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Organizing Audible Alarm Sounds in the Hospital: A Card-Sorting Study

Melanie C. Wright, Sydney Radcliffe, Suzanne Janzen, Judy Edworthy, Thomas J. Reese, and Noa Segall

***Abstract*—In hospitals, clinicians are presented with varied and disorganized alarm sounds from disparate devices. While there has been attention to reducing inactionable alarms to address alarm overload, little effort has been focused on organizing, simplifying, or improving the informativeness of alarms. In this article, we sought to elicit nurses' tacit interpretation of alarm events to create an organizational structure to inform the design of advanced alarm sounds or integrated alert systems. We used open card sorting to evaluate nurses' perception of the relatedness of different alarm events. A total of 70 hospital nurses sorted 89 alarm events into groups they believed could or should be indicated by the same sound. We conducted a factor analysis on a similarity matrix of the frequency of alarm event pairings to interpret how strongly alarm events loaded on different alarm groups (factors). We interpreted participants' grouping rationale from their group labels and comments. The urgency of response was the most common grouping rationale. Participants also grouped monitoring-related events, device-related events, and events related to calls and patients. Our findings support the standardization and integration of alarm sounds across devices toward a simpler and more informative hospital alarm environment.**

***Index Terms*—Alarm design, auditory displays, healthcare safety, human factors, interruption, knowledge elicitation.**

I. Introduction

Nurses and other hospital workers are bombarded with a cacophony of alarm sounds from different devices. Interpreting and responding to alarms is difficult, especially when patient care involves many devices and multiple patients. Efforts are underway to remedy this problem by reducing the rates of inactionable or low-priority alarms [1]–[4]; however, the work of standardizing, integrating, and improving the in-hospital alarm sound environment has been limited [1]–[3].

Humans have limitations for the number of different sounds that can be distinguished, recognized, and recalled [5]. These limits are further challenged in environments of high workload and stress. Recent research has shown that, compared with the conventional alarm sounds, auditory icons using metaphors (e.g., the sound of a beating heart for a cardiovascular problem) are more learnable and are identified more quickly and accurately [6], [7]. Researchers have proposed novel alarm sound designs to improve understanding and interpretation [8], [9]. In one example, the meaning is conveyed by an auditory icon and urgency is conveyed by manipulating sound features, such as melodic and harmonic intervals [8]. To apply these advanced sound designs, we must first understand what specific meaning should be conveyed by an alarm sound. For example, is it more important to know which device generates the alarm (e.g., infusion pump or ventilator), the type of clinical problem (e.g., cardiovascular or neurological), whether the alarm is technical (a low battery) or clinical (low blood pressure), or how quickly one needs to respond?

New alerting approaches, such as direct-to-nurse smart phone or watch-based auditory, tactile, and visual alerting systems, have shown promise for reducing workload and improving alarm response [10]. Understanding clinicians' information needs and perceived the conceptual organization of alarm events is also relevant to the design of these systems.

The current international standard for alarm systems design (IEC 60601-1-8 [11]) categorizes eight types of alarms: general, cardiovascular, oxygen, ventilation, artificial perfusion, temperature, drug administration, power down, and two priority levels (high and medium). The categories are based on a theoretical model justified by technologies and responder roles that may be outdated [12], [13]. Meaningful alarm sounds are most critical in settings where the clinician is not always physically present and remote interpretation is important. Common first responders in those settings are nurses. There is a need for rigorous human-centered design activities to support decisions regarding appropriate alarm categories [14], [15].

The goal of this project was to capture the needs of hospital nurses with respect to differentiating and interpreting audible alarms. The findings are expected to support system and device standardization efforts that can be combined with advanced sound designs or alternative alarm system design approaches to produce integrated, meaningful, and useful alerting of events that require timely clinician response.

II. Methods

A. Study Design

Card sorting is a user-centered design method frequently used to understand concept relationships and translate information into concept maps [16]–[18]. Participants are given a list of concepts (cards) to sort into meaningful groups (categories). For this study, we used open card sorting in which participants are asked to create and label groups from scratch. Participants used an online card-sorting application (OptimalSort) and were instructed to group together alarm events that should or could be conveyed using the same sound. They were instructed to follow

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their own preferences without deference to the perceived constraints of existing systems or limits on the number of cards in a group or the number of groups (see Appendix).

B. Care Settings and Participants

Due to minimal participant risk and anonymous participation, the Trinity Health Institutional Review Board (IRB) determined the study to be exempt from IRB review. Tullis and Wood recommend a sample size of 20–30 participants for the conventional card sorts [19]. We targeted the recruitment of 90 hospital nurses, 30 each with and without critical care, pediatric, obstetric, and emergency care experience. Participants were recruited at an American Association for Medical Instrumentation (AAMI) Conference in November 2017 and multiple Trinity Health hospitals between November 2017 and June 2018. Participants received either a thank you gift or the payment for participation. Participants provided information about their professional role, experience in direct patient care, and hospital care setting experience. We included data from participants with at least two years' experience in a hospital alarm first responder, direct care role.

C. Alarm Event Selection

To provide broad coverage of alarm events, we extracted data from alarm management surveys [4] from three Trinity Health hospitals. Starting with a comprehensive list of 293 alarm events from 31 devices, we consulted with biomedical engineering, critical care nursing, and respiratory therapy experts to reduce the list to a representative subset of 93 alarm events (cards), covering 31 devices with 1–5 alarm events per device (see the Appendix). To manage the task scope, 50 randomly selected cards were presented in a random order to each participant. We asked participants to leave any alarm event that they were not familiar with unsorted. The instructions, card labels, and online card-sorting activity were pilot tested and revised with feedback from five nurses and quality improvement specialists.

D. Analysis

We excluded data from participants who did not sort at least 20% (10 of 50) of the cards presented or did not create at least two groups that contained at least two alarm events each. Card sorting generates a similarity matrix that quantifies how frequently each pair of concepts is sorted together as a percentage. We used factor analysis to analyze the data because it provides insight into overlapping concepts across categories (factors) and is useful for our goal of revealing a broad, generalizable, and underlying structure [17]. Because cards were presented randomly and participants were allowed to skip cards, we only analyzed cards sorted by at least 12 participants. Guided by the interpretations of scree plots and goals of limiting a final hierarchical structure of one to three levels with fewer than seven subcategories at any level, we elected to include 13 factors in the final analyses. Item loadings within each factor indicate the strength of association of each event to that factor (or group). Thus, high loading items on each factor represent alarm events that are representative of that factor.

To generate factor labels, we manually reviewed participant data to identify card-sort groups that were similar to each factor (contained cards that loaded highly on the factor and did not contain cards that did not load highly on the factor). We identified frequent similar names used by participants to label those groups. We evaluated the underlying meaning of the grouping (including whether the group represented the intersection of two underlying categories, such as urgency and another feature) to generate meaningful factor labels.

To understand the grouping rationale, we listed the underlying features of the categories (e.g., urgency, devices, and clinical versus technical) for each participant's solution. We coded open-ended participant comments regarding their grouping rationale. We combined the solution provided from factor analysis with the interpretation of grouping rationale to generate a proposed organizational approach for in-hospital alarm categories.

We conducted subset analyses for participants with critical care, no critical care, and obstetric and pediatric experience. Because sample sizes for these analyses are small, factor analyses for these findings are reported in the Appendix.

III. Results

A. Participants

More than 118 individuals initiated the task and 85 met sorting inclusion criteria. Of these, 70 met participant experience and role inclusion criteria. Participants were registered nurses (66), a licensed vocational nurse (1), nursing assistants (2), and a respiratory therapist (1). In addition to the general hospital experience, participants had experience in critical care (31), obstetric or pediatrics (25), and emergency care (12). A total of 76% of participants (53) were in direct patient care roles when they completed the survey.

B. Descriptive Analysis of Card-Sort Structures

Participants sorted an average of 66% of 50 cards into a median of six groups and a mode of four groups.

Inclusion criteria defined the minimum number of groups generated (2). The maximum number of groups' participants generated was 21 (one participant; the next highest number was 13 for two participants). A total of 86% of participants created eight or fewer groups. See the Appendix for example card-sorting solutions from participants.

C. Factor Analysis

A total of 89 of the 93 cards were included in the analysis. A total of 13 factors accounted for 66% of the variance in the factor model. Table I displays analyst-defined factor labels and lists the top five highest loading alarm events for each factor (see the Appendix for detailed item loading data and analysis by clinical expertise subgroups).

Abbreviations: BiPAP—bilevel positive airway pressure; CO_2—carbon dioxide; CHP—continuous hemodynamic pressure; CRRT—continuous renal replacement therapy; ECG—electrocardiogram; ECMO—extracorporeal membrane oxygenation (heart–lung support); $ETCO_2$—end-tidal carbon dioxide; IABP—intra-aortic balloon pump; ICP—intracranial pressure; NIBP—noninvasive blood pressure; PCA—patient controlled analgesia; PEEP—positive end-expiratory pressure.

D. Grouping Rationale

A total of 64 participants labeled or commented on grouping rationale (six did not provide meaningful group labels).

1) Criticality or Urgency: The most common rationale for grouping alarm events was perceived urgency or criticality. A total of 59% of participants created groups that differentiated by urgency. Ten participants (16%) used criticality or urgency as their only classifying criteria, creating 2–5 categories based on time sensitivity or importance, such as "emergency," "high priority," and "medium priority." Two participants created category names that implied variable urgency depending on the patient context. Of 26 who did not use urgency as a

TABLE I
FACTOR LABELS, FIVE HIGHEST LOADING ALARM EVENTS FOR EACH FACTOR, AND VARIANCE ACCOUNTED FOR BY EACH FACTOR

FACTOR LABEL FIVE HIGHEST LOADING EVENTS (LOADING)	% VARIANCE
1. Abnormal signs – variable urgency	8.7%
Low mean arterial pressure, CHP monitoring (0.87)	
High mean arterial pressure, CHP monitoring (0.85)	
High systolic pressure, CHP monitoring (0.82)	
Low diastolic pressure, CHP monitoring (0.79)	
High central venous pressure, CHP monitoring (0.80)	
2. Respiratory: more urgent	8.5%
High airway pressure, ventilator (0.89)	
ETCO2 low, ETCO2 monitor (0.84)	
Low exhaled minute volume, ventilator (0.77)	
High PEEP, ventilator (0.76)	
Leak or blockage, ventilator (0.74)	
3. Emergency: critical care (devices)	8.5%
Low venous pressure, ECMO (0.87)	
Blood leak, CRRT (0.81)	
High pressure or kinked line, IABP (0.84)	
Gas leakage, IABP (0.81)	
Air in the venous system, CRRT (0.81)	
4. Lines and pumps: variable urgency	7.1%
Occluded – patient side, infusion pump (0.89)	
Syringe near empty- syringe pump (0.84)	
Infusion complete, infusion pump (0.82)	
Restricted flow – syringe pump (0.80)	
High upstream pressure, PCA pump (0.78)	
5. Instrument use: less urgent	5.6%
Cuff over-inflated, NIBP (0.78)	
Cuff side leak, electronic tourniquet (0.73)	
Low systolic blood pressure, NIBP (0.71)	
High patient motion, vital signs monitor (0.70)	
Low patient temperature, TTM (0.66)	
6. Pediatric and fetal monitoring: variable urgency	5.5%
Signals overlap, fetal monitor (0.98)	
ECG leads off, fetal monitor (0.86)	
High fetal heart rate, fetal monitor (0.79)	
Baby tag loose, pediatric security (0.78)	
Ultrasound signal loss, fetal monitor (0.76)	
7. Power and battery: variable urgency	5.2%
Critical battery, portable ECG monitor (0.79)	
Low battery, infusion pump (0.74)	
Critical battery, infusion pump (0.74)	
Critical battery, vital signs monitor (.0.64)	
Power failure, ECG monitor (0.62)	
8. Call: variable or less urgent	3.6%
Nurse call (0.86)	
Phone/page call (0.79)	
Bathroom call (0.69)	
Low battery, phone/page (0.60)	
Leads off, ECG monitor (0.50)	
9. Patient exit and urgent call: more urgent	3.2%
Chair exit (0.81)	
Bed exit (0.75)	
Baby tag exit, pediatric security (0.67)	
Urgent phone/pager call (0.48)	
Baby tag loose, pediatric security (0.38)	
10. Devices: less urgent	3.2%
High pressure, compression device (0.86)	
Technical problem, compression device (0.65)	
Check water flow, targeted temperature management (0.55)	
Critical battery, phone/pager (0.52)	
Restricted flow, syringe pump (0.39)	
11. Respiratory: urgency variable	
Oxygen too low, high flow nasal cannula (0.65)	3.1%
Low oxygen saturation, pulse oximeter (0.50)	
Respiratory rate high, ETCO2 monitor (0.45)	
Apnea, neonate apnea monitor (0.40)	
Low flow, ECMO (0.40)	
12. Devices: variable or more urgent	
Cooling fan failure (monitoring stopped), ICP (0.67)	3.1%
Heater failure, NICU bed (0.67)	
Air in line, epidural pump (0.52)	
Skin temperature low, infant warming (0.45)	
Breathing circuit disconnect, BiPAP (0.43)	
13. Emergency: all settings	
Asystole, ECG monitor (0.54)	2.5%
Ventricular fibrillation, ECG monitor (0.48)	
Apnea, respiratory rate monitor (0.40)	
Ventricular tachychardia, ECG monitor (0.38)	
Apnea, neonate apnea monitor (0.37)	

grouping criterion, three stated in comments (see the Appendix) that they perceived urgency as important but presumed it would be customizable or otherwise determined (beyond the structure they created).

Many participants (45%) differentiated between life threatening or critical events (e.g., ventricular fibrillation, asystole, and failure of a life-sustaining device) and urgent events that required an immediate response but for which failure or delay in response was not perceived to be immediately life threatening (e.g., bed exit and chair exit). In addition to common labels that implied general urgency, such as "critical events" or "emergency," participants used labels that implied urgency within a category, such as "RN/CNA emergency," "patient safety," "security," and "code pink."

2) Monitoring- Versus Device-Related Events: A total of 45% of participants separated events based on whether they were monitoring- or device-related events. Within monitoring-related events, some participants further subdivided events into respiratory, cardiac, or general signs (20%) or a different combination of three or more clinical subcategories (13%). Separately identifying pediatric, neonatal, fetal, or obstetric events also was common (20%).

Within the device category, participants commonly created unique categories for pumps and lines (28%), power or battery problems (11%), or by devices (13%). Four (6%) participants grouped alarm events solely by device independent of any other categorization (e.g., electrocardiogram, ventilator, and phone calls).

3) Calls, Exits, and Responder: Participants varied on how they grouped sounds associated with phone calls (urgent and normal), patient calls (nurse and bathroom), and patient exit (bed, chair, and baby) events. Some grouped these into a common category (e.g., "room" or "unit" alarms) (8%). Some generated a unique category for fall risk and exit alarms (19%). Some generated a unique category for patient calls (nurse or bathroom) (9%) and some generated a unique category for phone calls (6%). Four (6%) created group labels that considered the role of the best responder (registered nurse, nurse assistant, or respiratory therapist).

E. In-Hospital Alarm Sound Organizational Structure

We combined information from the factor analysis, grouping rationale, and qualitative comments of participants to generate an alarm organizational structure, which includes urgency (emergency, high, or

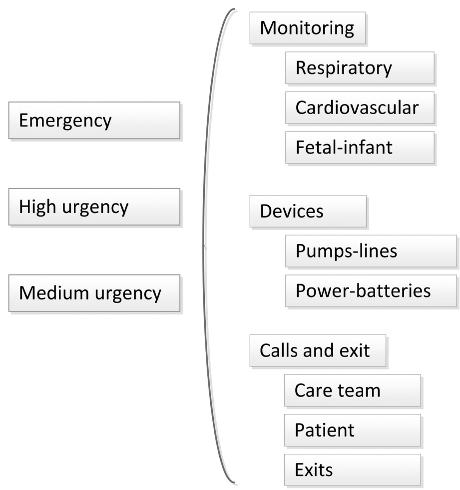

Fig. 1. Proposed alarm organizational structure.

medium) and alarm type (monitoring, devices, or calls and exit). Alarm types can further be specified with unique subcategories (see Fig. 1).

IV. Discussion

We elicited the conceptual organization of alarm events from 70 experienced nurses to generate the proposed alarm organizational structure (see Fig. 1). The structure does not necessarily imply that every alarm must convey all three levels of information. For example, our findings supported only two emergency sounds: one for rare, life-threatening, clinical monitoring events, and another for failures of life-supporting devices.

For events that were neither clearly a life-threatening emergency or clearly nonurgent, it was more important for nurses to understand the event behind the alarm (e.g., type of monitoring event; whether it was related to pumps, other devices, or power; or whether it was a patient call, exit, or team call). Because patient situations and care settings vary, it can be difficult to set a consistent, *a priori*, and level of urgency. Additional information helps nurses interpret the alarm in the context of their knowledge of specific patients (e.g., whether the patient is a high fall or elopement risk), treatments (e.g., criticality of a drug or a fluid that is infusing), or other circumstances (e.g., that another clinician is in the room with the patient) in deciding how to prioritize their attention. Another approach to helping nurses is to interpret the urgency of alarm events would be to support customization of urgency by patient or situation. However, actions required to customize alarm urgency must be both simple and error resilient to gain clinician acceptance [10], [20].

As an example of how to apply the proposed organizational structure, we generated a high-complexity alarm set involving 23 unique sounds (see Table II) and a low-complexity set involving nine sounds (see Table III). There are tradeoffs in choosing simpler or more complex solutions. A simple alarm set may not provide sufficient information, while a complex alarm set may suffer from the problems of memorability and learnability. We presume implementation of a complex alarm set that would integrate advanced human-system designs (e.g., advanced sounds to support category interpretation [6]–[9], or a design that includes a visual display component [10]).

Participants generally preferred simpler solutions with 86% of participants providing solutions with eight categories or fewer and the most common solution involving only four categories. However, some participants who generated only four categories presumed urgency that

TABLE II
Complex Proposed Alarm Sound Set Organized by Categories

	URGENCY	CATEGORY	SUB-CATEGORY
1.	Emergency	Monitoring	General
2.	Emergency	Devices	General
3.	Emergency	Calls & Exit	General
4.	High	Monitoring	General
5.	High	Monitoring	Respiratory
6.	High	Monitoring	Cardiovascular
7.	High	Monitoring	Fetal/infant
8.	High	Devices	General
9.	High	Devices	Pumps and lines
10.	High	Devices	Power
11.	High	Calls & Exit	General
12.	High	Calls & Exit	Exit
13.	High	Calls & Exit	Patient
14.	Medium	Monitoring	General
15.	Medium	Monitoring	Respiratory
16.	Medium	Monitoring	Cardiovascular
17.	Medium	Monitoring	Fetal/infant
18.	Medium	Devices	General
19.	Medium	Devices	Pumps and lines
20.	Medium	Devices	Power
21.	Medium	Calls & Exit	General
22.	Medium	Calls & Exit	Exit
23.	Medium	Calls & Exit	Patient

TABLE III
Simple Proposed Alarm Sound Set

	ALARM SOUND
1.	Emergency
2.	High urgency respiratory monitoring
3.	High urgency cardiovascular monitoring
4.	High urgency fetal or infant monitoring
5.	High urgency general monitoring
6.	High urgency device
7.	High urgency call or exit
8.	Medium urgency monitoring or device
9.	Medium urgency call

would be coded in addition to those categories. And some participants commented that specific events should have their own unique sound (e.g., staff member in distress, code blue, and bathroom call). Other researchers caution against oversimplification and advocate for greater informativeness in alarm designs [9], [21].

This study had limitations. First, participants were primarily hospital-based nurses and generalization beyond this population and the devices they are familiar with are limited. Second, the proposed structure is based on nurses' perceptions. Our methods do not account for how these perceptions may differ from behavior or performance in context [9], [21]. Third, our sample is subjected to self-selection bias. There may also be a response bias toward simpler card-sort solutions if that made the sorting task easier. Finally, our analyses primarily focused on audible alarm events generated by current clinical devices. Generalization of the findings to future devices or other novel approaches to informing clinicians may be limited.

There is a need for additional research to validate our findings. For example, closed card sorting (into prelabeled groups) and tree testing (tests whether participant's chosen path to information matches the intended design) can be used to further validate the proposed organizations [18]. Further design work and testing is also needed to evaluate how best to apply the sound sets of varying complexity to optimize learnability, memorability, and information needs.

V. Conclusion

Current alarm sound standards are variably interpreted by manufacturers. It may be feasible to improve these standards by providing detailed sound specifications (e.g., audio media files) and definitions for how to apply specifications to ensure consistency across devices, manufacturers, and care settings. Results from this article are being shared with the IEC/AAMI 60601-1-8 standards' committees and will be used to inform future standards for health care alarm sounds [11]. Our results can be applied to ongoing research to design the advanced alarm sounds for health care settings that are expected to improve learnability and memorability of alarm sounds [6]–[9]. These findings may also inform the design of alternative alerting systems, such as handheld or wearable devices [10].

Appendix

A supplemental pdf file contains task instructions, a list of alarm events, and full factor analysis structure for the 70-participant sample and subset analyses by clinical setting.

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