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# IMPROVING THE DESIGN OF WEARABLE ICU ALARMS

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## ABSTRACT[*]

The volume, design, and pervasiveness of existing ICU alarms can make it difficult for clinicians to quickly distinguish alarms' importance and meaning. We aim to evaluate the effectiveness of two design approaches in a newly developed smartwatch-based alarm system: (1) using audiovisual spatial colocalization and (2) adding haptic information. We compared the performance of 30 participants using newly developed ICU smartwatch alarms with two sensory modalities (visual and audio) against alarms with three sensory modalities (adding haptic cues). Additionally, we compared participant performance in two implementations of the audio modality: colocalized with the visual cue on the smartwatch's low-quality speaker versus delivered from a higher quality speaker located two feet away from participants. Participants were 13.5% (0.35s) faster at responding to alarms when auditory information was delivered from the smartwatch instead of the higher quality external speaker. Meanwhile, adding haptic information to alarms improved response times to alarms by 14.7% (0.31s) and response times on their primary task by 9.5% (.08s). Participants also rated learnability and ease of use higher for alarms that included haptics. Audiovisual colocalization and multisensory alarm design improve user response times without compromising accuracy, while also improving user performance in concurrent cognitively demanding tasks.

**Keywords:** *medical alarms, multisensory integration*

## 1. INTRODUCTION

The frequent sounding of alarms above recommended auditory thresholds in hospitals, especially in ICUs, presents a serious problem for both provider performance and patient recovery. Among physicians and nurses, recurring alarms have been correlated with slowed response time to patient needs and lower response rates (alarm fatigue), creating more hazardous patient situations and deaths related to alarm mismanagement, especially in the wake of COVID-19 [1]. Improved alarm design is regarded as one tool to combat alarm fatigue [2]. In our study, we sought to improve clinical alarm design by developing a novel alarm system with emphasis placed on four key design aspects: auditory icons (e.g. lub dub sound for heart rate), speaker quality, multisensory alarm input, and audiovisual spatial colocalization. Prior clinical research has demonstrated the clinical benefit of continuously informing vibrotactile displays for the physiologic monitoring and multitask performance, while laboratory-based research has validated the performance benefits of a trimodal (auditory, visual, and haptic information) wearable ICU alarm system with auditory icons and pre-alarming [3-4]. The present study developed a multisensory (auditory, visual, and haptic information) alarm system in an Apple Watch®, with alarm sounds that incorporated novel auditory icons with encoded patient severity, to isolate and analyze the importance of

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two design principles not yet explored for a wearable alarm system designed for ICU use: (1) using audiovisual spatial colocalization and (2) adding haptic (i.e., touch) information.

## 2. METHODS

The study was approved by the Vanderbilt University Medical Center IRB. We designed three experimental conditions for participants to undergo, described in Figure 1.

**Auditory Source Conditions**

| Haptic Conditions | | 1. Speaker at *same* location as visual display | 2. Speaker at *different* location than visual display |
|---|---|---|---|
| | **A. Haptic alerts *not* provided** | **Condition 1A:** Play alarm from the same source as the visual patient monitor. Haptic alerts *not* provided. | **Condition 2A:** Play alarm from a speaker that is at a *different location* from the visual patient monitor. Haptic alerts *not* provided. |
| | **B. Haptic alerts provided** | **Condition 1B:** Play alarm from the same source as the visual patient monitor. Haptic alerts provided. | |

**Figure 1.** Outline of the three experimental conditions in this study. We were focused on comparing conditions of haptics vs. no haptics and external vs. watch speaker individually, so we did not include a fourth condition, 2B (external speaker with haptic alerts).

Each participant underwent all three conditions in a randomized fashion over the course of six, 5-minute trials. 30 participants (ages 19-30) participated in this study after given a brief orientation. In each trial, participants were instructed to respond to a series of alarms, which each sounded for 10-20 seconds, when simulated patient blood pressures fell or rose outside of the normal range. Participants were also instructed to complete a visual distractor task, called the 2-back task, during these trials. The 2-back task is a working memory assessment. Participants were able to respond to the alarm again if they realized they identified the alarm incorrectly the first time. The six trials were divided into two blocks, one block comprising all trials where the speaker and visual display were at the same location (condition 1, four trials) and the other block including all trials where the speaker was at a different location than the visual display (condition 2, two trials). We measured participant's time to first response, time to correct response, and accuracy in identifying alarms (proportion of correctly identified alarms on the first attempt). Two-tailed, Wilcoxon signed-rank tests were performed to compare performance across different experimental conditions. We also compared participant feedback (collected via a survey) on alarm ease of use, alarm learnability, participant perceived success, and cognitive burden on participant.

Participants monitored the simulated patient vitals using the Apple Watch application developed by Burdick et al. (2022) [4].

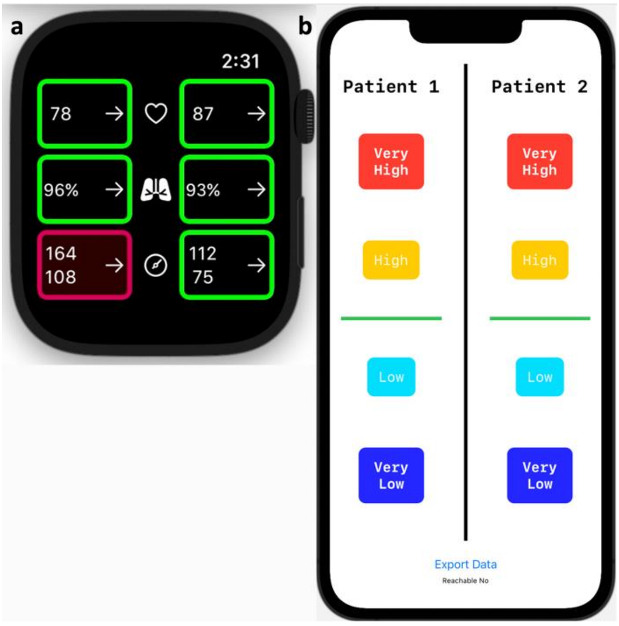


**Figure 2.** Part (a) shows the visual interface of the watch application to monitor vitals, while part (b) shows the iPhone application that participants used to identify the alarms they were alerted to. Only BP

levels varied significantly enough to trigger alarms in this study.

We created four different auditory alarms (increasing severe, increasing moderate, decreasing moderate, and decreasing severe), consisting of repetitions of the cardiovascular auditory icon interspersed with a short series of sound pulses, to use in all experimental conditions. The auditory alarms were designed such that the direction of the alarm (i.e. increasing or decreasing) was encoded as rising or falling pitch, respectively, and the severity of the alarm (i.e. moderate or severe) was communicate by the alarm's pace (slower or faster, respectively). An ambient soundtrack consisting of medical instrument sounds, pumps, and voices was played at a set volume of 60 dB to simulate an ICU environment. In conditions 1A and 1B, the Apple Watch not only served as the visual monitor for vitals, but its speaker also played the auditory alarms. In condition 2A, the Apple Watch visual display remained the same but the alarm sounds played out of an external speaker (JBL GO 3) positioned two feet in front of the participant. Both the Apple Watch and JBL GO speakers played at the same 70 dB volume when measured from the location of the listener. A larger diaphragm is required to produce lower frequencies making the frequency range of the Apple Watch narrower than the JBL GO 3 [5]. As a result, we believed that the Apple Watch speaker was of lower quality than the JBL GO 3 speaker.

## 3. RESULTS

### 3.1 Speaker Location: Watch Speaker vs. External Location

#### *3.1.1 User Performance on Responding to Alarms*

Participant initial alarm response time was 13.5% faster when the alarm sound originated directly from the watch speaker (2.25s) compared to from the external speaker (2.60s, p=.016), though calculated time to correct alarm response and accuracy was unchanged.

#### *3.1.2 User Performance on 2-back Task*

On the 2-back task, there was no significant difference between participant performance on various task-specific outcome measures (reaction time, number of correct matches, number of misses, and incidences of false input) from the trial with sound coming from the watch speaker compared to the trial with sound coming from the external speaker.

#### *3.1.3 Participant Feedback*

There were no significant differences in how respondents rated the following dimensions when the alarm sounds played through the watch speaker compared to from the external speaker: ease of use, learnability of the alarms, perceived success, and cognitive burden.

### 3.2 Adding Haptic Information

#### *3.2.1 User Performance on Responding to Alarms*

Participant performance was compared across a trial in which alarms were accompanied with haptic information and a trial in which the alarms did not have any such haptic information. As haptic information was only added to the "very high" and "very low" alarms, participant performance was compared only for these alarms which were capable of being augmented with haptic information. Adding haptic information improved both the time to correct response (1.75s) by 17.5% and the initial response time overall (1.80s) by 14.7% for eligible alarms compared to the trial without haptic information (2.12s, p=.002; 2.11s, p=.015 respectively), while accuracy was unaffected across the two trials.

#### *3.2.2 User Performance on 2-back Task*

The average response time on the 2-back task (0.79 s) was significantly faster by 9.5% in the trial in which eligible alarms had haptic information when compared to the average 2-back task response time (0.87 s, p=.008) in the trial in which eligible alarms did not present with haptic information. There was no significant difference between participant performance on the number of correct matches, number of misses, and incidences of false input on the 2-back task from the trial with haptic information enabled on eligible alarms compared to the trial without any haptic information on alarms.

#### *3.2.3 Participant Feedback*

Participants reported that adding haptics to alarms significantly improved their ease of use (5.52), learnability (5.19), and perceived success (5.58) when compared to using alarms without haptics (3.77, p=.001; 3.58, p=.003; 4.10, p=.003 respectively). There was no significant difference in reported cognitive burden.

## 4. DISCUSSION

Faster response times when participants were responding to alarms with sound coming directly from the smartwatch compared to a higher quality external speaker suggests the importance of spatial colocalization of auditory and visual stimuli. Previous research has indicated that reliable audiovisual spatial relationships independently enhance audiovisual integration and perception [6]. In this study, there were established and reliable spatial relationships perceived by participants in both trials between the visual information on the smartwatch and the sound from either the external speaker (stationary) or the smartwatch (on participants' wrists). However, the spatial relationship between auditory information from the smartwatch and visual information from the smartwatch was likely stronger given the spatial colocalization of audiovisual information. Furthermore, these results hold even though the external speaker was of higher quality.

Meanwhile, participants who were notified using an alarm with both auditory and haptic information had a faster response time. This is likely due to audio-haptic alarms being multisensory: audio-haptic alarms can take advantage of more neural pathways than just those of auditory processing. Additionally, multisensory signals such as auditory and tactile may even be synergistic [7]. Furthermore, participants found that audio-haptic alarms were easier to learn and use. Multisensory alarms have been previously shown to prolong the period during which a learned behavior is retained [8]. Surprisingly, adding haptic information to the alarms improved response time on the separate 2-back task that participants were completing while waiting for alarms to go off. Haptic information likely served as a more effective alarm for context switching when compared to just the auditory alarm, allowing participants to better focus on their task at hand in accordance with multiple resource theory.

## 5. CONCLUSION

Participants were significantly faster at responding to alarms when the alarm sound was delivered from the smartwatch instead of from a higher-quality, external speaker. Meanwhile, adding haptic information to alarms not only improved alarm response time but also improved response times on the cognitively demanding task that participants were asked to complete.

## 6. ACKNOWLEDGMENTS

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