Using Multisensory Haptic Integration to Improve Monitoring in the Intensive Care Unit

Kendall J. Burdick, Abigail S. Bell, Mary C. McCoy, Jonathan L. Samuels, Alex S. Jolly, Seema S. Patel, Julia B. Balas, K. Jakob Patten & Joseph J. Schlesinger

To cite this article: Kendall J. Burdick, Abigail S. Bell, Mary C. McCoy, Jonathan L. Samuels, Alex S. Jolly, Seema S. Patel, Julia B. Balas, K. Jakob Patten & Joseph J. Schlesinger (2020): Using Multisensory Haptic Integration to Improve Monitoring in the Intensive Care Unit, Auditory Perception & Cognition

To link to this article: https://doi.org/10.1080/25742442.2020.1773194

Published online: 04 Jun 2020.

Submit your article to this journal

View related articles

View Crossmark data
Using Multisensory Haptic Integration to Improve Monitoring in the Intensive Care Unit

Kendall J. Burdick\(^a\), Abigail S. Bell\(^b\), Mary C. McCoy\(^c\), Jonathan L. Samuels\(^c\), Alex S. Jolly\(^c\), Seema S. Patel\(^c\), Julia B. Balas\(^c\), K. Jakob Patten\(^d\) and Joseph J. Schlesinger\(^e\)

\(^a\)Medical School, University of Massachusetts Medical School, Worcester, MA, USA; \(^b\)Department of Neuroscience, Vanderbilt University, Nashville, TN, USA; \(^c\)Department of Biomedical Engineering, Vanderbilt University, Nashville, TN, USA; \(^d\)College of Health Solutions, Arizona State University, Tempe, AZ, USA; \(^e\)Anesthesiology and Critical Care Medicine, Vanderbilt University Medical Center, Nashville, TN, USA

**ABSTRACT**

**Introduction:** Alarm fatigue and medical alarm mismanagement reduces the quality of patient care and creates stressful work environments for clinicians. Here, the feasibility of a novel “pre-alarm” system that utilizes multisensory integration of auditory and haptic stimuli is examined as a possible solution.

**Methods:** Three vital signs (heart rate, blood pressure, and blood oxygenation) were represented by three musically distinct sounds that were combined into soundscapes and progressed through five pre-alarm zones (very low to very high). Three haptic conditions were tested with the auditory stimulus to determine the best combination of auditory and haptic stimulation. Qualitative data was collected through surveys and the NASA TLX index.

**Results:** Alterations in frequency and timbre were most effective at transmitting information regarding changing vital sign zones with comparatively higher accuracy and quicker reaction time (RT), \(p < .01\). The addition of haptic stimuli to the auditory soundscape caused no significant decline in study participant accuracy or RT. However, two weeks after training, participants performed the tasks significantly faster \((p < .001)\) and felt the alarm monitoring task was significantly less cognitively demanding \((p < .01)\), compared to the unisensory condition. Participants also felt more confident in identifying changing vital signs with the addition of haptic stimuli.

**Discussion:** The current study demonstrates that multisensory signals do not diminish the perception of transmitted information and suggest efficient training benefits over unimodal signals. Multisensory training may be beneficial over time compared to unisensory training due to a stronger consolidation effect. The potential integration of haptic input with existing auditory alarm systems and training is supported.
Introduction

Medical alarm mismanagement can have serious consequences: over 500 patients died between 2011 and 2015 due to poorly designed alarms (Edworthy, Schlesinger, McNeer, Kristensen, & Bennett, 2017; Kristensen, Edworthy, Özcan, & Denham, 2015). In medical environments where extensive and continuous monitoring of several physiological conditions is necessary, an excessive number of alarms seems unavoidable, leading to high levels of noise pollution. Unfortunately, research shows that 72% to 99% of all clinical alarms are false or do not require clinical intervention (MacIntyre & Day, 1992; Sendelbach & Funk, 2013), leading to mistrusted and often silenced alarms. When the true alarms are missed, the reaction has been to increase the acoustic intensity (volume) in an effort to render them more perceptible. The sheer number and intensity of alarms that require active and divided attention lead to alarm fatigue among healthcare providers (Wilken et al., 2017). Individuals respond to alarms at the rate perceived to be accurate, thus an overuse of alarms resulting in alarm fatigue may lead to dangerously low response rates and errors in patient care (Bliss, Gilson, & Deaton, 1995). As a result, novel medical equipment that improves response rates and clinically significant alarms may also improve patient safety (Kohn, Corrigan, & Donaldson, 2000).

The current threshold alarm sounds only after the patient condition worsens past a defined point. At that time, a life-saving intervention may require a split-second action, but is also inhibited by the mistrust in alarms and alarm fatigue. Previous research has demonstrated the numerous shortcomings of current threshold alarm systems (Schlesinger et al., 2018), and proposed a continuous alarm as a solution. With a continuous alarm, information could be introduced into the pre-alarm space, which would alert the user when a patient is trending negatively but before they reach the critical threshold. With a pre-alarm, the user may have more time and understanding of the clinical situation, and the error in alarm signaling and perception may decrease. The advantage of the continuous alarm lies in the ability of the user to identify a deleterious trend within the pre-alarm range before the condition worsens enough to require intervention at the threshold alarm trigger. By this means, care can be better informed and proactive rather than reactive. For example, by using an alarm escalation algorithm, a novel cardiac pre-alarm was effective at decreasing the number of dangerous “alarm situations” and improving reaction time (RT) of nurses to those alarm situations (Cvach, Frank, Doyle, & Stevens, 2014). This information can be enhanced by adding a multisensory component, such as auditory, haptic, or visual, that allows for faster cognitive processing, higher attentional capacity, and delivers interpretable information without interfering with a demanding task (Hecht, Reiner, & Halevy, 2006; Katzman et al., 2019).

The studies presented here use alarm sonification, data transformed into sound, combined with a haptic component in a pre-alarm system. The goal of this research is to utilize multisensory input to improve pre-alarm responses, measured both by accuracy and RT, and improve participants’ confidence in their own detection ability. The conclusions taken from this study may help create a medical alarm that improves clinician performance and ameliorates alarm fatigue in order to improve patient outcomes.
Neuroscience of Multisensory Integration: Cognitive, Behavioral and Neural

The development of the multimodal alarm system used in this experiment involved consideration of how integrated multisensory information leads to improved perception and performance. In this way, an alarm system that best fits the human body may be created, rendering signals more salient and therefore more likely to elicit physician response.

Multisensory Synergism at the Neuronal and Cortical Levels

Input from multiple modalities has synergistic effects, specifically by activating neurons of the superior colliculus (Ghose, Maier, Nidiffer, & Wallace, 2014; Meredith, 2002; Occelli, Spence, & Zampini, 2011; Stanford, Quessy, & Stein, 2005; Wallace, Wilkinson, & Stein, 1996; Wilson, Braida, & Reed, 2010), which modulates behavior and, thus, decreases RT (Amlôt, Walker, Driver, & Spence, 2003; Diederich & Colonius, 2004, 2009; Diederich, Colonius, Bockhorst, & Tabeling, 2004; Forster, Cavina-Pratesi, Aglioti, & Berlucchi, 2002; Stein, Magalhaes-Castro, & Kruger, 1976). Furthermore, specifically haptic input, when presented with an auditory stimulus, produces its own supplementary response in the auditory association cortex, suggesting that multisensory integration begins in the early stages of sensory perception (Schroeder et al., 2001). Haptic feedback also allows quicker target localization and texture discrimination (Akamatsu, Sato, & MacKenzie, 1994), requires few mental resources (MacLean, 2009), and does not require additional visual attention (Alirezaee, Girgis, Kim, Schlesinger, & Cooperstock, 2017; Kolodzey, Grantcharov, Rivas, Schijven, & Grantcharov, 2017; Patterson, Winterbottom, & Pierce, 2006). Therefore, haptic stimulation may minimize sensory and information overload (Jones, 2011) and is expected to aid in overcoming the current issues in alarm perception (Schlesinger, Stevenson, Shotwell, & Wallace, 2014).

The addition of multisensory stimuli is also inspired by the Principle of Inverse Effectiveness, which states that neuronal response to stimuli from one modality is enhanced when a stimulus from another modality is presented simultaneously (Alirezaee et al., 2017). It was hypothesized that using multisensory integration with haptic stimuli in the auditory pre-alarm system would allow participants to accurately detect and respond to the auditory signal even when administered at lower, near-threshold intensity levels.

Benefits of Multisensory Training

Finally, training with a multisensory alarm system benefits performance. Unisensory training is effective for medical professionals in improving frequency perception and, thus, alarm response (Schlesinger et al., 2014) but multisensory training, such as musical training, has a number of additional benefits in as little as two weeks (Luo et al., 2012; Pantev, Lappe, Herholz, & Trainor, 2009). Thus, it can be expected that robust training and experiential learning can result in more accurate use of a multisensory system via enhanced connections between sensory and motor cortices. The second experiment allows for observation of the effects of multisensory training, including a delay phase in order to also examine the deterioration of learned skills over time.
Engineering Considerations in Study Design

Expanding on Previous Research

The soundscapes used in this study are similar to those used in past studies (Burdick et al., 2019; Delft Design Labs, 2018; Greer, Burdick, Chowdhury, & Schlesinger, 2018). These soundscapes also incorporated auditory icons, brief sounds that mimic the sound of the biological variable, which were found to be beneficial in perception and response (McNeer, Horn, Bennett, Edworthy, & Dudaryk, 2018). The soundscapes used previously tested auditory icons that imitate the onomatopoeia sound of the heart, “lub-dub,” to represent the heart rate parameter in the soundscape. By creating a psychologically intuitive alarm, training becomes simpler and the required mental effort expenditure required is decreased (Delft Design Labs, 2018).

The Continuous Pre-alarm

By basing our protocol on previous research, a formal control condition of auditory icons alone was not needed for validation of auditory icon feasibility. The additional testing would have also caused the participant exposure time to be excessively long (approximately 50% longer) and could lead to fatigue and impart other issues of confounding and interpretation of the data. This would also result in more participants loss to follow-up. Furthermore, these first-in-kind approach studies focus on the pre-alarm space, which is not currently used in clinical environments. As mentioned before, the addition of multiple sensory streams in the pre-alarm space allows a reduced need for visual attention. This makes attentionally demanding tasks that require specifically visual attention, such as intubation, will not have to compete for visual attention resources.

Since these studies assess performance using solely auditory and/or haptic information in the pre-alarm space, a true test of a control condition would be giving no auditory and/or haptic information and asking participants to respond. Thus, participants would have no information, and responses would be due to chance alone (since there is no visual input in these studies). This would result in us comparing performances of auditory and/or haptic results to pure guessing alone, which would skew our results and analysis. The overall purpose of these studies is to integrate proactive care and show the feasibility of the multisensory pre-alarm approach to see if this scheme was learnable and had benefit. Therefore, a true control condition without any information is beyond the scope and need for a first-in-kind approach to auditory perception and cognition of novel sensory input.

A Two-part Study

The two studies presented here complied with the American Psychological Association Code of Ethics and were approved by the Vanderbilt University Medical Center Institutional Review Board (IRB# 170485).

Experiment 1 investigated the ways in which physiological zones may be represented by changes in a continuous alarm parameter’s intensity, frequency, timbre, and key. Three methods of auditory zone differentiation (Soundscapes 1–3) tested in this experiment are shown in Figure 1. The use of frequency change versus volume change...
in alarms has not yet been studied, so therefore, these soundscapes build upon previous knowledge of successful auditory icons, as well as introduce novel variable changes.

Experiment 2 investigated the effect of a multisensory alarm in performance and retention after a delay period, compared to a unisensory alarm. The most effective soundscape from Experiment 1 was used, in addition to a haptic stimulus, which was given either discretely or continuously.

**Experiment 1: Training and Soundscape Selection**

**Method**

**Participants**
35 undergraduate students (16 female, 19 male) at Vanderbilt University participated in this experiment. Each participant was provided a 10 USD gift card for their time.

**Procedure**
Three different soundscapes were created using Ableton Live software (Berlin, Germany). Each soundscape included distinct sounds for three different vital signs: heart rate (HR), blood pressure (BP), and blood oxygenation (SpO2). Each vital sign was also paired with an instrument-based auditory icon: drums with HR, piano with BP, and guitar with SpO2. The soundscapes varied in their differentiation of the five zones of the pre-alarm space: very low, low, normal, high, and very high. In all three soundscapes, the normal zone for each vital sign was represented by silence. Changes outside of the normal zone occur in either intensity, frequency, timbre (musical complexity), or tempo, all of which have been identified as salient, principal dimensions of auditory cognition (Johnson,
McBeath, & Patten, 2014; Melara & Marks, 1990; Misdariis et al., 2010; Patten, 2017; Patten, McBeath, & Baxter, 2019).

Additionally, providing individualized information to only the relevant clinicians via a personal headset, shown in Figure 2, would reduce Intensive Care Unit (ICU) sound levels that already exceed the World Health Organization’s recommended 30–35 dB (Qutub & El-Said, 2009). Bone conduction headphones pass vibrations through the zygomatic process to directly stimulate the cochlea and offer situational awareness of the environment without mechanically obstructing the ear (Martin & Voix, 2017). Therefore, participants listened to soundscapes with Trekz Titanium Bone Conduction Headset (AfterShokz, East Syracuse, New York).

**Soundscape 1.** The music in the first soundscape varied in intensity to indicate vital signs trending from normal to low or high zones. As the vital sign progressed into a very high or very low zone, the timbre became more distorted. The sounds for each vital sign were continuous and flowed methodically with each other in a legato manner.

**Soundscape 2.** The second soundscape also differentiated the very high/very low and high/low zones with timbre; however, the differentiation between high and low was made by varying the frequency rather than the intensity. Since percussion instruments cannot change in frequency, the drum component of the soundscape changed in tempo instead, increasing in high zones and decreasing in low zones. This soundscape was more staccato to promote succinct differentiation of each vital sign.

**Soundscape 3.** The third soundscape varied in frequency and key. Like Soundscape 2, Soundscape 3 differentiated high and low with frequency and distinguished very high/very low from high/low by changing to a minor key. The drums were similar to those in Soundscape 2; however, the tempo changed further in the progression from high/low to very high/very low zones, rather than changing in timbre. The articulation of sounds in Soundscape 3 was a blend of staccato and legato to allow for ease of listening as well as differentiation.

Three different four-minute templates consisting of a progression of seventeen singular, stepwise changes to the simulated physiological parameters were created. These templates were then applied to each of the three soundscapes, creating nine unique sound clips in total. The use of multiple templates allowed for the maximization of the number of combinations of tonal overlap that the subject pool would encounter. Each participant

![Figure 2. Trekz Titanium wireless bone conduction headphones by AfterShokz (Syracuse, NY).](image-url)
was randomized to listen to three sound clips, one from each soundscape. In this way, the ability of participants to discern the correct physiological parameter for each of the three soundscapes could be comparatively assessed. This process is depicted in Figure 3.

For each soundscape, participant training consisted of listening to each of the isolated components of the soundscape. Participants then completed a short quiz to ensure that they were familiar with the sounds and associated physiological parameter states. Following this, a randomized sound clip was played, and participants were instructed to indicate when a change in sound occurred using the graphical user interface (GUI) on a touchscreen monitor similar to that used in the ICU. This GUI, shown in Figure 4, displayed fifteen buttons, one for each zone (very low, low, normal, high, and very high) for all three vital signs (HR, BP, and SpO2). The participants were instructed to select the button that corresponded to the change that occurred in the sound clip. This procedure was repeated for the other two soundscapes.

During the testing portion, participants were assessed both on their RT and accuracy following a change in a simulated patient physiological parameter. Specifically, accuracy was assessed based on the ability of the participants to: (1) recognize a zone change at the correct time, (2) select the correct vital sign, and (3) identify the correct vital sign severity zone.

The scoring schema was generated in a way that rewarded participants for actions that result in positive patient health outcomes and punished them for actions detrimental to patient outcomes. For example, identifying the correct vital sign that changed had the highest weight in improving participant score, since an accurate interpretation of the signal by the clinician is the ultimate indicator of success for this pre-alarm system. An
Results

RT for different soundscapes were analyzed using repeated-measures ANOVA, with participant numbers entered as a covariate and averaging across the counterbalancing measure of soundscape variation, yielded a significant effect of soundscape and a large effect. Soundscape 1 was characterized by a significantly slower RT ($M = 6.84$ s, $SD = 0.24$) than either Soundscape 2 ($M = 5.76$ s, $SD = 0.15$) or Soundscape 3 ($M = 5.94$ s, $SD = 0.19$), $F(2, 66) = 8.03$, $p < .01$, partial $\eta^2 = .20$, a moderate effect according to Cohen’s norms (Cohen, 1988). Both pairwise comparisons between Soundscape 1 and its competitors were significant ($p < .0$), while Soundscape 2 and 3 were not significantly different.

Accuracy was also compared across the soundscape with a repeated-measures ANOVA, again entering participant as a covariate. Soundscape 2 had the overall highest accuracy rate. Soundscape 1 (intensity + timbre, $M = 6.96$, $SD = 0.80$) was characterized...
by a marginally lower accuracy score than either Soundscape 2 (frequency + timbre, $M = 12.94, SD = 1.35$) or Soundscape 3 (frequency + tonality, $M = 11.74, SD = 1.15$), $F(2, 66) = 1.85$, $p = .16$, partial $\eta^2 = .05$, a small effect according to Cohen’s norms. Pairwise comparisons revealed that Soundscape 1 had significantly lower accuracy rates compared to Soundscape 2 ($p < .01$) and Soundscape 3 ($p < .01$). While not otherwise noteworthy,

![Figure 5](image1.jpg)

**Figure 5.** Bar graph depicting RT differences between soundscapes. Soundscape 1 led to significantly slower responses. Error bars are two standard deviations.

![Figure 6](image2.jpg)

**Figure 6.** Bar graph depicting differences between soundscapes based on the accuracy of responses to cues. While the omnibus test was not significant, pairwise comparisons indicated Soundscape 1 led to significantly poorer responses. Error bars are two standard deviations.
these results corroborate those of RT and inform the choice of soundscape for future experiments. Figures 5 and 6 depict these differences graphically.

**Discussion**

Soundscape 2 had the highest accuracy of the tested soundscapes, and significantly quicker RT compared to Soundscape 1. Soundscape 2 used frequency to differentiate a normal physiological zone from a high or low zone and timbre to demarcate a very low or very high state. This succinct, staccato style soundscape was designed in accordance with the ideas of human factors engineering and was used in the continuation of Experiment 2.

**Experiment 2: Multisensory Assessment**

Experiment 2 is a continuation of Experiment 1 and consists of two phases: Primary Testing and Delay. In this experiment, participants were trained using the highest accuracy pre-alarm from Experiment 1, which was Soundscape 2. An additional haptic stimuli (described below) was added to the pre-alarm as either a discrete or continuous stimuli. In the Primary Testing phase, participant performance was measured by accuracy and RT. In the Delay phase, which occurred two weeks after training, participants were tested with the same procedure to assess retention of training and possible extinction. The same participants were used for both phases, and Figure 7 shows a diagram of the experimental flow. Experiment 2 investigated the effect of a multisensory alarm in performance and retention after a delay period, compared to a unisensory alarm.

![Figure 7. Flowchart of Experiment 2 testing phases.](image-url)
**Method**

**Participants**
31 undergraduate students (14 female, 17 male) at Vanderbilt University participated in this experiment. Each participant was provided a 10 USD gift card for their time.

**Primary Testing Phase Procedure**
Informed by the results from Experiment 1, Soundscape 2 was selected as the auditory pre-alarm stimulus for Experiment 2. In addition to auditory stimulus, the present experiment incorporates the additional sensory information of haptic vibration with the aim of improving participant accuracy and RT.

**Haptic Device Use and Placement**
Haptic vibration was delivered via two Basslet wearable subwoofers (Lofelt, Berlin, Germany), which were placed on each participant’s non-dominant wrist and the contralateral, dominant ankle.

In order to achieve synchronized benefits and detection of near-threshold haptic signals, at least two haptic actuators, shown in Figure 8, are needed in order to increase the maximum potential information transmission (Salzer, Aisenberg, Oron-Gilad, & Henik, 2014). To provide spatial contrast, one haptic device was worn on the non-dominant wrist and the other on the opposite ankle, near the distal fibula – locations determined based on previous research (Gay-Betton, Alirezaee, Cooperstock, & Schlesinger, 2017). Furthermore, placing the haptic actuators on skin that directly overlies bone as opposed to subcutaneous fat or muscle allows for improved conduction of the signal over a larger volume of tissue (Gilman, 2002). In addition to the spatial location, the duration of the haptic signal was changed to parallel the dynamic patient condition and convey more information to the user.

![Figure 8. Basslet by Lofelt (Berlin, Germany).](image-url)
Haptic signals were added over the three sound clips associated with the soundscape. These four-minute clips each consisted of seventeen stepwise tonal changes paired with a complementary haptic signal, with a change occurring every 7–21 seconds randomly to avoid a predictable pattern. Three haptic conditions were used for the haptic stimuli: None (unisensory), discrete, or continuous. In the discrete haptic condition, the signal was delivered as brief vibrational pulses. The continuous haptic condition consisted of the bass frequency of the auditory signal, generated by dropping the soundscape by an octave, a technique successfully used to pair music and haptic vibrations for live concert performances (Merchel & Altinsoy, 2014). Discrete and continuous haptic vibrations have been used for simple reaction studies and are both shown to be good indicators of a needed response (Salzer et al., 2014).

These haptic stimuli that occurred in conjunction with the soundscape during a transition from one zone to another and increased in duration as the vital sign moved into very high or very low zones. The haptic signals were generated at 40–100 Hertz, the key haptic sensitivity range of the Basslet subwoofers. They were also adjusted to an intensity that was comfortable and detectable for each user, no higher than the device’s maximum amplitude of 7.1 G.

Assessment
Participants were first trained on the soundscape and associated haptic conditions at their own pace for up to five minutes via an interactive GUI, and then completed a short quiz. Participants completed the same protocol as Experiment 1 for each of the haptic conditions (none/unisensory, discrete, and continuous). Haptic condition order was randomized for each participant. Following the Primary Testing phase, participants were given a survey to collect qualitative feedback and NASA Task Load Index (NASA TLX) score to assess the required effort (Hart, 2006; Hoonakker et al., 2011). Participant performance was measured by accuracy (using the same scoring method as Experiment 1) and RT.

Delay Phase Procedure
Two weeks after the completion of the Primary Testing Phase, participants returned for assessment of their retention of training on the different haptic conditions. There were no participants lost to follow-up, so 100% of participants completed both phases of Experiment 2. For each haptic condition, the participants listened to the auditory and haptic signal associated with each vital sign to remind them of the associations. Participants were then tested in the same manner as in Experiment 1 and completed the NASA TLX score and qualitative survey. Again, experimenters recorded accuracy and RT for each participant. Since training was the only altered variable between the Primary Testing Phase and Delay Phase and the testing schema were identical, ANOVA was used in both experiments.

Results
For RT analysis comparing different haptic conditions and time (at primary and delay phase testing), a two-way repeated-measures ANOVA indicated that RT two weeks after training was significantly faster ($M = 4.62$, $SD = 0.18$) than RT at primary training...
(\(M = 6.03, SD = 0.15\)), \(F(1, 29) = 15.72, p < .001\), partial \(\eta^2 = .35\), a large effect according to Cohen’s norms. There was also a significant (though likely spurious) main effect of haptics, \(F(2, 58) = 4.84, p < .05\), \(\eta^2 = .143\). The significance of this finding, while a moderate effect according to Cohen’s norms, is questionable because the least significant difference-corrected (the most liberal correction for multiple pairwise comparisons) showed only marginal significance \((p = .054)\) between continuous haptics and the no haptic information control condition. There was no significant interaction between haptics and RT, \(F(2, 58) = .26, p = ns\). These differences are depicted graphically in Figure 9.

A two-way ANOVA for accuracy performance revealed no main effect of either haptic condition or phase testing with no interaction, \(F_{\text{haptics}}(2, 58) = 0.84, p = ns\); \(F_{\text{time}}(1, 29) = 3.31, p = ns\); \(F_{\text{haptics*time}}(2, 58) = .48, p = ns\).

A third repeated measures ANOVA revealed no main effect for either haptics or the interaction of haptics and phase testing, \(F_{\text{haptics}}(2, 56) = 0.73, p = ns\); \(F_{\text{haptics*time}}(2, 56) = 0.32, p = ns\). However, there was a significant difference in participant confidence for the delayed testing phase, compared to the primary testing phase. TLX scores were significantly higher for the primary testing phase, indicating a greater perceived task demand \((M = 22.03, SD = 4.52)\) compared to the delay phase testing \((M = 20.47, SD = 4.25)\), \(F_{\text{time}}(1, 28) = 11.43, p < .01\), partial \(\eta^2 = .29\), a large effect by Cohen’s norms. These differences can be seen in Figure 10 and Supplemental Material.

**Discussion**

The results show that the inclusion of haptic stimuli did not significantly diminish participant ability to accurately discern changes in simulated physiological parameters, even after a two-week delay. Results of qualitative NASA TLX surveys showed that the addition of haptic stimuli decreased the perceived workload of the task and felt most confident using the discrete haptic multisensory pre-alarm.
Furthermore, RT measurements after a two-week delay were significantly faster compared to the primary testing phase, which may be due to the consolidation effect. Memory and RT often improve after training, due to the consolidation effect, where new information is processed from short-term memory to long-term memory after a delay period (McGaugh, 2000). Multisensory training has been shown to have similar effects with various multisensory modalities, all resulting in more effective learning (Kim, Seitz, & Shams, 2008; Shams & Seitz, 2008). Studies showed novel multisensory training took only 8 minutes to master (Seitz & Dinse, 2007). At the neuronal level, multisensory training increases in the firing rate (Allman, Keniston, & Meredith, 2008; Stein & Meredith, 1993) and decreases response latencies (Alpert, Hein, Tsai, Naumer, & Knight, 2008; Martuzzi et al., 2007), which both result in enhanced training and recall, as we see in our delay phase results. Therefore, the enhanced consolidation effect for multisensory training may be due to the bimodal stimulation of sensory neurons and cortical areas that results in greater brain plasticity and learned stimulus associations. Additionally, it would be expected that some amount of extinction, the slow decline of unapplied knowledge, would cause an increase in RT after the two weeks (Lattal, Mullen, & Abel, 2003). However, the opposite was observed in these results. Therefore, it is possible that the effects of multisensory training may persist and consolidate over a longer period of time, or have a delay in extinction, compared to unimodal training.

**General Discussion**

The two experiments presented here investigate the use of the pre-alarm space with both auditory and haptic stimuli. Experiment 1 investigated the ways in which physiological zones may be represented by changes in a continuous alarm parameter’s intensity,
frequency, timbre, and key. It was found that Soundscape 2, which was staccato and used frequency variation to differentiate between states, to have the highest accuracy rates of (1) recognizing a zone change at the correct time, (2) selecting the correct vital sign, and (3) identifying the correct vital sign severity zone. Experiment 2 then used Soundscape 2 to investigate performance and training effectiveness of using a unisensory or multisensory pre-alarm after training and a two-week delay. The results show that neither the addition of haptic stimuli nor a two-week delay did not hinder participant performance, and in fact, decreased RT. Additionally, the multisensory condition increased user subjective confidence and decreased perceived workload.

Overall, these studies found that the inclusion of additional sensory stimuli did not diminish participant ability to accurately discern changes in simulated physiological parameters. Of the tested soundscapes, the soundscape that altered in frequency and timbre was found to have the highest accuracy while transmitting information regarding changing vital sign zones. The addition of haptic stimuli decreased the perceived workload of participants and indicated that participants felt most confident using the system that used discrete haptic vibrations. Most notably, there was a decrease in RT two weeks after multisensory training, indicating a possible extended consolidation period, or delayed extinction onset. These results increase support for multisensory training as a possible improvement to alarm training accuracy, RT and long-term memory.

Limitations and Future Directions
The study was not conducted in an active ICU, and therefore, does not precisely reflect the ICU environment. However, these studies were focused on understanding general human response to haptic and auditory stimuli, rather than specifically targeting the ICU clinician population.

Additionally, participants in this study were undergraduate students, and may not accurately reflect the age and training of healthcare professionals. Again, these studies were focused on understanding general human response to haptic and auditory stimuli, which may be applied specifically to healthcare professionals in future research. By using this research as a small-scale proof of concept, future investigations should include ICU workers to determine the effect on the end-user.

In the future, we aim to develop an interoperable system with bone conduction headset and wearable haptic actuator that operates with hospital monitors, and allows the user to select which physiological variables he/she wishes to monitor. Future studies should also explore the incorporation of visual signals to derive additional benefits from the integration of other sensory channels and thus enhance pre-alarm tracking (Diederich & Colonius, 2004). Building on this, additional research should aim to determine the optimal number of pre-alarm zones for the maximization of information transfer and prevention of sensory overload. Further studies should aim to improve training and minimize extinction in order to promote long term retention in a distraction-filled ICU setting.

Conclusion
Past research in neuroscience indicates that multisensory stimuli promote faster RT and improved perception of the transmitted signal, allowing for a reduction in the intensity of
each of the component stimuli. The results of the study presented here support these findings and promote the feasibility of adding haptic stimuli for transmitting information to a user, thereby suggesting the possibility of minimizing reliance on the auditory stream. In the context of a pre-alarm system, a decrease in auditory stimulation would allow for a quieter ICU, improved patient sleep, and better clinician working conditions with fewer threshold alarms. Musical auditory signals with clear, easily discernible associations to physiological parameters and discrete haptic stimuli, as well as robust, regular training, are supported by this first-in-kind, feasibility research.

Alarm fatigue and mismanagement are significant issues that may result in poor patient care and even death. A promising solution to this problem is a reduction in the use of traditional threshold alarms in favor of musical pre-alarm systems that utilize human factors engineering and additive multisensory integration in order to redesign and revolutionize patient care and workflow within the ICU.

Acknowledgments
The authors would like to acknowledge Drs. Matthew Walker III and Michael King (Vanderbilt School of Engineering) for the time and support. Additionally, the authors would like to acknowledge Drs. Matthew Weinger and Pratik Pandharipande (Vanderbilt University Medical Center Department of Anesthesiology) for the time and support.

Disclosure Statement
No potential conflict of interest was reported by the authors.

ORCID
Kendall J. Burdick http://orcid.org/0000-0002-0565-4308
K. Jakob Patten http://orcid.org/0000-0002-7931-5413
Joseph J. Schlesinger http://orcid.org/0000-0003-3978-2647

References


