INVESTIGATING ALARM FATIGUE WITH ALARMVR: A VIRTUAL ICU FOR CLINICAL ALARM RESEARCH

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ABSTRACT

Alarm fatigue, wherein healthcare providers can become desensitized to alarm events due to extended exposure, is the root cause of one of the top health-technology hazards. However, investigating this phenomenon in clinical environments can be problematic due to privacy concerns and the risk of interfering with patient care. In this paper, we report the results of a preliminary survey conducted to understand current alarm conditions in clinical environments across the University of Michigan. Furthermore, we discuss our efforts to document such environments with 360º video and Ambisonic audio recordings. We then describe the implementation of a virtual ICU, namely AlarmVR, which is designed to facilitate research into clinical alarms and the auditory factors contributing to alarm fatigue. The proposed system enables healthcare professionals and audio practitioners to engage with alarm design to understand the acoustic parameter space of clinical alarms in terms of their perceived urgency. We detail the implementation of the system and outline possible use cases for it in research and instruction.

1. INTRODUCTION

Alarms are integral to clinical environments. Alarm fatigue, a condition where healthcare providers can become desensitized to alarm events due to extended exposure, is considered to underlie one of the top health-technology hazards [1, 2]. However, investigating this phenomenon in clinical settings can be problematic due to the risk of compromising patients' privacy or interfering with their care. To facilitate research into clinical alarms and the auditory factors that contribute to alarm fatigue, we designed AlarmVR, which is a virtual ICU implemented in three phases.

In the first phase, we used 3D panoramic video and Ambisonic audio to document a real-life training ICU to establish an immersive audiovisual benchmark for an alarm-heavy environment. In the second phase, we conducted a survey with healthcare professionals to probe the current alarm conditions across various critical care facilities at the University of Michigan. In the third phase, we developed AlarmVR based on the information gathered from the first two phases. The resulting system is a room-scale virtual ICU, where we can rapidly deploy a range of alarm conditions and log users' preferences, activities and reaction times.

In this paper, we provide details of our immersive documentation of an actual ICU and report the results of our survey, discussing how these efforts informed the design of AlarmVR. We then give an overview of the AlarmVR system and discuss its interactive and immersive affordances. Finally, we discuss possible scenarios where this system can be utilized as an immersive simulation platform for instruction and research in healthcare.

2. RELATED WORK

There is an extensive body of work that investigates the relationship between the acoustic properties of alarms and their perceived urgency. In one of the earlier studies in this area, Edworthy et al. carried out listening tests with psychology students and found fundamental frequency, speed, rhythm and melodic structure, among other parameters, to have consistent effects on the perceived urgency of an alarm sound [3]. Furthermore, they observed various interactions among parameters: For instance, changes in fundamental frequency prompted different degrees of perceived urgency when the alarm onset was altered. In a following study, Haas and Edworthy further confirmed that increased pitch and loudness contribute to faster response times [4].

Previous studies have utilized surveys with healthcare professionals and medical trainees to identify root causes of alarm fatigue in clinical environments [5, 6]. The factors that affect the audibility, identifiability and perceived urgency of alarms that are specific to clinical environments have also been extensively studied. In 2003, Mondor and Finley conducted a study on clinical alarms and found that the perceived urgency of these alarms were not proportional to the urgency of the clinical situations that they indicated [7]. In a recent study, Schlesinger et al. evaluated the effects of signal-to-noise ratio (i.e., that between alarm sounds and clinical background noise), and found that operator performance can still be maintained with alarms that are softer than the background noise [8]. In another recent study, Bennett et al. identified auditory icons (i.e. sounds that can function as metaphors for the events that they represent) to improve the identifiability and discernibility of alarm sounds in clinical settings [6].

Going beyond acoustic properties, such as loudness and pitch, researchers have also investigated the musical properties of alarms [9]. Drawing from music cognition research, Gillard and Schutz conducted experiments on the effects of melodic content on alarm identifiability, and found that alarms with musically distinctive features can improve alarm identification performance [10].

Recently, Özcan et al. have proposed a collaborative approach to clinical alarm design [11]. They argue that the actors operating in clinical settings, such as clinicians, patients and visitors, should actively inform and participate in the design of alarm sounds before such sounds are deployed in such settings. Promoting a human-centered approach to medical alarm design, the researchers argue that a co-participation of the stakeholders should take place in living lab environments, where alarms conditions naturally occur.

Following a similar approach, we utilize VR to create a virtual ICU, where auditory factors that contribute to alarm fatigue, and how alarms are perceived in general, can be investigated *in virtual situ*. The platform presented here, which is under ongoing development, allows us to incorporate healthcare providers into the auditory study of medical alarms in a virtual context without having to interfere with patient care in actual clinical settings.

3. PRELIMINARY SURVEY

We conducted a survey to evaluate the current alarm conditions in various clinical facilities across the University of Michigan and to understand some of the acoustic factors that contribute to how healthcare professionals perceive and react to clinical alarms. The survey contained written, graphical, and ranked-choice questions as well as a listening section that asked participants to compare hypothetical alarm sounds in terms of their perceived urgency.

3.1 Participants

19 participants completed the survey. The average age of the participants was 39.3 (SD=9.29). Among the participants were 8 physicians, 8 registered nurses, 1 nursing student and 2 certified registered nurse anesthetists (CRNAs). None of the participants reported having impaired hearing.

3.2 Results and Discussion

3.2.1 Reactions to Nuisance Alarms

Alarms that are accurate yet clinically insignificant are called nuisance alarms [12]. These alarms indicate non-actionable conditions that can distract the providers from patient care. As seen in Fig. 1, when asked to rate the frequency of actions taken to minimize distractions caused by nuisance alarms, the participants most frequently selected“check patient” (M=5.11, SD=0.30) and “resolve the alarm” (M=4.84, SD=0.30), [5.00 aligning with *Often* (71-90%)]. In decreasing order of frequency, other actions included “ignore alarm” (M=3.21, SD=0.34), “request assistance” (M=2.89, SD=0.29), “turn down volume of device” (M=2.84, SD=0.33), and “replace device” (M=2.68, SD=1.26) [3.00 aligning with *Not Often* (11-40%]. Participants reported “turn off device” (M=1.74, SD=0.18) as the least frequent action performed to minimize distractions, aligning with *Very Rarely* (≤10%).

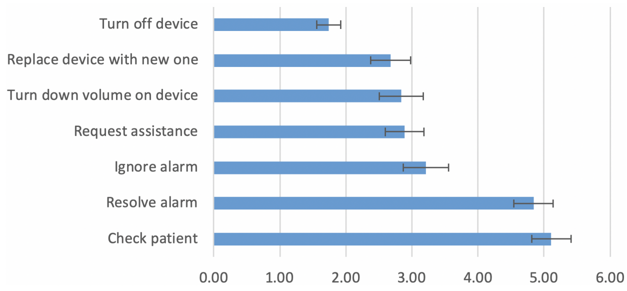

Figure 1. Ratings for actions taken to address nuisance alarms.

3.2.2 Acoustic Factors Contributing to Annoyance

In one of the questions, the participants were asked to rank auditory factors that contribute to the annoyance caused by alarm sounds. The choices presented in this question were derived from our interviews with healthcare professionals and included loudness, high-pitched or piercing qualities, repetitiveness and melody. The results of the participants' ranking of these factors in terms of annoyance are shown in Fig. 2, with the pitch of the alarm sound ranked as the most likely to cause annoyance, followed by loudness, repetitiveness and melodic content.

In a follow up questions, the participants were asked to identify any other acoustic aspects of alarm sounds that they perceive to be annoying. While one participant identified the inability to adjust the sounds as a factor, another participant described the similarities between different alarm sounds to be annoying. Other responses included “inability to talk over an alarm and” “loudness not being in line with the criticalness of the monitoring”. One participant mentioned that some alarm sounds give them anxiety and that the acoustic properties of those alarms make them feel very irritated especially when busy. Another participant reported annoyance with not being able to sustain silence amid a persistent alarm even when they know the alarm is false, for instance, when the monitor mistakes shivering for ventricular tachycardia.

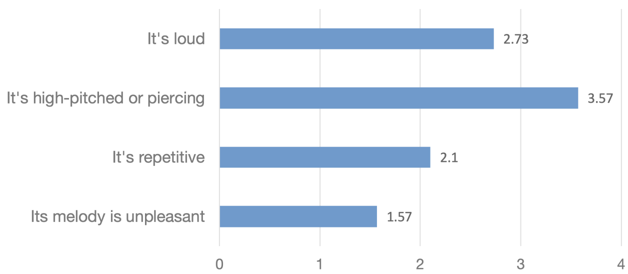

Figure 2. Participants' average ranking of acoustic annoyance factors in clinical alarms.

3.2.3 *Similarities between alarm sounds*

Acoustic similarities between alarm sounds can be a cause of confusion in clinical environments. In the survey, the participants have identified several monitoring devices that gave out similar alarm sounds. For instance, participants likened the sound of the bed alarm to those of the ventilator, the wound vacuum, and the sequential compression device. One participant mentioned that the sounds of the intra-aortic balloon pump are similar to that of the dialysis machine.

A common cause of confusion was the sound of the pulse oximeter, which was described to give out similar sounds under different conditions, for instance, when it reads 98% blood oxygen level and when it is not reading anything during an MRI. The sound of the same device at a 95% blood oxygen level was likened to that of an electrocardiogram (ECG) machine without a pulse oximeter tone. The IV infusion pump was also characterized as putting out similar sounds across many different states (e.g., 0.9% normal saline vs benign fluid; vasopressor vs other life sustaining liquids). The alarm that indicates a change in ECG was also likened to the alarm that a temperature probe gives out when it has been removed. Other advisory alarms were also described to share similar acoustic properties with those that could indicate urgent conditions.

3.2.4 *Acoustic Prominence vs Perceived Importance*

The participants were asked to place common medical monitoring devices on a 2-dimensional graph with the X axis indicating acoustic prominence (-1 representing low acoustic prominence and +1 representing high acoustic prominence) and the Y axis indicating perceived importance (-1 representing low perceived importance and +1 representing high perceive importance). The following description was provided to the participants:

> Alarms can have varying degrees of acoustic prominence: some can be piercing whereas others can be soft. The acoustic prominence of an alarm can depend on its loudness, pitch, and rate among other factors. All these parameters contribute to an alarm's perceived importance. A loud alarm can draw more attention and be perceived to be more important than a quiet alarm. However, some alarms can be acoustically prominent yet indicate conditions that do not require your immediate attention. For instance, the smoke detector in your home can go off while cooking even when there is no active fire. In this case, the alarm is acoustically prominent despite the lack of an actionable situation of high importance.

An interactive graph allowed the participants to drag nodes that correspond to medical monitoring devices anywhere on the graph. They were asked to base this evaluation on their overall experiences with these devices rather than on specific cases with patients.

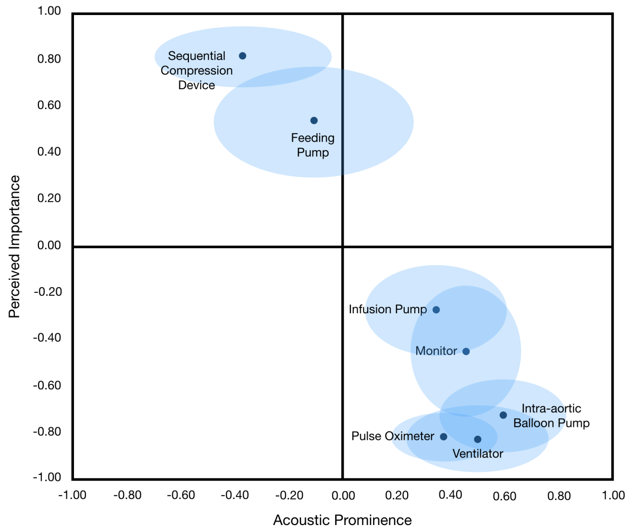

Figure 3. Responses to the question where the participants moved nodes representing medical monitoring devices on a 2D-plane with X-axis indicating acoustic prominence and Y-axis indicating perceived importance. The blue circle around a node represents the standard deviation.

The average of the responses to this question are shown in Fig. 3 with the blue circles indicating standard deviation. Most devices were placed in the High Acoustic Prominence – Low Perceived Importance quadrant with the exception of the Sequential Compression Device and the Feeding Pump, which were characterized as displaying low acoustic prominence and high perceived importance. These results indicate an overall disparity between the acoustic prominence of clinical alarms and how important or actionable healthcare professionals perceive them to be.

3.2.5 *Comparison of Hypothetical Alarm Sounds*

In the listening portion of the survey, the participants were asked to listen to pairs of alarm sounds and pick the one that they perceived to be more urgent. These sounds were designed using our alarm sound prototyping tool, seen in Fig. 6, which we will further detail in the next section. Four of the seven questions were aimed at comparing variations in a single acoustic parameter (e.g., volume, rate, pitch), whereas the other 3 questions compared pairs where two parameters were changed in opposite direction at the same time (e.g., both an increase in pitch and a decrease in rate).

The alarm pairings in individual questions were as follows: high pitch vs. low pitch; low rate vs. high rate; high volume vs. low volume; high pitch, low volume vs. low pitch, high volume; low pitch, high rate vs. high pitch, low rate; high volume, low rate vs. low volume, high rate; no melodic variation vs. with melodic variation.

There was strong agreement among participants with questions where only one parameter was altered. Supporting the results from [4], participants generally associated increase in pitch, volume and rate with an increase in perceived urgency. Alarms with no melodic variation were found to be more urgent than those with melodic variation.

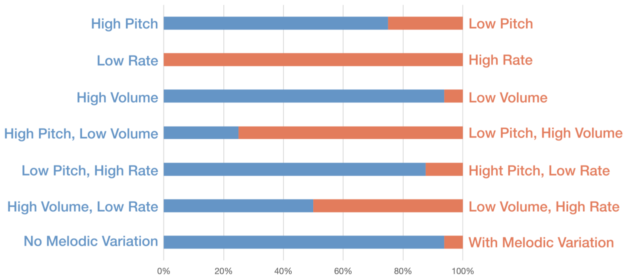

Figure 4. Participants' comparison of perceived urgency between alarm pairs with different acoustic properties.

With questions where two parameters were changed in opposite direction, participants generally rated a low pitch, high volume alarm as indicating a higher level of perceived urgency than a high pitch, low volume alarm when the alarm rate was kept constant. This shows a tendency towards prioritizing the loudness of an alarm, as opposed to its pitch, when determining how urgent it is. With the question where a low pitch, high rate alarm was paired with a high pitch, low rate sound, participants generally ranked the increased rate to indicate a higher level of perceived urgency. This shows a similar tendency towards rate being perceived as a more prominent indicator of urgency when compared to pitch. Interestingly, in response to the question where a low volume, high rate alarm was paired with a high volume, low rate alarm, the participants were split evenly. While this result aligns with how loudness and rate were ranked against pitch, it also indicates that loudness and rate has comparable effects on perceived urgency.

4. IMMERSIVE DOCUMENTATION OF AN ICU

To develop AlamrVR, we first performed an immersive documentation of one of the intensive care units in the Clinical Simulation Center at the University of Michigan. These units are fully functional medical facilities that are designed for training purposes. Since these settings are not used for actual patient care, we were able to setup video and audio systems to capture controlled alarm situations.

We used an Insta 360 Pro camera to capture a VR video of the ICU. This camera can record 3D panoramic videos at 8K resolution using its array of stereoscopic lenses. Additionally, we used a Sennheiser Ambeo 1st-order Ambisonic microphone to capture audio in synchronization with the video. After the 4-channel A-format recordings were converted to Ambisonic B-format, they were exported to Adobe Premiere for spatial alignment with the video. The monitoring devices were also recorded individually for reference with close microphone techniques.

Figure 5. Immersive documentation of an ICU at the University of Michigan's Clinical Simulation Center.

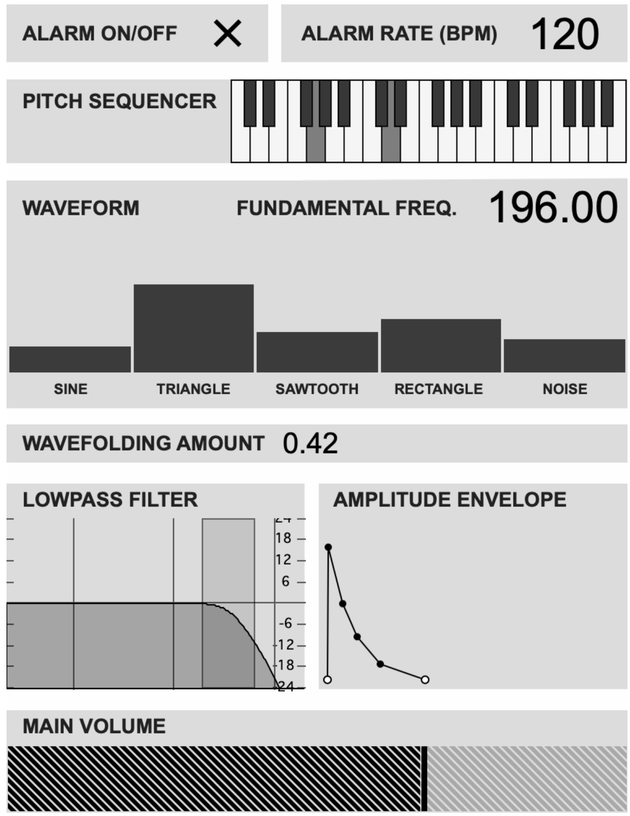

Figure 6. Alarm designer software interface.

The resulting video informed the design of AlarmVR as outlined below. A screenshot from this video can be seen in Fig. 5. The video is currently available on YouTube. [1]

4.1 Alarm Designer

For the design of new alarm sounds, we developed the prototyping tool seen in Fig. 6 using the multimedia programming platform Max. This tool allows us to rapidly sketch alarm sounds based on 8 parameters: alarm rate, pitch sequence, fundamental frequency, waveform type, wavefolding amount, low-pass filtering, amplitude envelope and main volume. Through waveform mixing, wavefolding and filtering, a wide range of timbres with varying degrees of spectral complexity can be achieved. In addition to setting a fundamental frequency, the user can input a pitch sequence to add melodic variation to the alarm sound. Finally, an amplitude envelope controller allows the user to arbitrarily draw contours that define the dynamic evolution of an alarm sound over time. This tool was used both to prototype the alarm sounds employed in our survey and to determine the parameters displayed to users in AlarmVR.

[1] `https://youtu.be/aHj6yTqUW4I`

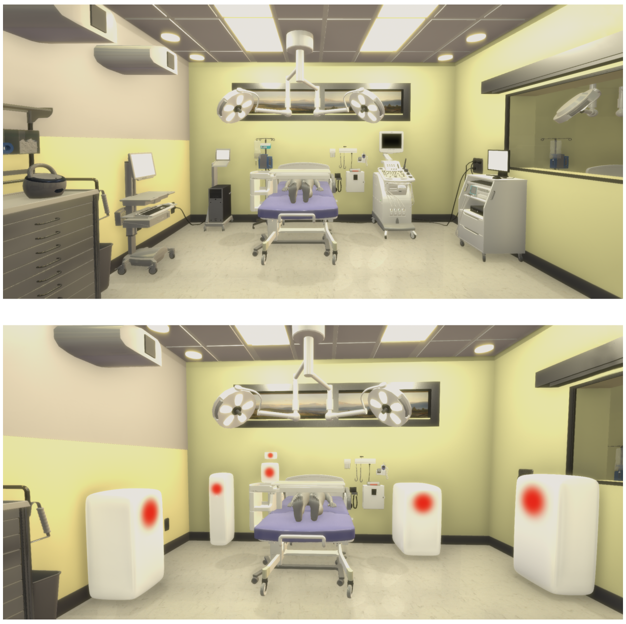

Figure 7. (Top) View of the virtual ICU in AlarmVR with medical monitoring devices. (Bottom) View of AlarmVR with monitoring devices replaced with abstract models.

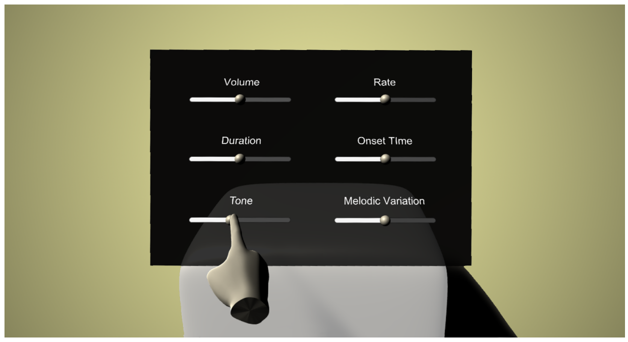

Figure 8. A user controlling the parameters of an alarm emitted from one of the abstract models in AlarmVR.

5. ALARMVR

We developed AlarmVR as a virtual platform to investigate auditory issues related to alarm fatigue and clinical alarms in general. Research in this area is often abstracted from clinical environments due to the risk of interfering with patient care. Although training spaces, such as the one we used for our immersive documentation, can facilitate studies on clinical alarms, these are expensive facilities that are not available at every institution. AlarmVR leverages modern VR systems to make research into clinical alarms immersive and accessible at the same time.

The virtual ICU seen in the top panel of Fig. 7 was modeled after the training ICU that was documented in the first phase of our study. The environment, interaction mechanics and logging system were implemented using the game engine Unity.[2] The system supports both virtual navigation with hand-held controllers and room-scale VR experiences, where the user can navigate the VR space physically within the pre-defined play area. It can be deployed to a variety of VR systems including the Oculus Rift and the HTC Vive.

The system allows the tester to administer varying combinations of alarm sounds that are mapped to the virtual monitoring devices with spatial and directional sound using Google Resonance Audio.[3] In the virtual ICU, the user hears the alarms binaurally and can mute or solo them either with direct interactions with the virtual device or with remote interactions using a pointer mechanism. Each user interaction is logged with timestamps and can be played back for review.

[2] https://unity.com
[3] https://resonance-audio.github.io/resonance-audio/

The system consists of a second state where the medical models are replaced with abstract shapes as seen in the bottom panel of Fig. 7. This allows the tester to disassociate hypothetical alarm designs from specific monitoring devices when it is necessary to test the perceived urgency of a sound regardless of the medical condition it may indicate. Alarm events are visualized with pulsating red dots as seen in the figure.

In a third state of the system, the monitoring devices (either with representative or abstract models) are overlaid with the user interface (UI) seen in Fig. 8. The UI allows the user to adjust the acoustic parameters of the alarm sound emitted by the corresponding device in real time. This state of the system allows the tester to prompt the user with various tasks that promote the active participation of the user in designing an alarm sound.

AlarmVR is designed to serve both training and research applications. On the training side, our platform can be used to acclimate medical students to current alarm conditions in clinical settings. Instructors can easily deploy various alarm conditions, monitor student reactions, and log the results for further analysis. Since the system supports both room-scale and virtual navigation, it can be adapted to various use cases and simulation scenarios. On the research side, AlarmVR can be used both to evaluate existing alarm conditions and to design new alarms in an immersive context. The users can modify alarms in real-time and experience them in a spatial context individually or in various combinations.

Our first user evaluations with AlarmVR slated for April 2020 was postponed due to the COVID-19 pandemic. We hope to continue with this evaluation in Spring 2021 and report our findings in a future publication. In the meantime, we will continue to establish AlarmVR as a virtual platform that can facilitate research into clinical alarms.

6. CONCLUSION

In this paper, we outlined our ongoing efforts to implement a virtual ICU in order to facilitate research into alarm fatigue and clinical alarm design in an immersive context. We reported the results of a preliminary survey, highlighting some of the auditory factors that can contribute to alarm fatigue in clinical environments. The participants reported their experiences with the inconsistent pairings between the acoustic prominence and the perceived importance of the alarm sounds emitted by monitoring devices that are commonly utilized in clinical settings. They also characterized alarms with high-pitch and piercing qualities as causing more annoyance than the loudness, repetitiveness or the melodic properties of an alarm sound. While the increase in pitch, loudness and rate indicated a higher degree of urgency as expected, pairing inverse variations in these parameters yielded some interesting results with respect to the prioritization of loudness and rate. We outlined our efforts to document alarm heavy environments for immersive simulation purposes. We then described our implementation of AlarmVR and our ongoing work on establishing it as a platform that facilitates the active involvement of healthcare professionals in clinical alarm research.

7. ACKNOWLEDGEMENTS

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