Exploring the Effectiveness of Haptic Alarm Displays for Critical Care Environments

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***Abstract*— Noise in critical care units, in particular, from patient monitor alarms, is harmful for clinicians and patients alike. This has motivated research aimed at shifting the delivery of physiological vital sign information and annunciation of alarm events from visual and auditory devices to haptic transducers. We compare performance in perceiving and identifying the specific type and level of a vital sign that has entered a high or low state, i.e., an alarm event, using several designs of a vibrotactile display, against that of the traditional auditory alarm in conjunction with a graphical patient monitor. A distractor activity was used to simulate competing task demands in the clinical environment. Responses were assessed with respect to response time and accuracy. With sufficient anatomical separation of the actuators, certain vibrotactile information rendering strategies demonstrated performance that was not significantly different from that of the baseline condition, both in response time and accuracy. We conclude that vibrotactile delivery of patient vitals can support alarm-state vital sign identification competitive with graphical and auditory alarm display conditions, without significantly impacting performance on a parallel attention-demanding activity. This suggests the possibility of improving high-impact healthcare environments by replacing disturbing auditory alarms with vibrotactile information delivery to clinicians.**

I. Introduction

The need to attend to patients' vital signs in hospital environments poses significant demands on clinicians. Patient-monitoring devices typically integrate a visual display with a loud auditory alarm, for which the volume cannot be attenuated but only silenced. This is despite recent research demonstrating the safety and efficacy of alarm volume softer than background noise [1].

The problems with alarm algorithms of patient monitoring devices not only elevate stress levels of the clinicians but also result in potential health hazards for the patients. Exacerbating the problems, these devices suffer from poor positive predictive value, often triggering under false positive conditions. A further problem to note, although not addressed by our research, is that alarms in the Operating Room (OR) and Intensive Care Unit (ICU) may be nearly indiscriminable, in particular, when multiple alarms annunciate in parallel [2] [3]. The aforementioned factors promote dangerous behavior such as desensitization of clinicians to the alarm sounds, which leads to alarms often being ignored, missed or silenced. All of these result in harm to patients, as documented in the FDA Manufacturer and User Facility Device Experience (MAUDE) database, a collection of device-related safety issues [4].

Moreover, the visual display of patient vital signs, often relied upon during alarm scenarios, poses additional problems. Not only must clinicians turn their attention away from the patient to view the display, but it may be occluded.

Our motivation is to introduce haptic information displays in hospitals and explore their effectiveness in improving clinician performance. If a haptics-only display can alert clinicians to abnormal physiological conditions, it can result in obviating the need for the highly distracting auditory alarm signal to draw attention to the visual monitor. This offers the potential to achieve a quieter and safer hospital environment, for clinicians and patients alike, reducing disruptions to sleep as well as ICU delirium and long-term cognitive impairment that has been found to result [5] [6]. In addition, a haptics information display offers the possibility of reducing reliance upon a graphical patient monitor, thereby better allowing clinicians to focus visually on the patient and their clinical tasks.

II. Literature Review

Haptic feedback has been explored as an effective means of alerting in a variety of critical scenarios. In the driving domain, for example, vibrotactile cues were employed for steering guidance [7] and collision avoidance alerts [8], while Spence and Ho provide an excellent review of prior work involving warning signals for drivers [9], highlighting the importance of intuitive tactile icons that can convey their meaning without extensive training.

A wide body of literature has similarly investigated the usability of wearable information displays [10], [11], [12]. An important advantage of vibrotactile stimuli as a means of information delivery in clinical environments is that they exploit a comparatively underutilized sensory channel, relative to vision and audition [13]. Baldwin et al. reported a panel discussion on the effectiveness of different modalities in high consequence environments where time-sensitive information is being communicated to the user [14]. They concluded that when tactile signals are effectively mapped to the desired meaning, haptics can be a promising information display in complex environments, provided that concurrent tasks do not overload the user's cognitive resources. An additional benefit is that vibrotactile stimuli can be conveyed privately to individual clinicians, thus offering the possibility of personalized alerts without disrupting other staff or patients [15].

Ng et al. implemented a haptic arm band with two actuators to convey alarms related to three levels of change

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in patient heart rate. The alarm state was mapped to spatial location, i.e., the actuator closer to the wrist pulsed once while the level of decrease was delivered to the actuator near the elbow by the number of pulses and the interval between them [16]. Results indicated statistically significant superior performance in alarm identification using the haptic arm band than with auditory alarms, but no difference in response time or learnability.

Cobus et al. designed an armband with three vibration motors, and compared perception accuracy, learnability, distinguishability, and perceived urgency for six vibration patterns through simulated nursing tasks. A vibration pattern similar to that used by Ng et al. [16] offered the best performance, although performance was not compared to a traditional auditory signal [17]. Nurses who participated in their study reported good usability and comfort of the apparatus.

Due to sterility concerns during procedures, the arm is often not a suitable location for attaching such haptic hardware in a clinical context. Other researchers have instead delivered patient information to other body locations. As an example of such an approach, Ford designed a haptic belt with four tactors, two worn in the front, and two at the posterior of the participant, to communicate changes in respiratory physiologic components of mechanical ventilation [18]. In either case, the anterior tactor of the pair vibrated to indicate increase, and the posterior tactor to indicate decrease of the corresponding parameter. Results on a simulated anaphylaxis incident, with anesthesiologists and anesthesiology residents, indicated that participants were significantly faster in treating the case when receiving information from vibrotactile stimuli than the control condition of conventional auditory alarms ($p < 0.05$). However, the study found no significant differences in situational awareness of the participants between the two conditions.

Ferris and Sarter designed a garment holding sets of C2 tactors at spatially relevant body locations to respiratory physiology. Patterns of actuation followed what the authors termed a "metaphorically accurate natural mapping for each of the parameters", with increasing parameters associated with progression of actuation toward tactors placed higher on the clinician's body. The authors also tested a hybrid mapping in which, in addition to the spatial progression of actuation, as described above, the severity of the change in the parameter was associated with the salience of vibration [19]. Clinical performance was then assessed on a simulated intubation task, with the use of the vibrotactile garment compared to the baseline auditory-visual display. The addition of tactile signals was found to result in a significant reduction in detection time of abnormal conditions and correction time for normalization of the physiological signs. However, no analysis was conducted as to which modality the participants relied upon to monitor the patient status. However, the vest itself, with all of its constituent tactors, represents a fairly significant burden, both in terms of apparel and hardware requirements.

III. Methodology

Although the prior literature investigated the benefits of adding vibrotactile display of patient state, it has not considered the potential to *replace* or *reduce* the dependence on auditory alarms and graphical displays in the clinical context. Thus, we seek to demonstrate the performance of a vibrotactile patient monitor as a potential alternative to the baseline condition of auditory and visual displays in the OR or ICU.

If successful, such an approach would offer several benefits, namely, reducing the sound level in the OR and ICU environments, improving the ability of clinicians to retain their visual focus and attention on the patient, and offering the possibility of personalized alarms delivered to individual clinicians.

To investigate this possibility, we conducted an experiment to determine how effectively participants could discriminate both the vital sign and its state (high or low) during alarm events, when this information was rendered haptically. Additionally, to reflect real-world conditions in which clinicians are actively attending to clinical activities in a noisy environment, we required participants to perform a parallel distractor task, while an audio recording from an OR of Montreal's Sainte-Justine Hospital played continuously in the background, at a volume between 56.7 dB and 62.7 dB, as measured by an Scosche SPL1000 meter using C-curved measurement. The experimental apparatus, described in the remainder of this section, is shown in Figure 1.

This research complied with the American Psychological Association Code of Ethics and was approved by the Institutional Review Board at McGill University and Vanderbilt University Medical Center. Informed consent was obtained from each participant, who signed a consent form at the beginning of the test.

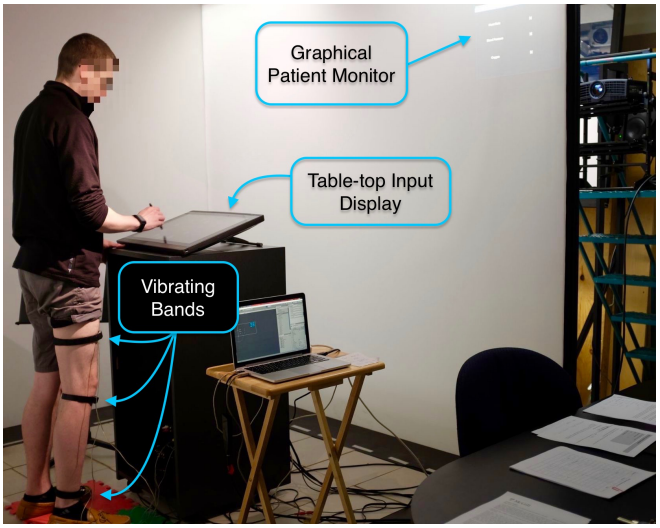


Fig. 1: Placement of the patient monitor, input display, and the vibrating bands, worn by the participant.

A. Input Interface

The graphical user interface that appeared on the input display is pictured in Figure 2. Participants detected alarm events by selecting one of six buttons appearing in the upper right quadrant of the user interface, each corresponding to a particular alarm condition. In parallel, participants must attend to the competing distractor task, designed to occupy a portion of their attention and cognitive resources [20]. For this purpose, we employed a Fitts' law task [21], involving repetitive pointing to an on-screen target that changes position after each selection. Importantly, this distractor task does not interfere with the auditory or haptic modalities, which are occupied attending to the alarm signals. The Fitts' law task additionally meets the ergonomic requirements of a medical procedure, in which the participant remains standing, with a downward visual focus, performing a precise task with the dominant hand, such as placing a right internal jugular central venous catheter.

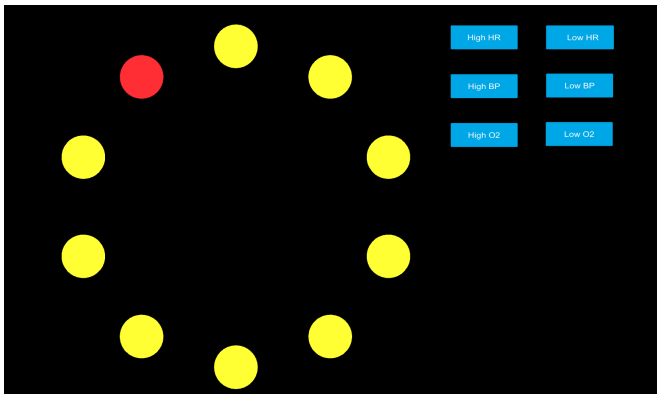


Fig. 2: Graphical User Interface (GUI) appearing in the table-top input display, used for the distractor task (yellow and red circles in left half of screen) and to record participant responses to the vibrotactile cues (blue boxes in upper right).

B. Patient Model and Vital Sign Display

Three vital signs, chosen for their importance to morbidity and/or mortality, were introduced to the participant: heart rate (HR), blood pressure (BP), and oxygen saturation (O_2). Each of three vital signs was represented internally as one of five levels: normal, nominal-low, nominal-high, low, or high. All vitals begin at a normal level, and only the low and high levels are used to trigger alarm events. At every simulation step, 2.5 s in duration, each vital sign has an 80 % probability of remaining in its current state, a 10 % probability of increasing, and a 10 % probability of decreasing, until reaching either of the extrema, i.e., low and high. This method is meant to randomize the time it takes for a parameter to reach alarm state from normal state. A separate thread was responsible for driving the patient monitor, auditory alarm, vibrotactile display, or a combination of these, as appropriate to the experimental condition. On each iteration, the three vital sign levels were checked, and the appropriate output is rendered, as described in the remainder of this section.

For each experimental condition, response time is measured from the start of the delivery of the alarm event to the participant's response, indicated through a table-top pen display (Wacom DTU-2231) to select which vital sign had gone out of bounds, and its level (low or high), thus simulating a clinical intervention to the alarm states.

C. Auditory Alarm

The auditory alarm was based on a recording of the Philips MP-70 (Amsterdam, Netherlands) patient monitor red/crisis alarm, played at 74.5 dB, easily audible above the background noise. This was presented simultaneously with the rendering of the associated vital sign through either the graphical patient monitor or the vibrotactile display, as per experimental condition, for a duration of 2.0 s, ensuring that response time measurements began from a common starting point.

D. Graphical Patient Monitor Display

A graphical patient monitor, situated at an azimuth of approximately 45° relative to the participant and elevation of approximately 1.7 m off the ground, displayed patient vital signs. This configuration was based on typical arrangements found in hospital environments.However, turning to glance at the patient monitor would involve a temporary disruption of attention to the distractor task running on the input display directly in front of the participant.

Each vital sign is displayed on a separate line by its name and the associated state. The display updates immediately in response to changes in vital signs of the patient model. For the purpose of highlighting states associated with alarm conditions, the graphical display indicates both low and high states by displaying a downward ↓ or upward ↑ arrow adjacent to the out-of-bounds vital sign. This simple informational layout was chosen so as not to require any interpretation of the displayed data on the part of our participants.

E. Vibrotactile Display

The vibration signal, encoding the patient vital signs, was delivered by Tactile Labs Haptuator Original tactors. We supplied driving signals at 170 Hz, a value determined through pilot testing as the most perceptually salient on the participant's leg. The amplitude of the signals was determined individually per participant through a calibration step at the beginning of the experiment, based on their perception of what constituted a "comfortable intensity" of the actuator vibration. The duration of vibrotactile stimuli in each of the experimental conditions is shown in Table I. These durations were determined empirically through multiple pilot tests. At the start of the actual experiment, participants were instructed to adjust the amplitude of the delivered stimuli so that the vibrations from the three Haptuators are perceived as equally strong, but not irritating.

Our design of haptic icons, or "Tactons" [22], to represent patient state was intended to convey through vibration both the type and level (high, nominal, or low) of three different

vital signs: heart rate (HR), blood pressure (BP), and oxygen saturation (O_2). To do so, we drew from the guidance from Brown et al., who investigated the role of roughness, rhythm, and spatial location as vibrotactile parameters, reporting the highest recognition rate (99.8 %) when spatial location for information delivery was varied [23], [24]. As such, we assigned the most important variable (vital sign) to the most easily discriminated rendering parameter, i.e., spatial position of the associated actuator. Moreover, we employed minimalist tactile encodings to express the level of the associated vital, so that these could be rendered quickly, and with the intent of minimizing the cognitive demands placed on participants.

Initially, we explored the possibility of using a vibration pattern based on the spoken (English) rhythm of the words representing each vital sign. However, feedback from a pilot test indicated that differentiating patterns with the same number of syllables ("blood pressure" and "oxygen") was difficult, and the patterns were too long, with the result being that participants preferred instead to obtain the necessary information from the visual patient monitor.

For the study described in Section IV, we instead employed spatial location and vibration duration of multiple actuators as a means of representing the vital signs, as shown in Table I. We experimented with positioning of the actuators at different locations on the leg, finding that the discrimination ability of the different patterns was, in general, improved with greater actuator separation. In this regard, previous research found that localization of the tactile stimulus is improved when delivered to locations close to joints [25]. This motivated our final placement of the actuators each near a different point of mobility: ankle, knee and hip.

IV. Experiment

Our experiment evaluated performance of a simple haptic alarm representation, consisting of a series of short pulses of 200 ms separated by gaps of 100 ms for a high vital sign or long pulses of 1 s separated by a gap of 500 ms for a low vital sign. The pulses continued until the participant responded with the correct selection to acknowledge the alarm event.

We hypothesized that this would require less cognitive effort to parse than spatio-temporal swipe patterns or sequences of two or three pulses, to represent low and high states, respectively. Although there are strong arguments to be made for the benefit of periodic delivery of a signal indicating that each vital sign is within an acceptable range, we opted to focus the experiment purely on perception and response performance to alarms. We thus included the baseline condition and three different haptic conditions, in which each of the three actuators, placed on the right leg, represents the status of a different vital sign, as illustrated in Table I:

- *baseline:* graphical display with auditory alarms
- *swipe:* haptic leg swipe patterns
- *1-2-3:* 1 pulse for normal, 2 pulses for low, and 3 pulses for high level of vital signs
- *haptic alarm-only:* rate-based patterns indicating low or high vital signs

To gain familiarity with the experimental stimuli, participants first carried out a training tutorial lasting approximately 10 min, after which, they progressed to the actual experiment. All participants completed one block of every experimental condition, each lasting approximately 10 min. During each condition, participants were asked to indicate the type of the out-of-bound vital sign and its level for 10 randomly chosen alarm events. To mitigate against possible fatigue, participants were offered an optional break of approximately 5 min between conditions. The entire experiment took approximately one hour to complete.

The test was conducted with 14 participants, 5M/9F, ages 18-30, $\bar{x}$=24. Conditions were presented using Latin squares ordering. Two of the participants were excluded from analysis due to a failure in logging the data as well as non-compliance with the experimental instructions.

A. Results

Response times for the three conditions are shown in Fig. 3.

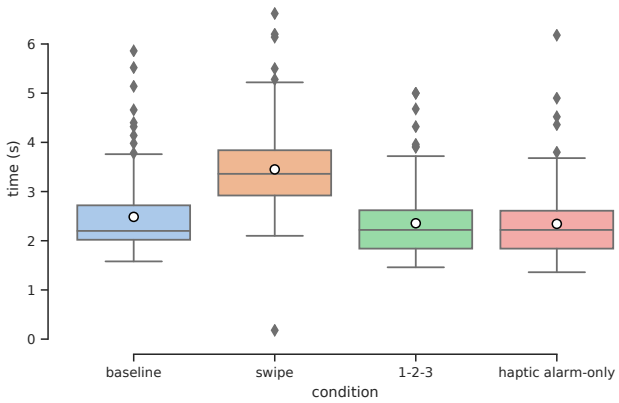
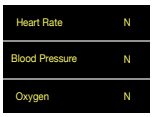
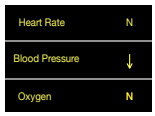
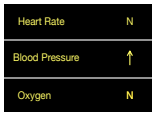
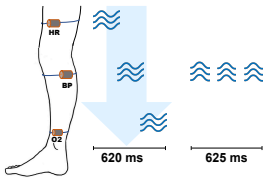
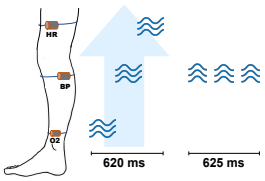
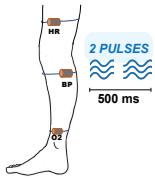
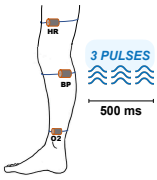
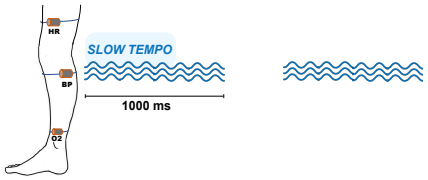
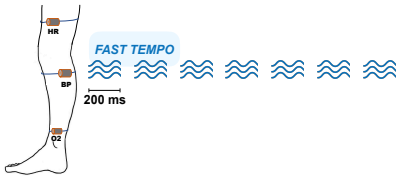


Fig. 3: Response time by condition.

The distribution of the results does not follow a normal distribution, but is skewed, as confirmed by a Shapiro-Wilk test. Consequently, non-parametric tests are used to assess the statistical significance of the results. A Friedman test found a statistically significant difference between the experimental conditions. A pairwise Wilcoxon test, with Holm correction, confirmed a significant difference between the *swipe* condition and the other three conditions ($p < 0.001$, $W = 1569$ for baseline, $W = 765$ for *1-2-3*, $W = 545$ for *haptic alarm-only*). A significant difference was also found between the baseline and the *haptic alarm-only* condition ($p < 0.05$, $W = 2387$) with a small effect size (Hedges' g of 0.4). Equally important, the improved response time for these last two conditions did not come at the expense of a high error rate, as seen in Figure 4.

A Friedman test of the response accuracy and a following pairwise Wilcoxon test, with Holm correction, confirmed that the *swipe* condition was significantly different from the

TABLE I: Experimental vital sign feedback cues by condition. A sample scenario is illustrated in which BP enters an abnormal condition triggering an alarm event. The pattern remains similar for other vitals on different spatial locations on the leg.

Condition	Cues for		
	Normal Vital	**Low Vital**	**High Vital**
baseline		 + Auditory Alarm	 + Auditory Alarm
swipe			
1-2-3			
haptic alarm-only	[silent]		

baseline, with $p < 0.05$ and $W = 2$. However, the test found differences between the baseline and the other conditions of *1-2-3* and *haptic alarm-only*, with $p > 0.05$, for which we cannot draw conclusions.

A two-one-sided t-test (TOST) procedure [26], applied to the response accuracy results, confirmed a within 15 % equivalence between the baseline and *1-2-3* condition ($p < 0.05$, $dof = 11$). The equivalence test between *haptic alarm-only* condition and the baseline was not conclusive.

As a means of assessing the combination of response time (speed) and correctness of response (accuracy), we plot the inverse efficiency scores (IES), as proposed by Townsend and Ashby [27], in Figure 5. Lower IES scores correspond to improved efficiency. The results of a Friedman test of the response accuracy, followed by a pairwise Wilcoxon test, with Holm correction, indicated that the IES values of the *swipe* condition were significantly different from the other conditions, with $p < 0.05$, $W = 0$ for baseline, $W = 1$ for *1-2-3* and $W = 4$ for *haptic alarm-only*.

A TOST procedure on the IES scores with equivalence bounds of 0.5 s suggests equivalence between the baseline and the *1-2-3* and *haptic alarm-only* conditions ($p < 0.05$, $dof = 11$). The overall scores for the distractor task are computed as the Fitts' index of performance [21] divided by the total time spent, per condition, with the results shown in Figure 6. For all conditions, the distribution of the scores likely follows a normal distribution, as checked with both QQplots and a Shapiro-Wilk test. A one-way repeated measures ANOVA found a statistically significant difference among the experimental conditions, ($F(3, 33) = 3.8$, $p = 0.02$, with an achieved power of 0.92). A pairwise T-test shows a statistically significant difference between the *haptic alarm-only* and *swipe* conditions ($p < 0.05$) with a medium effect size (Hedges' g close to 0.5) but no significant difference between the other conditions.

The IES results demonstrate superiority of the *1-2-3* condition over the baseline, suggesting not only that vibrotactile rendering of alarm events is feasible, but that it may even support improved clinical performance in recognizing and responding to these events. Moreover, performance on the distractor task suggests, encouragingly, that the vibrotactile rendering did not impose a greater workload on participants than the baseline condition.

V. Discussion

The results of our experiment offer strong support for the possibility of reducing clinical dependence on auditory alarms and graphical displays. However, several important caveats regarding the experimental results are in order. First,

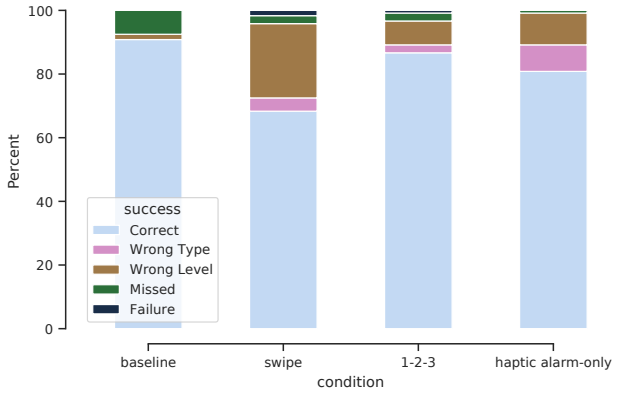


Fig. 4: Accuracy of first response by condition. Missed responses are considered to be those for which the participant does not respond before the second representation of the alarm, whereas failures are those for which the participant errs in identification of *both* the type and level of the vital sign.

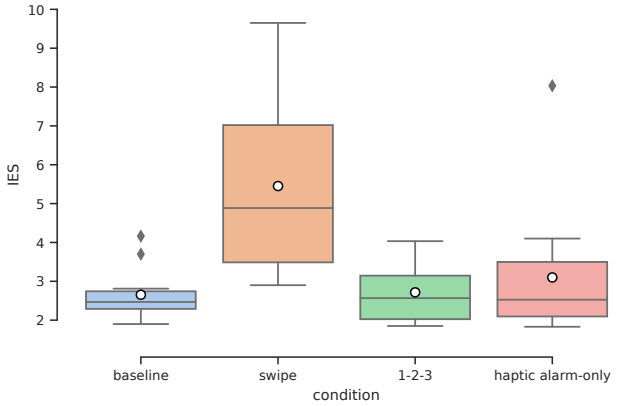


Fig. 5: IES scores by condition.

given that our participant pool was drawn from the general university population rather than trained clinicians, their level of experience attending to patient monitors and medical alarms is not necessarily reflective of realistic hospital conditions. Accordingly, their skills in monitoring of vital sign levels in parallel with other workload is likely to be inferior, which may have impacted either or both response time and recognition accuracy, in particular across conditions. These factors serve as an advisory note for our intended future experimentation with clinician participants.

On the other hand, we biased our experiment against the vibrotactile condition by the choice of a visual information display that was trivial to interpret. The information display on actual hospital monitors is dramatically more complex and demanding of clinician visual search and interpretation. We should note, however, that these monitors could help clinicians resolve any uncertainty of parsing the information provided via the vibrotactile display. Had the graphical monitor been included in the vibrotactile conditions, as would be

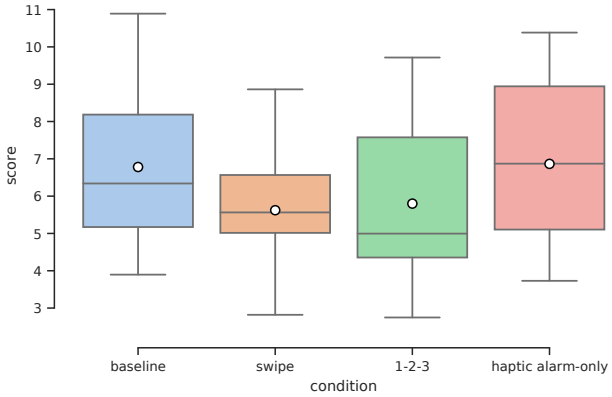


Fig. 6: Performance on Fitts' law distractor task.

more reflective of an actual hospital environment, this could well have reduced the incidence of incorrect vital sign or level identification observed in our experiments.

From a practical deployment perspective, another contribution of our study is in demonstrating the efficacy of a haptic display comprising a reduced number (3) of actuators for conveying similar information as used in previous studies (17) for example implemented in a haptic vest [19].

While our intent is to deliver the necessary information via haptics only, thereby reducing demands on visual attention, the co-presence of these monitors would be likely to further reduce the error rates seen, for example, in Figure 4. It should also be mentioned that since training was minimal, the results are likely to improve with time.

For the present stage of this research, we made a modest compromise by distributing the hardware over different points on the body. While it is likely that this could be improved over time, we believe that the results obtained thus far will motivate further efforts to develop an optimized hardware package that is better suited to the intended use case.

In the longer term, we anticipate that such haptic feedback based monitoring would be integrated as a first layer within a multimodal ecosystem for alarm delivery. In this scenario, a clinician would first be notified of an out-of-bounds vital sign through vibrotactile feedback, with additional information available through visual monitors. Physiological sensing techniques could be employed to determine whether the clinician perceived the notification [28], and if not, the alarm event could be conveyed with greater urgency, either by increasing the amplitude of the vibrotactile stimulus or switching to a disturbing auditory alarm.

VI. Conclusion

The results of our studies demonstrate strong promise for reducing the highly disturbing noise of audible alarms in hospital OR and ICU environments. We found that the delivery of alarm information through vibrotactile actuators, instead, can be similarly effective as auditory alarms in conjunction with graphical patient monitors in terms of both response

time and accuracy, and without significant impact on performance on a parallel, attention-demanding task. It should be emphasized that this comparison deliberately biased *against* the vibrotactile condition by comparison performed against a very simple graphical patient monitor, which required essentially no interpretation of displayed information. We anticipate that our approach may have attentional-sparing benefits across sensory modalities in cognitively demanding environments.

Further studies should be conducted to determine the practical effects of such haptic alarm information delivery mechanisms in conjunction with patient monitors, and under competing task loads more closely replicating actual hospital conditions. Nevertheless, it should be emphasized that the consequences of alarm fatigue will persist until the sheer number of alarms, volume, and disturbingly high rate of false positives, are also reduced. Future work should continue to tackle this serious problem, but also to improve the robustness of vital sign information delivery via vibrotactile cues, and to reduce the hardware requirements for doing so with the goals of improving monitoring and patient safety.

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