quotes that best describe the main contributors to the change in sound levels from a human account. However, the interviews were also rich in content describing the daily routine of the nurses and intensivists. Therefore, we will present the findings in two folds: daily routines that shape the overall sound levels of the ICU, and experts' reflection on the decreased sound levels in general.

3.3. Results: General layout and routine of the ICU

Routines of nurses vs intensivists. The interviews pointed out that nurses and intensivists have different routines and nurses are the main users of the unit by circulating between the patient room and nurse stations in all the three shifts. Intensivists are the most active in the day shift after the handover between 9:00 and 12:00, when they do the rounds with nurses to visit each patient and check their daily status. There are four intensivists in the day shift and only one on duty in the late and night shifts. All handovers take place in the corridors. It was also clear that the daily caregiving activities hardly changed except for the delivery of medicine which is now prepared by pharmacists and nurses only administer it in patient rooms. Medication is administered every six hours and 6:00 and 18:00 are the main medication moments. The main routine events are changes of shifts when nurses and intensivists arrive at work and enter the unit, and visits to patient rooms every two hours. The last visit of each shift is reserved for a final check up and other medical activities. The morning shift requires cleaning activities (8:15 and 10:00). The night shift has bedtime routine (20:30 and 23:00). Visiting hours are between 11:00 and 21:00. It is clear that the routines of nurses and intensivists have a major impact on the ICU sound levels. Changes of shifts are the loudest moments in nurse stations with peaks at 7:30, 15:00, and 22:45 during the handover moment with twice as many healthcare professionals interacting with each other and with the environment. Nurses' morning visits with intensivists to the patient rooms also show an increase in sound levels in patient rooms. There is also a reverse relationship between the measured sound levels for nurse stations and patient rooms: when nurses are in the patient room,

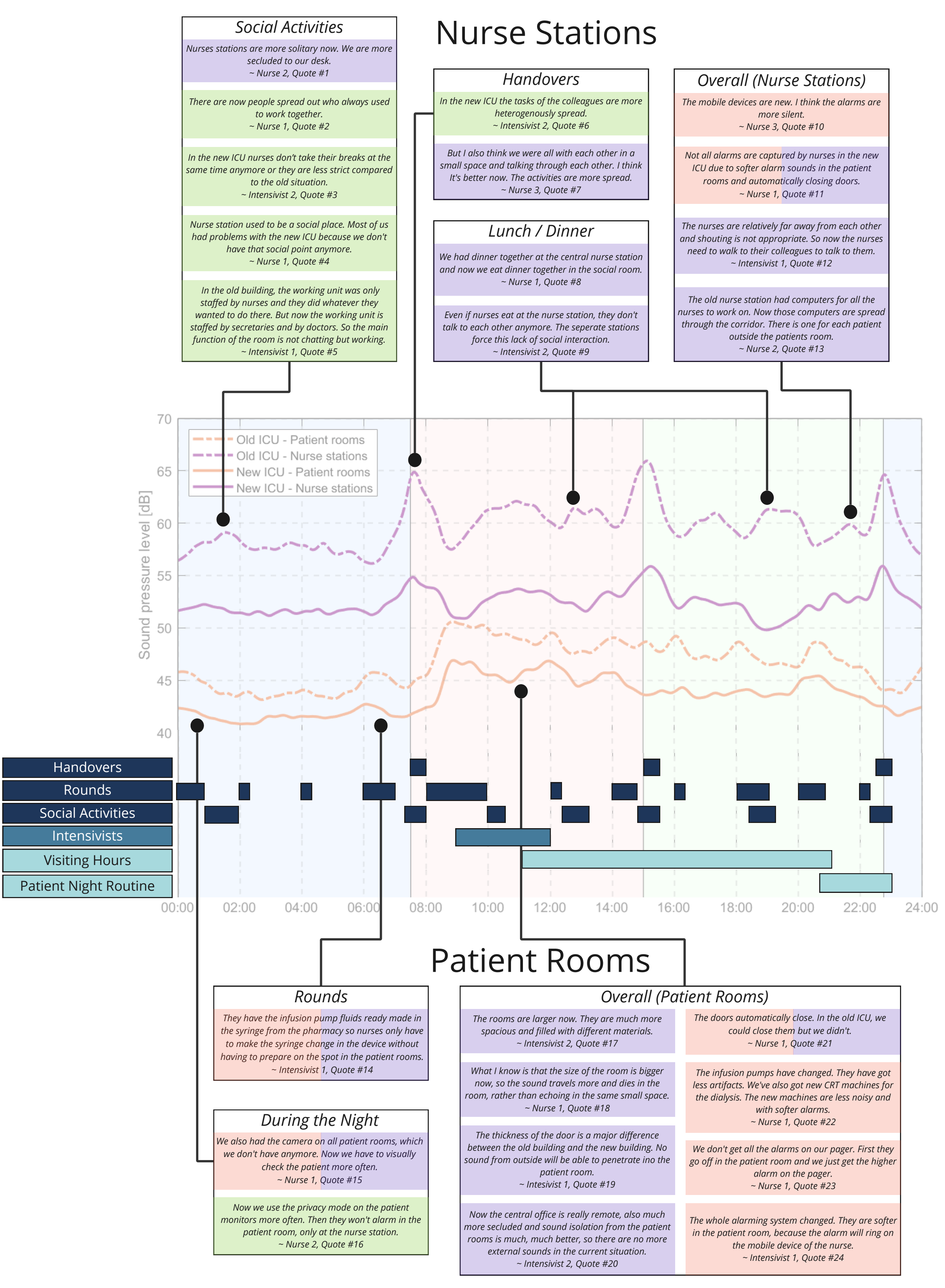


Figure 5: The results from the expert interviews: typical daily timeline and quotes (purple background: layout/architectural change; green: culture change; salmon: technological change).

the sound levels in the patient rooms increase and sound levels in nurse stations decrease and vice versa when nurses are in nurse stations. Between 21:00 and 2:00 is the quietest moment of the day in patient rooms (with a small peak at midnight due to the regular nurse visit) in line with the night routine of the patients.

Architectural layout and active spaces. The layout of the ICU at Erasmus MC is mainly planned around single patient rooms, nurse stations, office, pharmacy, and a social room (in addition to the nurse leaders' office and intensivists' office which are located outside of the unit). Nurses and intensivists circulate between these rooms mostly occupying the nurse stations and patient rooms, followed by the sporadic use of the office and social room. The difference between the old and the new ICU is the size and quantity of these rooms and splitting of the nurse stations. Currently, instead of two large central stations that served two units, now there are five nurse stations per unit each shared by two nurses, and one main office and a pharmacy in the middle of two different units. The social room is now large enough to accommodate nurses from four units and is located outside of the units. Each new patient room is about twice as big as the old one. Moreover, in the old ICU patients were monitored by a camera and nurses observed the patient remotely in the central nurse station while still being with their peers eventually increasing the sound levels in nurse stations. In the new ICU, a nurse station is attached to a patient room and has a direct view to the patient which also further encourages the nurses to stay close to the patient and away from their peers. These layout and size changes possibly play a role in the distribution of sound waves, having an impact on the overall sound level.

Nurses are sociable workers around their strictly planned activities. Every shift starts with a handover meeting which is scheduled at 7:30, 15:00 and 22:45 at nurse stations. Regardless of their shift, nurses do their rounds to visit patients every two hours. Nurses have lunch at around 12:30 and dinner at 19:00, mostly collectively. In between their tight schedule and duties, nurses enjoy being together and do activities that keep them busy, especially in the night shift. This is an important aspect as social and leisure activities (e.g., reading, studying, chatting, and watching something together) allow nurses to keep themselves awake and active especially at night. Nurses regularly meet in the corridor to have coffee together at least once a shift. The social aspect of the lunch and dinner times has an observable impact on the sound levels. In the old ICU, there is an increase in the sound levels during lunch and dinner times. In the new ICU, often lunch and especially dinner is eaten outside of the ICU in the social room. If the nurses eat in the unit, they do it at their individual nurse station. These two aspects are most likely to explain the differences in sound level trends between the old and new ICU.

3.4. Results: Reduction in sound levels according to healthcare professionals

New spaces offer new habits. The interviewees believe that the new architectural layout drastically changed their social interactions. Being in one central nurse station allowed them to be together more often (Quotes 2, 4). Their workstations being separated forces them to be more independent (Quote 7). The tasks are now more heterogenously spread (Quote 6). Teams also became more sound-conscious (Quote 12). Nurses' work is also more solitary as everyone has their own computer and are close to their assigned patient (Quotes 1, 13). The office space in between is frequently used for discussing their work or patient care which removes the sound from nurse stations (Quote 5). Therefore, the significant overall drop in sound levels in nurse stations are attributed to the aspect of working separately at a distance. There are less breaks together (Quote 3). Lunch and dinner are eaten outside of the unit which, according to the interviewees, is the reason for the drop in sound levels in nurse stations approximately at 13:00 and 19:00 (Quotes 8, 9). Thus, the new eating routine especially made the nurse stations quieter between 12:00–14:00 and 18:00–20:00. In the current ICU, dinner time has become the quietest moment of the day.

Air-tight doors make a quiet patient room. Much of the work and social activities naturally take place in the corridors. It was also evident in our measurements that the sound levels of corridors did not change. Both nurses and intensivists highlighted that currently, the patient rooms are equipped with electric doors that automatically close very tightly, which ensures that the patient is protected from the noise outside (Quotes 11, 19, 21). The significant drop in the overall sound levels in patient rooms are mainly attributed to this.

New medical equipment emits less sounds. According to the intensivists and nurses, new infusion pumps and dialysis machines were introduced that emit less sound and therefore are quieter (Quote 22). As the majority of the patients are connected to infusion pumps either for receiving medication or fluid nutrients, these devices are used daily and continuously. Moreover, interviewees also mentioned that the alarm forwarding and delivery system has changed in the new ICU and a new mobile system is now being used, meaning less and softer alarms in patient rooms (Quotes 10, 23, 24). Both of these technological interventions possibly contribute to the reduction in overall sound levels.

Less noisy nurse visits. The sound level measurements in the old ICU indicated a peak pattern in the patient rooms every two hours (e.g., 2:00, 4:00, 6:00, etc.). Measurements in the new ICU present a less pronounced pattern. One of the reasons for the reduction is likely the new medication pharmacy routine by which the required medicine is prepared by pharmacists and delivered by nurses (Quote 14). The introduction of this new routine allows for less activity and less time spent in patient rooms which results in less sound producing events eventually reducing the sound levels at the time of the main nurse visits (6:00–7:00, 13:00–14:00, and 20:00–21:00). Interviewees also suggested that the larger size of the new patient room plays a role in dampening sound (Quote 17, 18). The main reason is likely to be the automatic doors which shield patients from the corridor noise when nurses enter and stay inside patient rooms (Quotes 11, 19, 21). Nurses often silence patient monitors using the privacy mode at nights, forwarding alarms to their nurse station or mobile devices (Quote 16). Now, nurse stations are right next to patient rooms allowing a direct view to the patients (Quote 15) which also reduces the visits to patient rooms.

4. DISCUSSION

We set out to observe reductions in sound levels in the Adult ICU of Erasmus MC after moving to a modern hospital and wanted to explain the possible changes in sound levels with the input from nurses and intensivists who have had daily experience with sound producing events in the old and the new ICUs. The comparison of sound level measurements indicate that the new hospital is significantly quieter than the old hospital, both in nurse stations and patient rooms. Nurse stations measure on average 9–10 dB less on the daily peaks (i.e., shift changes) and 10–12 dB less at lunch and dinner times; patient rooms measure 3–4 dB less overall and nurse visits every two hours are significantly less pronounced in the measurements. The corridors showed no significant change.

The expert interviews identified three main topics that contributed to the reduction in sound levels: new architecture (layout and fittings), introduction of new medical devices, and change in the team dynamics. The larger architectural plan with a distributed layout split or eliminated the sound sources in the most noise-prone spaces (i.e., nurse stations). The new automatic doors isolated the patient rooms from corridor sounds and especially the regular nurse visit became quieter. The new medical devices emit softer sounds and alarms in addition to the new alarm distribution system which allows for silencing alarms in patient rooms while emitting softer alarms on mobile devices. Finally, and very importantly, nurses' team dynamics changed in the new ICU. They work more separately, stay close to their own nurse station, discuss topics in the central office, and also socialise less only with one coffee break per shift in the corridor and their dinner and lunch either at the nurse station or in the social room outside of the unit.

According to the experts, these changes affected how they work in an acoustic environment despite minimal changes in their daily routine imposed by management. Their interpretation is that structural changes forced them to adjust their behaviour into the needs of the new environment. They are now more sound conscious but also isolated at times. They feel that their work is more solitary with less social activities which creates a focused and calm environment around their nurse station. Nurse stations have become their work space which makes them visibly connect to patients and their needs encouraging less alarms in patient rooms. Yet, they also feel more uncertain with their activities as help and support is not always around the corner.

5. CONCLUSIONS

Our mixed-method study demonstrated the richness of information we were able to gather from expert interviews with the healthcare professionals. While sound level measurements guided us in identifying the time frames in which a reduction took place, expert interviews detailed the physical environment, daily routines and activities indicating possible causes of sound reduction and unravelled the mixed feelings the experts experienced as part of the structural change towards a new acoustic environment. Our findings support the ongoing work with soundscapes: That is, to truly understand the effect of acoustic environments on its listeners, soundscape researchers need to explore the experience of soundscapes beyond physical measurements that only depict the physical experience of sound. Our study contributed by highlighting the importance of studying the context and situations from different perspectives and the need for sound source identification in context as a requirement for evaluation of acoustic environments.

We also conclude that reducing sound is not limited to noise mitigation in sound-producing electronic products, it is a collective effort with behaviour change required of the healthcare professionals as much as a corporate effort to purchase quieter equipment, introduce less noisy caregiving protocols, and possibly change the architecture.

We are limited by the fact that we lack information regarding architectural design decisions (e.g., insulation) and material choices (e.g., flooring). These factors unknown to us must have contributed to overall consistency in sound level reduction. Our measurement method also had limitations as we were not able to capture sound levels with advanced measurement devices. However, our method allowed us to remotely and continuously monitor the sound environment. The resulting sound levels still accurately depicted the relative change of sound levels between the old and the new ICUs and allowed us to annotate the possible causes with the help of healthcare professionals. Following this study, we developed a new research line "Auditory Footprints" to be able to accurately capture sound events in an ICU with the help of sound computing methods.

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