Single-Actuator Simultaneous Haptic Rendering for Multiple Vital Signs

Juliette Regimbal[0000-0003-4902-046X], Nusaiba Radi[0000-0002-7816-7674], Antoine Weill–Duflos[0000-0002-2782-3678], and Jeremy R. Cooperstock[0000-0002-3392-2541]

Department of Electrical and Computer Engineering and Centre for Interdisciplinary Research in Music, Media and Technology, McGill University
Montreal, Canada
{juliette,antoinew,jer}@cim.mcgill.ca

Abstract. Haptic displays have been investigated as a possible way to reduce the effects of alarm fatigue in clinical environments. Previous displays have employed multiple vibrotactile actuators, using the spatial dimension to aid in conveying information of a number of vital signs. However, inspired by prior work investigating multidimensional tactons, we wished to examine the effectiveness of a single actuator to communicate information regarding multiple vital signs simultaneously. The results of our evaluation suggest that this is not only feasible, but that with a carefully designed encoding strategy, we may be able obtain perception performance comparable to that achievable with multi-actuator displays.

Keywords: Single actuator · Haptic chord · Simultaneous signals.

1 Introduction

The World Health Organization recommends noise be limited in hospital environments to avoid increasing stress in patients [2]. Recommended values are often exceeded by large margins in real-world operating rooms (OR) and intensive care units (ICU) [7, 16]. These high noise levels not only exacerbate the stress levels of hospital clinicians, but can negatively impact patient recovery by reducing their quality of sleep [18].

A significant proportion of this noise comes from medical alarms, which exhibit high error rates. This exacerbates "alarm fatigue", in which medical professionals become desensitized to the alarms, and tend to ignore or silence them [6, 17], with detrimental effects on patient outcomes, including death.

Although it would not address the problem of false positives, a haptic display for patient alarms would transfer stimulus from the overloaded audio channel to the less used haptic channel, and further allow for personalized delivery of alarm information only to those clinicians for whom it is relevant. Moreover, the addition of haptic signaling to a pre-existing auditory display was found to reduce the perceived workload of responding to the display, without decreasing participant performance [5]. These factors could significantly alleviate noise in the OR and ICU, thereby helping to reduce alarm fatigue.

Previous research has explored haptic displays for use in medical alarms. These have primarily used multiple vibrotactile actuators, or "tactors", distributed across the body, employing spatial and temporal location to encode information [9,14,15]. To date, the presentation of multiple vibrotactile features for this purpose has been largely sequential: one or more tactors are actuated in series in order to convey information to the wearer regarding one or more vital signs [13], which may be overly demanding of the wearer's short-term memory.

Earlier examples of haptic rendering for vital sign levels also tended to use multiple tactors. Notably, Ferris and Sarter employed an apparatus consisting of eighteen tactors. Their comparison of a discrete tactile alarm condition against different designs of a continuous tactile display for monitoring multiple vital signs found that the former was preferred by participants, but the continuous monitoring displays resulted in superior performance in terms of response time, diagnostic accuracy, and physiological management scores [9]. If similar benefits could be obtained with reduced hardware requirements, this would offer a more energy- and space-efficient solution that would likely face fewer hurdles to adoption.

We were thus motivated to tackle the challenge of designing a vibrotactile encoding strategy that could efficiently convey information regarding multiple vital signs, in parallel. This requires the use of multiple vibrotactile features to encode separate, simultaneous messages. In practice these features may conflict with each other in unexpected ways, resulting in an effect known as "tactile clutter" [8], which decreases the intelligibility of the information conveyed. To be usable in a medical environment, a display must also be understandable when the user's attention is focused on another task rather than on the display itself.

This paper introduces a method of encoding the levels of three vital signs—heart rate, blood pressure, and peripheral oxygen saturation (SpO_2)—each of which can take on one of three different states—normal, high, and low—using a single vibrotactile actuator. Our approach differs from previous work, which also conveyed through a single actuator information regarding three parameters, each of which may take on multiple values [4]. First, similar to the behavior of present-day auditory patient monitors, we render a haptic representation of patient vital signs in both alarm states and "normal" (i.e., non-alarm) states, and second, we display these vitals continuously. Of central importance to the success of this approach is the design of an effective encoding strategy, described in the following section.

2 Display Design

The vital signs are encoded into a multidimensional haptic icon or "tacton" [3], composed of a series of vibrations rendered by a tactor attached to the wrist. Each vital sign is represented by a different feature of the tacton.

2.1 Beats, Tempo, and Chords

Our vibrotactile encoding employs a train of four-beat measures, with the tempo (number of beat per minute) varying based on the parameters described in Section 2.2. A second parameter available to us is the number of beats of each measure in which a vibration is rendered, and the third parameter relates to frequencies of vibration. Human vibrotactile perception is sensitive to a smaller range of frequencies than audition [11]. A person's ability to haptically discriminate between frequencies separated by intervals of 20 Hz decreases at frequencies greater than 60 Hz [10]. As such, frequency is generally a poor feature for information encoding, especially while other features of the signal may vary simultaneously. An alternative to a single frequency is to present two frequencies simultaneously as a chord, consisting of the base frequency, f, and the chordal frequency, f_c. The difference between the two frequencies, expressed as the number of equally tempered semitones separating them, results in a sense of consonance or dissonance [20]. Dissonance is perceived by the user as the sense of roughness in the rendered waveform.

The degree of overall consonance tends to increase with the base frequency, attaining a maximum as f_c reaches $2f$, i.e., 12 semitones or a full octave, and decreases to a minimum for chordal frequencies slightly offset from the base frequency [20]. A difference of zero semitones (rendering a single frequency) is by definition in perfect consonance with itself.

2.2 Mapping

In designing the display, care was taken to make changes to each feature sufficiently distinct so as to facilitate their disambiguation. For example, a user should not mistake a change in a haptic chord with a change in tempo. The encodings used for our vibrotactile display are summarized in Table 1.

		Level		
Vital Sign	Feature Modified	Low	Normal	High
Heart Rate	Tempo	80 bpm	160 bpm	320 bpm
Blood Pressure	Pulses per Measure	1 pulse	2 pulses	3 pulses
SpO_2	Chord	80 Hz and 25.2 Hz	80 Hz	80 Hz and 190.2 Hz

Table 1: Each vital sign is related to the modified feature of the pulse train and the value of that feature at the different vital sign levels.

Blood pressure is expressed as the number of beats per measure in which a vibration is rendered, which we refer to as "pulses": one pulse for low blood pressure, two pulses for normal, and three pulses for high. The remaining beat(s) of the measure are silent to delimit the different groupings.

The most obvious mapping is that of expressing the heart rate as the tempo at which the beats are rendered. For the purposes of our experiment, we selected heart rates of 40, 80, and 160 heartbeats per minute as low, normal, and high heart rate values, respectively. However, we doubled these rates to obtain the corresponding tempi of 80, 160, and 320 beats per minute (bpm). Thus, for the case of a normal heart rate and normal blood pressure, the pulse train consists of measures in which pulses are rendered for two out of the four beats, at a rate of 160 bpm. This feels equivalent to an actual heart rate of 80 bpm, illustrated in Figure 1 (upper), whereas for a high heart rate and high blood pressure, we have 320 bpm of which pulses are rendered three beats out of every four, as seen in Figure 1 (lower).

This mapping was chosen since different levels of the vital signs are represented discretely, making it difficult to confuse them. Furthermore, since a new rendering occurs every few seconds, independently of the previous values, the user is not required to focus continuously on the number of pulses.

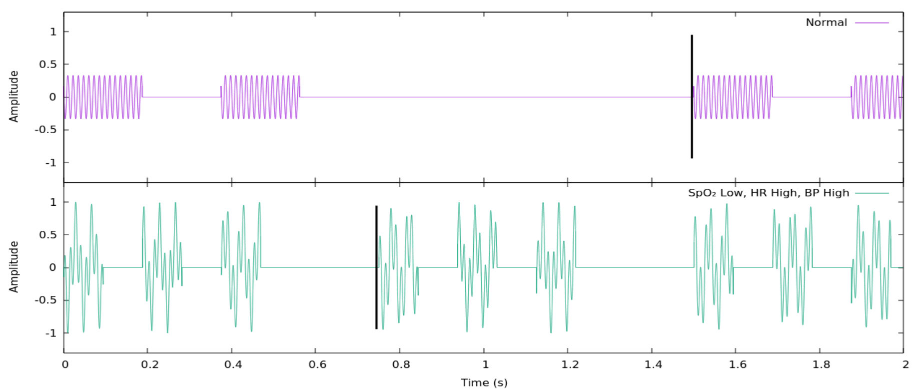


Fig. 1: Examples of haptic waveforms representing the vital signs. The upper waveform occurs when all vital signs are normal. Two pulses occupy the first two beats of each measure. The lower waveform occurs when SpO_2 is low, heart rate is high, and blood pressure is high (although such a combined alarm event was not allowed in our experiment). This waveform is represented by a dissonant chord at increased tempo, three beats per measure. The first measure starts at 0 s for both waveforms and lasts until the black bar.

We opted to use the haptic chord for SpO_2 level, since this vital sign is typically represented by hospital monitors using auditory tone pitch [12]. A single frequency (0 semitones) was chosen to represent a normal level of SpO_2. Through trial and error, chordal frequency offsets of -8 and +3 semitones were found to be significantly dissonant to be distinguishable from the single frequency and perceived sufficiently distinctly to express the two abnormal levels (high and low). To further distinguish the resulting chords, the respective chordal frequencies, f_c, associated with high and low SpO_2 were then offset by ± 12 semitones (one octave), resulting in chordal frequency offsets of -20 semitones

(25.2 Hz) for low SpO_2 and +15 semitones (190.2 Hz) for high SpO_2. A base frequency of 80 Hz was selected through multiple rounds of pilot testing.

To reduce the risk of desensitization to the semi-continuous haptic stimuli, amplitude was maintained at 40 % of maximum, except for abnormal levels of SpO_2 or blood pressure, when it was increased to 100 %. Through pilot testing, we determined that abnormal heart rate states could still be easily discriminated at the reduced amplitude.

3 Evaluation Methodology

A portable implementation of the display described in Section 2 was developed and used to evaluate participants' response accuracy and response time to events in which one of the vital signs changed to an abnormal level.

3.1 Apparatus

The encoding method described above was implemented as a set of Pure Data patches, which take inputs for the values of the three vital signs. An Android application, running on a Xiaomi Mi Pad 4 tablet, generates vital signs in accordance with the procedure described in Section 3.3, and renders the encoded vitals using libpd. This application also collects user responses and runs a simultaneous distractor task.

The apparatus, illustrated in Figure 2, consists of a Haptuator Original (Tactile Labs, Montreal) [19] vibrotactile actuator, driven using one audio channel from the Android tablet, and amplified by a SURE Electronics class-D audio amplifier, while the second channel provides audio input to a pair of headphones.

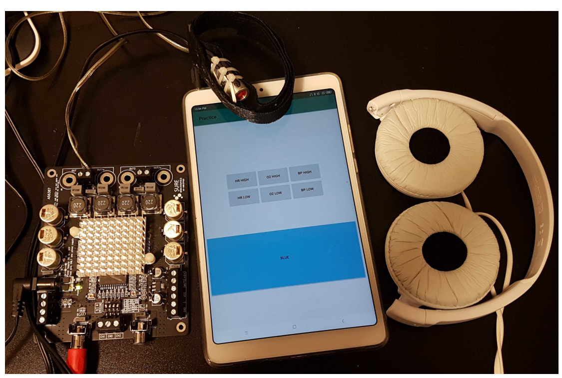


Fig. 2: The Xiaomi Mi Pad 4 audio is split with one channel sent to the headphones and the other to a SURE Electronics audio amplifier connected to the Haptuator Original.

3.2 Participants

Participants were recruited under approval of the McGill Research Ethics Board, file number 388-0217. A total of fourteen participants performed the experiment, and were compensated 10 CAD for their time.

3.3 Procedure

Participants first had the Haptuator strapped to the top of one wrist. The experiment consisted of a calibration phase, training phase, a practice test, and a full test. The headphones were worn during the practice and full tests.

Calibration During the calibration phase, the overall amplitude of the pulses was adjusted by the participants so that they could be easily felt but were not too strong. Participants were allowed to return to calibration during the training phase as they were exposed to the actual encoding.

Training All the vital signs began rendered in normal states. Participants were then introduced to the abnormal states one at a time, in a set order of blood pressure, heart rate, and SpO_2. For the purposes of our experiment, only a single vital sign was allowed to enter an abnormal state at any particular time. Participants were then allowed to manually control the states of each vital sign and indicate when they are ready to continue.

Practice At this point, the distractor task was introduced. The names of colors were spoken at a rate of one per second, played through headphones with pink noise overlaid. Participants listened to this audio stream and tapped a button labelled "blue" whenever the word "blue" was heard.

The practice test proceeded through five different abnormal states. The times between abnormal states were generated using a Poisson distribution with $\lambda = 20\,\mathrm{s}$. The specific abnormal states rendered were selected with a discrete uniform distribution. Participants were instructed to consider the distractor task as their primary activity. They were also informed that when a vital sign enters an abnormal state, a correct answer will result in the vital sign returning to normal, as if a clinician had corrected the problem causing the abnormal value. If participants did not respond correctly to an abnormal state within 30 s, the vital sign would return to normal on its own. Participants were allowed to ask questions during this test.

A metric was imposed before testing began that participants must respond correctly to four of the five different states, within two trials, to proceed to the next test. This performance metric ensured a reasonably short training time, and was designed to exclude participants who were either having difficulty learning the encoding or were otherwise non-compliant. In this case, which occurred for only one of the fourteen recruited participants, that participant's data were excluded from the results.

Full Test The full test proceeded in the same manner as the practice with some adjustments. Participants were not allowed to ask questions, and the number of abnormal states was increased to ten, with $\lambda = 90$ s for the Poisson distribution. Participants still had to respond to the distractor task as before.

4 Results

One of the fourteen recruited participants was excluded for failing to pass the practice test metric in Section 3.3. The remaining participants responded correctly to 95.38 % of the (13 participants $\times$ 10 events/participant =) 130 events presented within the thirty seconds necessary to avoid being considered as a "miss". Three of the "missed" presentations were for low heart rate, two were for high SpO_2, and one was for low blood pressure. As shown in Figure 3a, participants took on average 4.96 s to enter the correct response after an abnormal condition began to be rendered. The average time for a participant to enter their first response, correct or not, was 4.12 s.

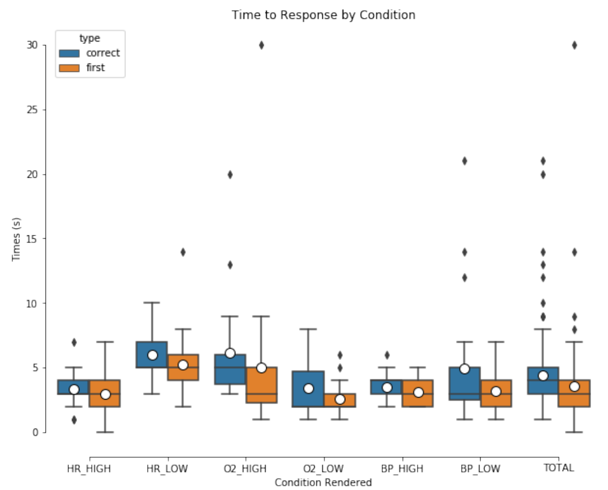
The correct rate for first responses was 73.85 %. This was highest in response to high heart rate (88.00 % of first responses correct) and lowest in response to high SpO_2 (55.56 % of first responses correct). A more detailed comparison of the types of first responses by condition is shown in Figure 3b. For alarm events related to heart rate and blood pressure, the most common error was incorrect recognition of the associated vital sign, for example confusing high heart rate with high blood pressure. However this was not the case for SpO_2, for which the most common error was in interpretation of the level, which occurred in 33.3 % of the instances of high SpO_2 and 14.3 % for low SpO_2. This suggests that the selected chords are not easily distinguishable.

Clearly, incorrect recognition of a vital sign alarm event would be unacceptable in a real hospital scenario, but it bears emphasis that detection of the "event" itself was impressively high, with misses only on the SpO_2 high event, which occurred one time. In practice, a clinician would consult a patient monitor upon perceiving the change of the vital sign, as conveyed through the haptic mechanism, to verify their understanding of the actual patient condition, as is the case at present with audio alarms.

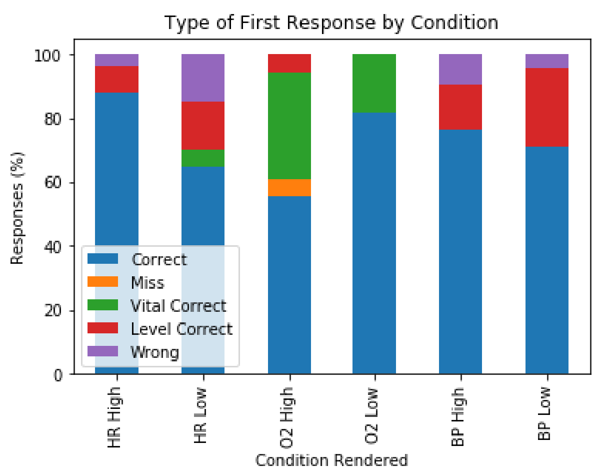
For the distractor task, participants responded to the word "blue" in 83.08 % of cases. The mean time to respond to the distractor was 920 ms.

5 Conclusion

The results show that participants are generally capable of (i) perceiving a change from a normal to an abnormal state and (ii) quickly identifying the abnormal state. First response accuracy rates and first response times are comparable to those achieved with a three-actuator apparatus, worn on the leg, in a different experiment conducted by our group [1]. Based on more recent pilot data, we believe that the relatively poor disambiguation of the dissonant chords rendered may be resolved with different values of the chordal frequencies. Once



(a) Comparison of time for participants to respond to a rendered event, as well as the time to respond *correctly* to the event.



(b) Types of first responses to rendered events. “Vital Correct” and “Level Correct” refer respectively to a participant answering the correct vital sign but not the level and the right level but not the vital sign.

Fig. 3: Response times and first response types by rendered event.

such tuning of the various encoding parameters has been carried out, an important test for future work would be to compare these displays under the same conditions. This would offer a clearer understanding of the tradeoffs between the single-actuator display and more complicated hardware, in the context of vibrotactile displays for medical purposes. It bears emphasis that the device, consisting of a single vibrotactile actuator, strapped to the wearer's arm, is highly mobile, and therefore, suitable for testing in a realistic hospital use-case scenario. Additionally, the portable nature of the apparatus allows for future work to employ more realistic settings.

Acknowledgment

We would like to thank Joseph J. Schlesinger and Parisa Alirezaee for their time and advice throughout this project.

References

1. Alirezaee, P., Weill-Duflos, A., Schlesinger, J., Cooperstock, J.R.: Exploring the effectiveness of haptic alarm displays for critical care environments. In: Haptics Symposium. IEEE, Washington DC, USA (Mar 2020)
2. Berglund, B., Lindvall, T., Schwela, D.H.: Guidelines for Community Noise (Apr 1999)
3. Brewster, S., Brown, L.M.: Tactons: Structured tactile messages for non-visual information display. In: Proceedings of the Fifth Conference on Australasian User Interface - Volume 28. p. 15–23. AUIC '04, Australian Computer Society, Inc., AUS (2004)
4. Brown, L.M., Brewster, S.A., Purchase, H.C.: Multidimensional Tactons for Non-visual Information Presentation in Mobile Devices. In: Proceedings of the 8th Conference on Human-computer Interaction with Mobile Devices and Services. pp. 231–238. MobileHCI '06, ACM, New York, NY, USA (2006). https://doi.org/10.1145/1152215.1152265, event-place: Helsinki, Finland
5. Burdick, K.J., Bell, A.S., McCoy, M.C., Samuels, J.L., Jolly, A.S., Patel, S.S., Balas, J.B., Patten, K.J., Schlesinger, J.J.: Using multisensory haptic integration to improve monitoring in the intensive care unit. Auditory Perception & Cognition **0**(0), 1–19 (2020). https://doi.org/10.1080/25742442.2020.1773194, `https://doi.org/10.1080/25742442.2020.1773194`
6. Cvach, M.: Monitor Alarm Fatigue: An Integrative Review. Biomedical Instrumentation & Technology **46**(4), 268–277 (Jul 2012). https://doi.org/10.2345/0899-8205-46.4.268
7. Darbyshire, J.L., Young, J.D.: An investigation of sound levels on intensive care units with reference to the WHO guidelines. Critical Care **17**(5), R187 (2013). https://doi.org/10.1186/cc12870
8. Erp, V., Jan, B., Veltman, J., van Veen, H., Oving, A.: Tactile torso display as countermeasure to reduce night vision goggles induced drift. Tech. rep., Human Factors Research Institute (Soesterberg, Netherlands) (2003)
9. Ferris, T.K., Sarter, N.: Continuously Informing Vibrotactile Displays in Support of Attention Management and Multitasking in Anesthesiology. Human Factors **53**(6), 600–611 (Dec 2011). https://doi.org/10.1177/0018720811425043

10. Formby, C., Morgan, L.N., Forrest, T.G., Raney, J.J.: The role of frequency selectivity in measures of auditory and vibrotactile temporal resolution. The Journal of the Acoustical Society of America **91**(1), 293–305 (Jan 1992). https://doi.org/10.1121/1.402772
11. Franzén, O., Nordmark, J.: Vibrotactile frequency discrimination. Perception & Psychophysics **17**(5), 480–484 (Sep 1975). https://doi.org/10.3758/BF03203298
12. Goldman, J.M., Robertson, F.A.: Pulse-OX Tone Conveys Vital Information. APSF Stresses Use of Audible Monitor Alarms p. 20 (2004)
13. Gomes, K.M., Reeves, S.T., Riggs, S.L.: The evaluation of tactile parameters and display prototype to support physiological monitoring and multitasking for anesthesia providers in the operating room. IEEE Transactions on Haptics pp. 1–1 (2019). https://doi.org/10.1109/TOH.2019.2960017
14. Katzman, N., Gellert, M., Schlesinger, J.J., Oron-Gilad, T., Cooperstock, J.R., Bitan, Y.: Evaluation of tactile cues for simulated patients' status under high and low workload. In: International Meeting. Human Factors and Ergonomics Society (HFES) (Oct 2019). https://doi.org/https://doi.org/10.1177/1071181319631285
15. Ng, J., Man, J.: Vibro-Monitor: A vibrotactile display for physiological data monitoring. In: Human Interface Technologies Conference (2004)
16. Otenio, M.H., Cremer, E., Claro, E.M.T.: Noise level in a 222 bed hospital in the 18th health region - PR. Revista Brasileira de Otorrinolaringologia **73**(2), 245–250 (Apr 2007). https://doi.org/10.1590/S0034-72992007000200016
17. Sendelbach, S., Funk, M.: Alarm Fatigue. AACN Advanced Critical Care **24**(4), 378–386 (Oct 2013). https://doi.org/10.4037/NCI.0b013e3182a903f9
18. Xie, H., Kang, J., Mills, G.H.: Clinical review: The impact of noise on patients' sleep and the effectiveness of noise reduction strategies in intensive care units. Critical Care **13**(2), 208 (Mar 2009). https://doi.org/10.1186/cc7154
19. Yao, H.Y., Hayward, V.: Design and analysis of a recoil-type vibrotactile transducer. The Journal of the Acoustical Society of America **128**(2), 619–627 (Aug 2010). https://doi.org/10.1121/1.3458852
20. Yoo, Y., Hwang, I., Choi, S.: Consonance of Vibrotactile Chords. IEEE Transactions on Haptics **7**(1), 3–13 (Jan 2014). https://doi.org/10.1109/TOH.2013.57