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Annoyance by Alarms in the ICU: A Cognitive Approach to the Role of Interruptions by Patient Monitoring Alarms

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Abstract

Nurses rely on patient monitoring systems for care delivery in ICUs. Monitoring systems communicate information to nurses and alert them through audiovisual alarms. However, excessive numbers of alarms often interrupt nurses in their tasks, and desensitize them to alarms. The affective consequence of this problem is that nurses are annoyed and feel frustration towards monitoring alarms. This situation leads to stress on nurses and threatens patient safety. Literature on sound annoyance distinguishes between annoyance induced by bottom-up (perceptual) and top-down (cognitive) processing. Extensive research on perceptual annoyance informs us on how to alleviate the problem by better sound design. However, addressing the cognitive aspect requires a broader understanding of annoyance as a construct. To this end, in this paper we distinguish between the annoyance induced by sensory unpleasantness of alarm sounds, and annoyance induced by frequent task interruptions. We present a conceptual framework in which we can interpret nurses' annoyance by monitoring alarms. We further present descriptive analysis of the occurrence frequency of patient monitoring alarms in a neonatal ICU to illustrate the current state with regards to alarms. We aim to support nurses' organizational well-being by providing an alternative hypothesis to explaining nurses' affective states caused by auditory alarms. Future research can benefit from this paper through understanding of the context and familiarizing with the cognitive processes relevant to processing of patient monitoring alarms.

Introduction

Intensive care unit (ICU) nurses deliver care to patients by observing and evaluating patients' condition, assisting doctors in their assessments, administering treatment, and supporting all-round recovery. Through their workflow nurses rely on patient monitoring systems to observe the vital parameters and changes in patients' status. Rapidly advancing technologies have allowed us to monitor an increasing number of

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parameters. Patient monitoring systems display vital parameters visually. Information about emerging medical and technical conditions, such as vital parameters exceeding thresholds or sensors getting detached, are communicated to nurses through audio-visual alarms. Consequently, with the increase of the number of measured parameters, the number of alarms in the ICU has also increased (e.g., monitoring blood oxygenation rate, ventilating patients, connecting patients to dialysis machines). Alarms are designed to attract attention and prompt action. However, up to 90% of alarms have been identified as false or non-actionable (Cvach, 2012; Deb & Claudio, 2015; Siebig et al., 2010). Consequently, they often interrupt the workflow without benefiting care delivery. This situation can result in desensitization; inducing stress in nurses and posing threats to patient safety (Lewandowska et al., 2020; Özcan & Gommers, 2020; Wilken et al., 2017). As a result, the affective outcomes are annoyance and frustration towards alarms (Cho et al., 2016; Sowan et al., 2015). Despite the research on solution strategies to mitigate problems related to alarms, there has not been a gratifying improvement until now (Sowan et al., 2016; Yue et al., 2017). In this paper, we present a conceptual framework of cognitive annoyance supported by a data collection from eight patient monitors in the Erasmus Medical Center ICU. With this framework, we aim to inform system design to support organizational well-being of nurses.

Research to support healthcare industry in challenges related to alarms has been ongoing for several decades. Studies mostly focus on improving (psycho)acoustic characteristics of alarms to make them less annoying (Foley et al., 2020; Sreetharan et al., 2021). Indeed, psychoacoustic characteristics such as sharpness, roughness, loudness, and tonalness have been shown to influence sensory (un)pleasantness of alarm sounds (Zwicker & Fastl, 1999). However, research indicates that acoustic characteristics only explain a small portion of variance in annoyance ratings. In fact, several psychological and contextual factors, such as noise sensitivity or time of day, have been shown to play larger roles in annoyance by sounds (Janssen et al., 2011; Paunović et al., 2009; Pierrette et al., 2012). Consequently, research indicates that there are two aspects to annoyance; perceptual and cognitive (Guski et al., 1999; Sreetharan et al., 2021). The perceptual aspect of annoyance relates to (psycho)acoustic characteristics of sounds, which induce annoyance in a bottom-up processing manner. On the other hand, influences by top-down processing are categorized as cognitive annoyance and relate to the disturbing effects, such as frequent repetitions or task interruptions (Zimmer et al., 2008). As stated, an inventory of knowledge on perceptual predictors of annoyance exists; however, mechanisms of cognitive annoyance remain unexplored. We believe the persistence of the alarm annoyance problem, despite all the efforts and extensive research, stems from the knowledge gap in understanding of nurses' cognitive needs during interaction with the monitoring system. Sounds may be well designed but poorly positioned within the workflow, therefore causing annoyance.

In this paper, we aim to identify the mechanism underlying nurses' annoyance of patient monitoring alarms. We argue that alarms are annoying to nurses on a cognitive level due to the conflict they pose in their information processing; rather than simply being unpleasant sounds. To support this hypothesis, we present data of an IC unit that captures the current situation of interruptions that nurses experience.

Cognitive Annoyance

In our approach, we frame cognitive annoyance as the negative feeling induced by a sound that is the result of the cognitive processing of the sound; rather than its perceptual qualities. In the following section, we present a series of cognitive processes that take place during nurses' interaction with patient monitoring alarms, and attempt to explain the potential reasons to nurses' annoyance of them. We consider the interruptions caused by alarms as a form of conflict in information processing, which is a well-established theory in the field of cognition (Botvinick et al., 2001).

Alarms in Human Information Processing

While tending to alarms is an essential part of nurses' workflow, the excessive number of alarms limits the time and attention for other clinical tasks. Furthermore, high rates of false alarms burden the cognitive load without requiring immediate action. In the field of cognitive science, the negative impact of task interruptions is well known. Interruptions are highly costly to performance and cognition: they increase reaction time, error rates, anxiety, annoyance, and perceived task difficulty (Bailey et al., 2000). This can be interpreted using the Human Information Processing model (HIP) (Figure 1, adapted from Wickens), which explains how the mind receives and processes physical stimuli (Wickens et al., 1992). The first stage of HIP is *perception* in which incoming physical stimuli are received by the senses, and formed into basic perceptual elements. In the case of patient monitoring alarms, this is when sound waves are received by the ears and turned into electrochemical signal for further processing. Within this stage, basic features of sounds (e.g., frequency, amplitude) are detected as perceptual elements that gives rise to psychoacoustical evaluation of alarms (e.g., sensory unpleasantness caused by loud or sharp tones). The second stage is *cognition*, in which meaning is attributed to perceptual elements. This stage involves evaluation of current information against prior knowledge, and decision making on the basis of meaning within the context. Attention is engaged to selectively direct resources to relevant stimuli and task related motor functions. For the processing of alarms, this stage involves an evaluation of the alarm to determine its source (e.g., oxygen saturation, or device such as mechanical ventilator), meaning (e.g., too much oxygenation), and actions it requires (e.g., reduce the oxygen intake by adjusting the dosage). Finally, the *response* stage is when a reaction to the physical phenomenon occurs. For alarms this can involve a physical action (such as tending to the patient or to the device for adjusting settings), or simply deciding the alarm is not relevant and therefore ignoring it.

Conflict in Human Information Processing

Attention is a limited resource, as also exemplified in the HIP model (Figure 1). When multiple stimuli are competing for the same resource, a conflict occurs. Resources must be shared between competing stimuli, limiting availability and therefore impairing performance. Different modalities engage different resources, so the degree of overlap between the competing stimuli influences the loss in performance (Wickens, 2008). Monitoring alarms initially engage visual and auditory resources for perception, then cognitive resources for processing, and finally motor resources for response. Within the workflow, nurses are often engaged in various clinical tasks, to which alarms add competition with ongoing tasks. It might often be the case that several alarms are generated within one unit at the same time, inducing further conflict to information processing.

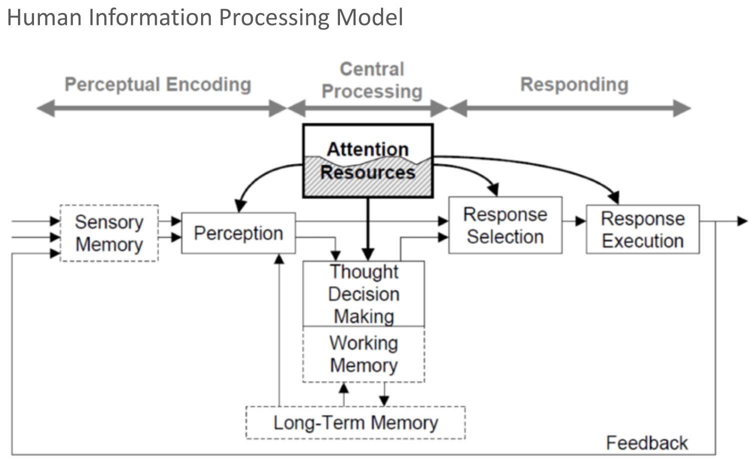

Figure 1. Human Information Processing Model (adapted from Wickens) demonstrating the processing of physical stimuli by the human mind. Consists of main stages: perception, cognition, and response. Note that attention is depicted as a limited resource.

Conflict in information processing is most commonly demonstrated by Stroop task (Stroop, 1935). In this paradigm, participants are asked to name the colour of the ink a word is written in aloud, disregarding the word itself. In congruent trials, ink colour matches the semantic meaning (“blue” written in blue); while incongruent trials demonstrate a mismatch (“blue” written in red). Incongruent trials involve higher error rates and increased reaction times. This is due to the competition between the response of reading the word and the response of verbalizing the ink colour. Both responses demand resources, resulting in a conflict.

Conflicts signals are well established to be instrumental for cognitive functioning. The mind monitors the degree of conflict in the environment, modulating level of cognitive control to match the demands (Botvinick et al., 2001). Remarkably, research indicates that conflicts are further registered as aversive signals (Dignath et al., 2020; Dreisbach & Fischer, 2012). Meaning that even in neutral and arbitrary conflicts such as the Stroop task, where the conflict holds no personal or emotional significance, people perceive it as negative affect. Therefore, the mind can be thought to keep count of conflicts in information processing and registering them as negative signals on a micro scale.

Conflict Resolution

Tasks competing for the same resources create bottlenecks in information processing (Broadbent, 1958). In order to complete both tasks, one must either multi-task or switch task. Mechanism underlying multitasking is modelled by the Threaded

Cognition Theory, which draws the analogy of a thread for each 'train of thought', or task-related processing (Salvucci & Taatgen, 2008). The theory posits that multi-tasking, even when seemingly concurrent such as talking and writing at the same time, is actually a serial process in which processing related to both tasks are sequentially alternated on a range of milliseconds. According to this view, threads are executed by favouring the least recently processed thread to balance performance outcomes. However, more recent research indicates that people have personal preferences in task prioritization (Jansen et al., 2016). When multiple arbitrary tasks are competing for resources, individual preferences influence which task is prioritised for serial processing. By rapidly alternating between multiple tasks, bottlenecks in information processing are resolved with minimal loss in performance.

Despite the efforts to attenuate the loss in performance, switching between tasks is still costly. Task switching is well known to increase error rates and reaction times (Monsell, 2003), and multi-tasking increases stress levels (Appelbaum et al., 2008). Remarkably, performance costs are less during voluntary task switching compared to involuntary task switching (Douglas et al., 2017; Vandierendonck et al., 2010). This phenomenon is thought to be due to anticipation of approaching conflict in the case of voluntary switching, in which elevated cognitive control alleviates the loss. This means frequent task-switches and periods of multi-tasking threaten the efficiency of workflow while burdening the cognition.

Annoyance by patient monitoring alarms

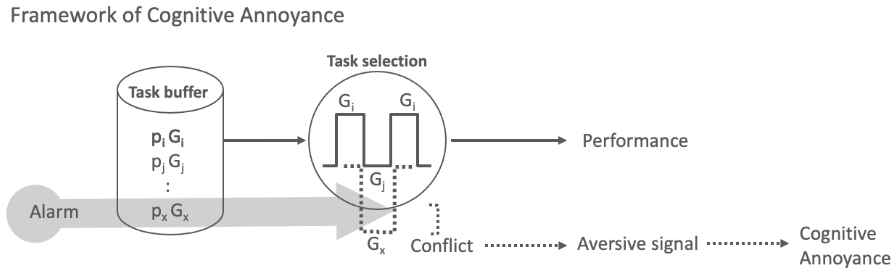

Figure 2. Schematic representing alarms inducing new tasks into the central processor. Each alarm adds a new, involuntary task (Gx), and over burdens cognitive resources. (p) is the prioritization coefficient of each task. While people have personal preferences on task prioritization, alarms, by design, override other tasks. Alarms have varying priority weights based on whether they are high, medium, or low level of priority. More task demands than available resources create conflict. Conflicts are registered as aversive signals. Accumulation of conflict signals is experienced as annoyance. Adapted from Jansen et al. (2016) with permission.

In light of the series of cognitive functions presented above, in this section we will attempt to describe how nurses might get annoyed by patient monitoring alarms. In the ICU, each new alarm imposes a new task for the nurse. Even a false alarm still requires re-allocation of perceptual and cognitive resources to identify them as false alarms, and potentially motor resources to silence the alarm. Each alarm induces a new thread to the multi-tasking processor. Therefore, alarms interfere with ongoing tasks and require frequent task switching. Discrepancy between available resources and demands induced by multitude of tasks induces conflict in information processing, and triggers aversive signals. Since task-switches are not voluntary but imposed by alarms, they are more detrimental to cognition and performance. Consequently, we hypothesize that nurses' annoyance of monitoring alarms is an accumulation of aversive conflict signals in information processing. A schematic explanation is portrayed in Figure 2.

Data Collection

In order to quantify the frequency of alarms in the ICU and establish a description and understanding of the context, a data collection was conducted in Erasmus Medical Center, Rotterdam in the Netherlands between March and April 2022. All output from the patient monitoring system was recorded in a neonatal intensive care unit (NICU). Monitoring system automatically logs all events, so we accessed the logs to draw the data set. This study focused on alarms generated solely by the patient monitoring system. All other devices that generate audiovisual alarms, such as infusion pump or ventilation device, were not included in the analysis.

The neonatal unit contains eight patient beds in an open layout; where all beds are located close to each other and facing towards a central nurse station. This means all the alarms generated within the unit are audible to all the health care providers and patients in the unit. Nurses work in three shifts: morning, afternoon, and midnight.

Results

In a span on one month, 25 different patients were registered to the unit over different periods of time. Distribution of number of alarms per patient through the month is indicated in Figure 3. During this period, 83.023 alarms were recorded in total. Mean number of alarms per day in the unit was 2594.69, SD = 866.15. Minimum daily alarm count was 1296, and maximum was 4451. Median number of alarms generated by one patient was 1460, with a minimum of 100 and maximum of 13405.

Number of generated alarms fluctuated throughout the day. An hourly distribution of number of alarms summer over the month is presented in Figure 4a. On average, there were 111.45 alarms an hour, SD = 49.24. Minimum number of alarms per hour was 2, while maximum was 332. A frequency distribution of alarm counts per hour is presented in Figure 4b. While approximately 100 alarms per hour was the most commonly observed case, it was possible to observe over 300 alarms per hour.

Number of alarms peaked between 8:00-9:00. This period is known to be patient handover and the start of the morning routine. Patients are cleaned and daily check-ups are performed, in which sensors may get detached and trigger alarms. This is further exemplified by examining the condition that generates the alarm. Alarms were categorized into medical (those triggered by vital parameter measurements, e.g., blood oxygenation threshold exceeded, asystolie), and technical alarms (those related to the monitoring system and devices, e.g., sensor detached). Overall, 82.62% (68593) of alarms were of medical events, and 17.38% (14430) were technical events. Zooming into the time window of 8:00-9:00; 77.08% were of medical events (3377) while

22.92% (1004) were technical. This indicates more device related technical alarms were generated during the morning rounds compared to the daily averages.

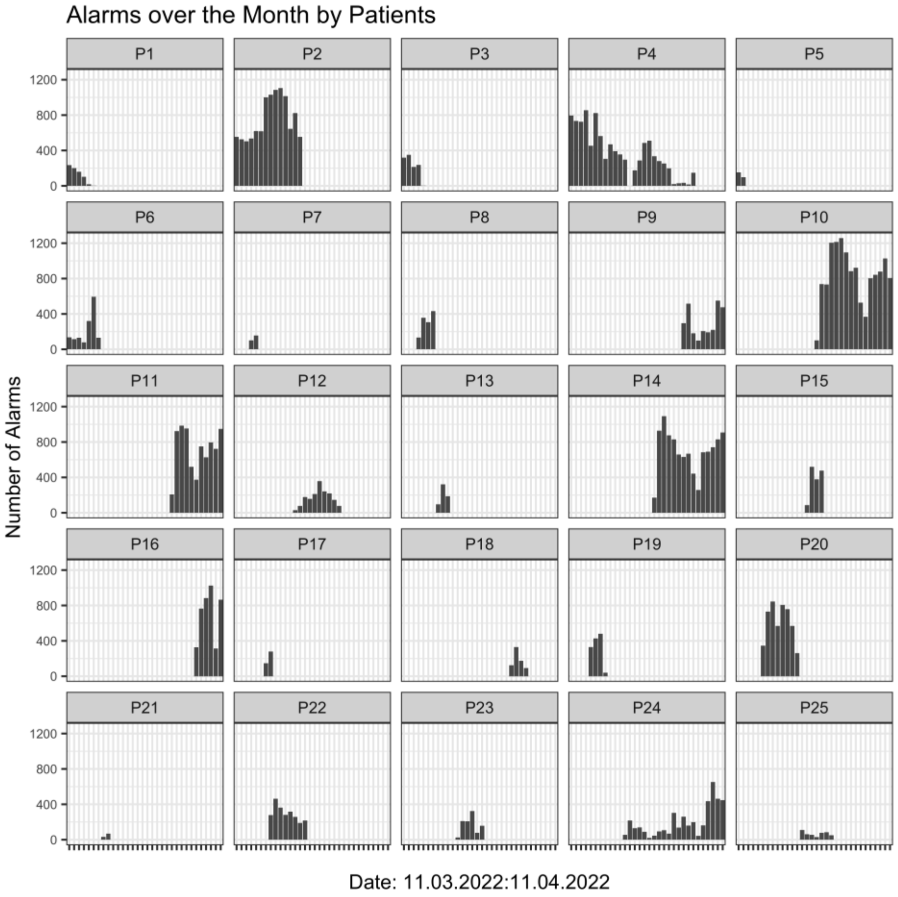

Figure 3. Number of alarms generated by each patient over the month. While some patients stay for longer periods of time; some are discharged quicker, as can be observed from the number of bars representing one day per patient.

We investigated the differences between morning, afternoon, and midnight shifts. Summarised over the patients, a daily average of 1151.84 (35.81%) alarms were generated during morning shifts, 1135.16 (32.67%) during afternoon shifts, and 1033.92 (31.52%) during midnight shifts. The number of alarms per shifts was converted into proportions for each shift and patient. These proportions were analysed by a within-subjects General Linear Model with shifts as the within-subjects factor of 3 levels. Wilk's Lambda was used a multivariate test, $F(2, 23) = 2.71$, $p = .087$. However, contrasts between levels showed a significant difference, in which there were more alarms in the morning shift (.36) compared to the midnight shift (0.32), $F(1, 24) = 5.65$, $p = .026$.

By medical standards, alarms are categorized into high, medium, and low levels of priority. Exploring the output from the patient monitor, majority of the alarms were medium priority (76.91%), while 12.97% were low priority, and only 10.05% were high priority alarms. High and medium priority alarms were often originated by medical conditions, while low priority alarms were often due to technical conditions (Table 1).

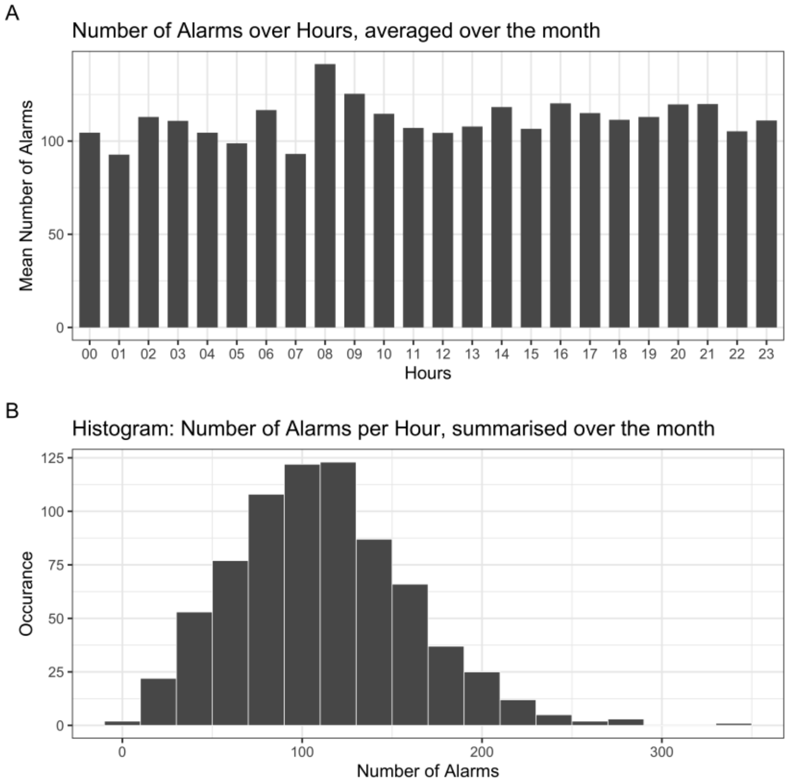

Figure 4. (A) Hourly distribution of mean alarm counts over the day. Number of alarms generated peaks around 8:00-9:00. (B) Frequency distribution of count of alarms per hour. While approximately 100 alarms per hour is commonly observed, it was possible to observe over 300 alarms per hour.

Table 1. Number of alarms per level of priority and alarming condition. Numbers are presented along with the percentage of the condition within one level of priority.

	Alarming Condition	
Level of Priority	*Medical*	*Technical*
Low	224 (2.08%)	10547 (97.92%)
Medium	60215 (94.22%)	3697 (5.78%)
High	8154 (97.77%)	186 (2.23%)

We investigated the variation among individual patients. Proportions of alarm priority levels and causes of alarms varied by patients. Distribution of priority levels for each patient is displayed in Figure 5a, and distribution of alarming condition is displayed in Figure 5b. Figure 5a demonstrates that the majority of alarms were medium priority for most of the patients. However, more low priority alarms were generated by certain patients (e.g., P6, P18, P19). Figure 5b illustrates that these patients also generate relatively high proportion of technical alarms. This indicates that these patients are relatively more mobile than others, resulting in more sensors getting detached and therefore generating more technical alarms.

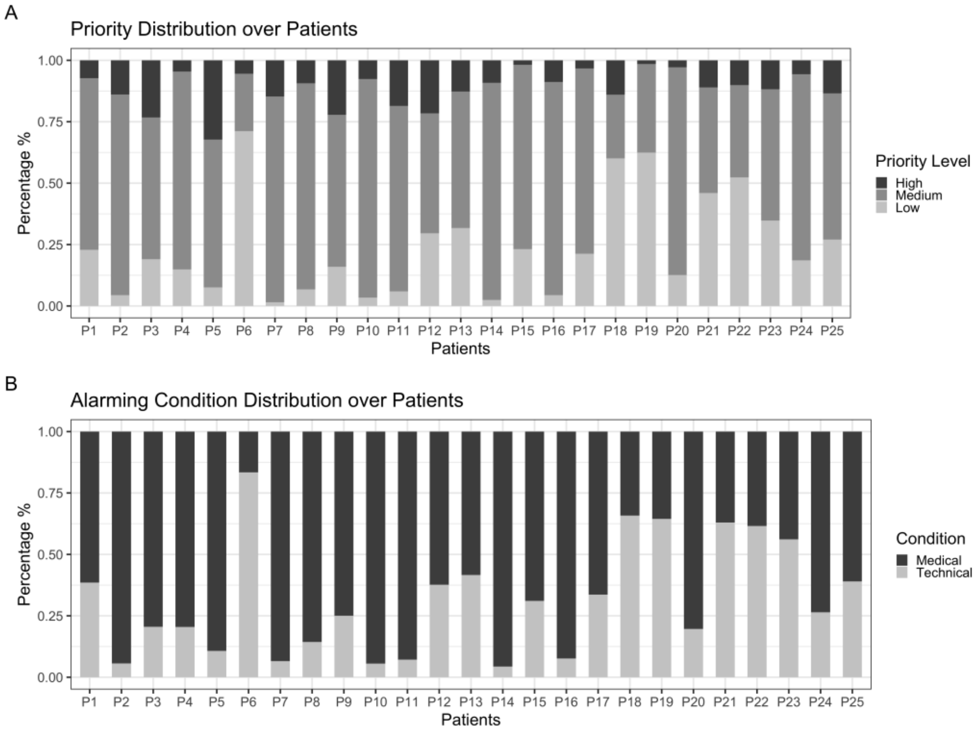

Figure 5. (A) Stacked chart of alarm priority level distribution per patient. (B) Stacked chart of alarming condition distribution per patient.

Vital parameters that generate the alarms were analysed to investigate which medical and technical conditions were most relevant for this IC unit. The patient vital parameter that generated most of the alarms was oxygen saturation level (SpO$_2$, 56.81%), followed by electrocardiogram (ECG, 10.43%) technical alarms. A breakdown of number of alarms by alarming vital parameter is presented in Table 2.

Table 2. Breakdown of vital parameters which trigger the alarms. Threshold refers to the alarm being triggered by vital parameter exceeding the set threshold; while technical refers to technical alerts such as artifacts, or sensor being detached. Parameters that occur less than 1% of the time are aggregated as 'other'. SpO2: oxygen saturation, ECG: electrocardiogram, HR: heart rate, RRi: impedance respiratory rate.

	Percent	*Count*
SpO_2 threshold	56.81%	47162
ECG technical	10.43%	8658
SpO_2 desaturation	9.19%	7631
HR threshold	5.41%	4491
SpO_2 technical	5.35%	4444
HF threshold	5.21%	4327
RRi threshold	3.21%	2665
Temperature threshold	2.05%	1699
RRi technical	1.43%	1186
Other	1.00%	760

While the number of alarms presented so far represent the alarming instances, alarms are often audible for longer periods of time. Therefore, the auditory stimuli present in the IC unit is in fact more prevalent than the number of alarms indicate. To capture this, we analysed the duration of alarms. Excluding the outliers where alarm duration was greater than 180 seconds, median alarm duration was 10 seconds, mean was 22.81, and SD = 30.85. A histogram of alarm durations is presented in Figure 6a. Alarm durations differed for levels of priority. High priority alarms had a mean duration of 14.15 seconds, medium alarms had mean of 25.54, and low priority alarms had a mean of 13.77 seconds (Figure 6b). Alarm durations also varied by the vital parameter that generates the alarm. Mean duration in seconds per parameter is presented in Figure 6c.

Cumulative number of alarms in the unit represent the total auditory stimuli in the environment. While the alarms are audible within the whole unit, each nurse is responsible for tending to the alarms generated by the patient assigned to them. To capture the demand of responsibility, we analysed the number of alarms generated by each patient during one shift. Averaged over the month and patients, mean number of alarms generated by one patient during one shift was 123.90, SD = 78.71.

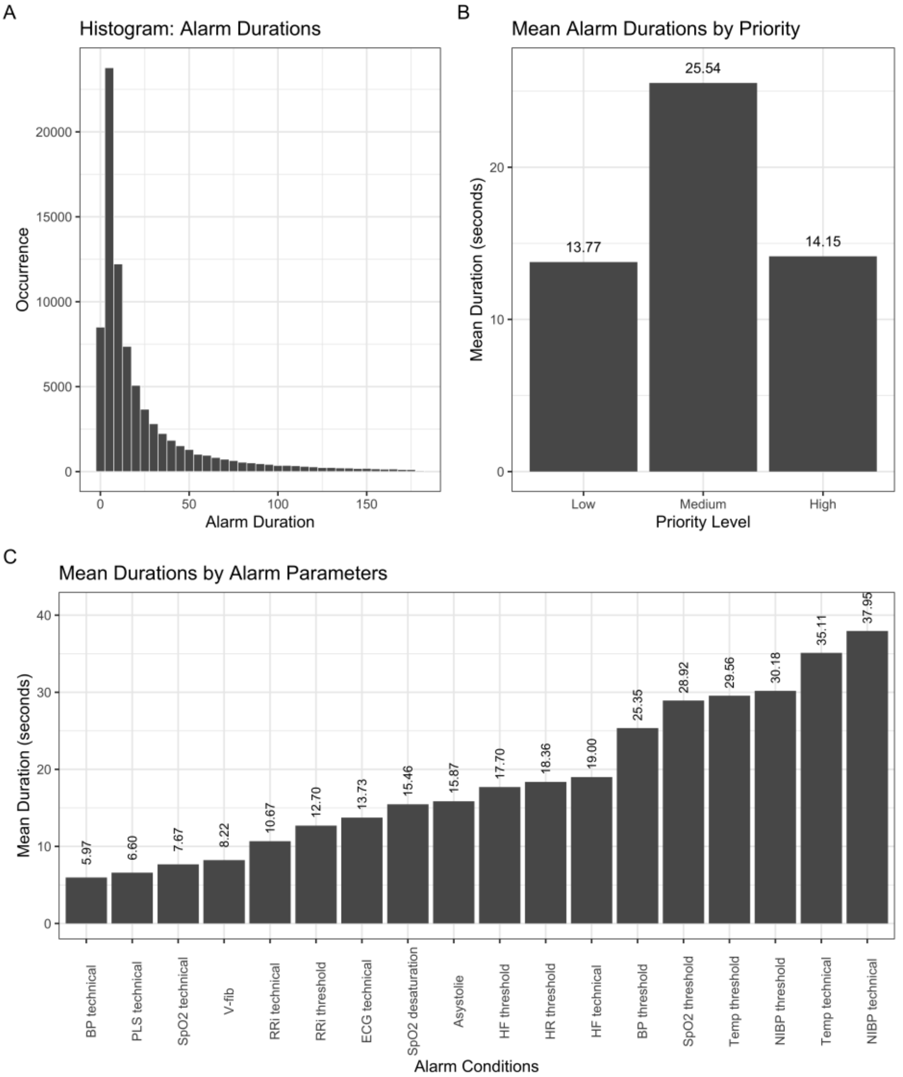

Figure 6. Alarm durations in seconds, outliers greater than 180 excluded. (A) Histogram of alarm durations. (B) Mean alarm durations by alarm priority levels. (C) Mean alarm durations in seconds by vital parameters.

Discussion

Our results of the output from patient monitors demonstrate the prevalence of alarms in the ICU. Realizing the excessive number of alarms helps us understand the experiences of ICU nurses within their workflow. Our results show that almost two alarms per minute were generated in the unit, and one patient generated an alarm every 3.22 minutes. Average duration of alarms was over 20 seconds, indicating that alarms are almost constantly audible in the IC unit. These results paint a clear picture of the auditory stimuli present in the unit as experienced by nurses and patients. The majority of studies aiming to improve patient monitoring alarms has focused on the acoustic characteristics of alarm sounds (Edworthy et al., 2018; Foley et al., 2020; Schlesinger et al., 2018; Sreetharan et al., 2021). While efforts to improve the sound design of alarms will benefit the sensory experience, our results make it clear that the main cause of the problem is the excessive number of alarms. This number indicates the frequency by which nurses are interrupted in ongoing tasks. Consequently, we argue that the understanding of the cognitive mechanisms of the processing of alarm sounds is more important to explain the experienced annoyance. In our framework, each interruption burdens the cognitive resources by creating conflict in information processing. As conflicts are experienced as aversive signals by the mind, each interruption adds to the feeling of annoyance towards patient monitoring alarms in nurses. Therefore, we argue that efforts to improve nurses' organizational well-being requires an approach beyond enhancing the alarm sounds. Consideration of nurses' cognitive needs, capabilities, and preferences is needed to improve the information communication between patient monitoring systems and nurses.

More specifically, our analysis of the generated alarms reveals potential points to improve system design. Results demonstrate that high priority alarms are the least occurring alarms, which is the only type of alarm that requires immediate action. Low and medium priority alarms constitute the majority of alarms. These can be reduced in number by human interventions (such as customizing alarm limits), or by improvements in the system design (such as smart algorithms to prioritize and eliminate alarms). Most commonly observed cause for alarms was related to blood oxygen saturation level, which is typical for neonatal patients. Interventions that target the optimization of blood oxygen saturation monitoring can yield considerable improvement in the number of generated alarms.

We found that there is a large variation in the number and type of alarms generated by each patient. Currently, the settings of the monitoring system remain similar for each patient. However, the distribution of vital parameters that generate the alarms varies over patients. This can be explained either by the patients' medical status (relatively stable or critical), or by the frequency of movements. Patients who move around frequently cause sensors to become detached more often, leading to more technical alarms. The same effect is also visible in the reduced number of alarms during night shifts. Patients are more likely to be sleeping during the night; and there is a reduced number of lights, sounds, and general activity during night time; leading to fewer alarms generated. Such differences in patient characteristics, and conditions surrounding the patient could be an input for the monitoring system to supress non-actionable alarms based on current needs.

For essential events that do need to be notified to the nurse, literature has suggested methods to minimize the negative consequences of task interruptions. These involve methods to design smart algorithms to prioritise alarms. This can be achieved by context aware computing that supress notifications based on location signals or certain periods of time, and user aware computing that generates notifications based on attentional cues from the user (Ansari et al., 2016; Bailey & Konstan, 2006; Welch, 2011). These methods aim at notifying the user to system conditions on particular moments where the interruption is thought to yield the minimum negative effect on performance and cognition. By understanding the cognitive mechanisms that make patient monitoring alarms annoying to nurses, we can employ design strategies in a targeted manner to minimize these effects.

In this paper, we suggested a framework in which accumulation of aversive conflict signals caused by interruptions are experienced as annoyance towards monitoring alarms (Figure 2). Our theoretical framework opens up new directions for future research. One of these is to measure annoyance when task interruption is induced by another modality, since different modalities require different resources. Another intriguing direction would be to build up on the research suggesting increased costs for involuntary task switches compared to voluntary switches. This difference is thought to be caused by anticipation of conflict (Vandierendonck et al., 2010). Endsley (1995) indicates that anticipation is an important factor in Situation Awareness. This aspect is often overlooked in the interaction between nurses and patient monitoring systems. Investigating the role of anticipation on annoyance ratings can present insights into how nurses handle (un)expected information presented through alarms. This knowledge would then inform design of the interaction between the system and the nurse as a user. These aspects will form the basis of our future research activities on cognitive annoyance in ICUs.

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