Overlapping Melodic Alarms Are Almost Indiscriminable

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Objective: We explore how accurately and quickly nurses can identify melodic medical equipment alarms when no mnemonics are used, when alarms may overlap, and when concurrent tasks are performed. **Background:** The international standard IEC 60601-1-8 (International Electrotechnical Commission, 2005) has proposed simple melodies to distinguish seven alarm sources. Previous studies with nonmedical participants reveal poor learning of melodic alarms and persistent confusions between some of them. The effects of domain expertise, concurrent tasks, and alarm overlaps are unknown. **Method:** Fourteen intensive care and general medical unit nurses learned the melodic alarms without mnemonics in two sessions on separate days. In the second half of Day 2 the nurses identified single alarms or pairs of alarms played in sequential, partially overlapping, or nearly completely overlapping configurations. For half the experimental blocks nurses performed a concurrent mental arithmetic task. **Results:** Nurses' learning was poor and was no better than the learning of nonnurses in a previous study. Nurses showed the previously noted confusions between alarms. Overlapping alarms were exceptionally difficult to identify. The concurrent task affected response time but not accuracy. **Conclusion:** Because of a failure of auditory stream segregation, the melodic alarms cannot be discriminated when they overlap. Directives to sequence the sounding of alarms in medical electrical equipment must be strictly adhered to, or the alarms must redesigned to support better auditory streaming. **Application:** Actual or potential uses of this research include the implementation of IEC 60601-1-8 alarms in medical electrical equipment.

INTRODUCTION

It has often been remarked that medical equipment alarms are uninformative and that it is difficult to discriminate among them (Edworthy & Hellier, 2005). In September 2005 the final version of a new international standard for medical equipment alarms was published that addresses such problems: IEC 60601-1-8 (International Electrotechnical Commission, 2005). Notably, IEC 60601-1-8 proposes the use of melodic alarms to help users discriminate alarms. The alarms are described and explained in Block, Rouse, Hakala, and Thompson (2000).

Unfortunately, the melodic alarms were not tested for identifiability or discriminability before the standard was released. Recently, Sanderson, Wee, and Lacherez (2006) and Williams and Beatty (2005) have shown that nonmedical participants cannot accurately identify the IEC 60601-1-8 melodic alarms after reasonable amounts of practice. Moreover, participants show entrenched confusions between certain pairs of alarms. In addition, Sanderson et al. (2006) compared learning with the mnemonics supplied by the standard versus learning without the mnemonics. Although there was no difference in speed or accuracy between the two conditions, participants learning without mnemonics tended to share fewer entrenched confusions with other participants and to have slightly more idiosyncratic confusions.

Several drawbacks of that research are as follows. First, nonclinical participants were used, whereas medical or nursing personnel may learn faster because they are aware of the significance of the state indicated by the alarms. Accordingly, in the present research we tested how effectively registered nurses working at a large metropolitan

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teaching and research hospital could learn the alarms. Second, although the mnemonics are supplied in the standard, because personnel in many hospitals will not learn the alarms via standard in-service training sessions and will not read the manuals, they may not be aware of the mnemonic mappings. As one part of our program of investigation we wished to test the effectiveness of the melodic alarms under conditions in which no information about mnemonic mappings is at hand.

Third, in previous studies participants could always concentrate on recognizing the alarms and did not have to perform other tasks, whereas in the busy operating room or intensive care unit medical staff time-share many tasks. In the present research we compare participants' ability to identify alarms while performing a concurrent true-false test of simple arithmetic expressions versus while performing no concurrent task. Mental arithmetic tasks are reasonably common in medical contexts. Nurses frequently must calculate the correct dosage of a drug, assess a patient's body weight in order to interpret other signs, calculate time intervals between observations and deliveries of drug, and relate vital signs to normal ranges. Such tasks may engage the articulatory loop of working memory (Baddeley, 1986; Logie, Gilhooly, & Wynn, 1994), which may compete with nurses' need to encode and identify alarms and hold the conclusion in memory while selecting an appropriate motor response. Many other distractions and concurrent activities compete with alarm identification, but we focused on mathematical tasks to achieve a consistent, controlled level of distraction from the alarms.

Finally, in previous studies the discriminability of single alarms was examined, whereas alarms can overlap with each other. The IEC 60601-1-8 standard notes that melodic alarms should be distributed in time, so that even if they are triggered simultaneously they will not overlap in time when they sound, or a single prioritized alarm will sound in preference to all the individual alarms. However this will not always be easy to achieve, as it requires a centralized controller for all alarms or intelligent alarm management. Medical equipment is increasingly integrated, but the full integration required to ensure satisfactory prioritization so that no alarms overlap in time is still some way off (Imhoff & Kuhls, 2006). Moreover, in an intensive care unit or postanesthesia recovery unit there are many adjacent patient bays with similar but nonintegrated equipment whose alarms may overlap in time.

Auditory scene analysis (Bregman, 1990) would predict that melodic alarms in the same musical register and with similar rhythm, pitch, and timbre will be difficult to identify when they overlap. Differences in these parameters are a necessary condition for auditory streaming, which is the effective segregation of several simultaneous sound sources (Bregman, 1990). Moreover, being able to hear the first few notes of a melody is crucial to identifying it – denying this will also make alarm identification more difficult (Schulkind, 2004). Finally, McGookin and Brewster (2004) demonstrated a marked decrease in participants' ability to identify overlapping earcons (short musical motifs; e.g., melodic alarms) as the number of overlapping earcons increased, but performance improved if different timbres or staggered onsets were used.

In the following experiment we hypothesized that nurses will share the confusions between alarms seen in prior studies. Alarm identification will become slower and less accurate when a concurrent task is performed and as alarm overlap increases.

METHOD

Participants

Fourteen nurses (11 women, 3 men) were recruited for participation when off duty from the intensive care and general medical units of two Brisbane teaching and research hospitals. Participants were paid $40 (Australian) for around 3 hr of participation and were also given a small gift. The mean age of participants was 36 years (maximum = 52 years, minimum = 23 years). Five of the 14 nurses had at least 1 year of formal musical training. No participant reported any diagnosed hearing impairment. The study was conducted in accordance with the ethical review processes of the University of Queensland and within the guidelines of the National Health and Medical Research Council.

Apparatus and Materials

A computer program written in Java Version 1.4 controlled the learning and test cycles on Days 1 and 2 and also controlled the transfer phase on Day 2. For each learning phase, a screen presented eight buttons, each labeled with the name of one of the eight alarms. Participants heard the corresponding alarm when they pressed each button. For each test phase a similar screen was shown, but participants had to listen to an alarm first and then press the button with its name.

An Acer Pentium 4 laptop with an AC97 64-bit soundcard and a 1.70-GHz CPU was used for the experiment. Two Sony Megabass Active Speakers played the alarms at a sound pressure level comfortable for the participant. A sound pressure meter was used to ensure that the sound pressure level was as near as possible to 80 dB(A) while not exceeding this value, as this is the acceptable volume specified in the Australian standard (National Occupational Health and Safety Commission, 1991). Amplitude was measured using a slow A-weighted average from the position of the participant's ear while sitting at the computer. All alarm sounds gave the same reading, fluctuating around 79 to 80 dB(A). From the Fletcher-Munsen equal loudness contours (Benson, 1986) this is approximately 70 dB above the normal threshold for free-field tones in this frequency range. Participants performed the learning and test phases in a quiet room at their workplace. The ambient noise level was always low, fluctuating from a minimum of below 40 dB(A) and a maximum of 56 dB(A) as verified by a 15-min sample at each location. No participant reported difficulty hearing the alarms.

Alarm audio files. Only the eight high-priority alarms were used because they were the most critical and because testing all alarms would have lengthened the experiment unduly. The melodic alarms had a pattern of five notes in a 3-2 pattern, repeated, and were in the scale of C major.

General: C4-C4-C4 – C4-C4,
C4-C4-C4 – C4-C4

Oxygen: C5-B4-A4 – G4-F4,
C5-B4-A4 – G4-F4

Ventilation: C4-A4-F4 – A4-F4,
C4-A4-F4 – A4-F4

Cardiovascular: C4-E4-G4 – G4-C5,
C4-E4-G4 – G4-C5

Temperature: C4-D4-E4 – F4-G4,
C4-D4-E4 – F4-G4

Infusion: C5-D4-G4 – C5-D4,
C5-D4-G4 – C5-D4

Perfusion: C4-F#4-C4 – C4-F#4,
C4-F#4-C4 – C4-F#4

Power failure: C5-C4-C4 – C5-C4,
C5-C4-C4 – C5-C4

Alarm design was guided by the IEC 60601-1-8 standard. The alarms were created with Csound and processed on a Pentium 4 1.9-GHz PC with a Soundblaster Live 5.1 soundcard. Pulse rise time (for amplitude to rise from 10% to 90% of maximum) and pulse fall time (downwards equivalent) for each tone was 8 ms. Pulse duration was 102 ms: 100 ms at maximum amplitude plus 1 ms each for the period from 90% to 100% and 100% to 90% amplitude. Pulse spacing from end of one pulse (when amplitude fell to 90% of maximum) to start of the next pulse (when amplitude rose to 90% of maximum) was 48 ms (inadvertently 2 ms less than required). Spacing between the end of pulse 3 and start of pulse 4 was 198 ms (pulse start and end defined as above). Spacing between pulses 5 and 6 was 498 ms (defined as above). Total alarm duration was 2220 ms. Tone fundamental frequencies ranged from middle C (C4: 261.626 Hz) to the octave above (C5: 523.251 Hz). A simple harmonic spectrum was added to the fundamental using harmonics f3, f5, f7, and f9 at 15 dB less than the fundamental.

The eight high-priority melodic alarms were recorded as separate audio tracks using the Audacity™ software. For the transfer phase, audio tracks were created on Audacity™ by pairing a first alarm with a second alarm at three levels of overlap.

- For nearly overlapping alarms, the second alarm intercepted the first alarm between the first and second note of the first alarm (e.g., between the first C5 and B4 of the oxygen alarm). All 40 possible pairs were used because the nearly overlapping alarms were our principal focus.
- For partially overlapping alarms, the second alarm intercepted the first alarm between the third and fourth notes of the first alarm (e.g., between the first A4 and G4 of the oxygen alarm). A random selection of 14 pairs was chosen from the 40 possible pairs to provide a contrast with the overlapping alarms and to help prevent the development of stimulus-specific strategies for handling the overlapping alarms.
- For sequential alarms, the second alarm sounded when the first alarm had finished. All 40 possible pairs were used for purposes of comparison with the nearly overlapping alarms.

In addition, each of the seven single high-priority alarms appeared twice at transfer, making 14 in all. The single alarms allowed us to test the effect of the transfer context on learning. In sum, 108 alarms or alarm pairs were used at transfer.

In the transfer task, not all pairs of high-priority alarms were used. First, pairings of an alarm with itself were excluded because there would not be multiple simultaneous soundings of the same alarm from a piece of equipment. Second, the general alarm was excluded because it would be superceded by melodic alarms. Third, perfusion/cardiovascular and cardiovascular/perfusion alarm pairs were excluded because they are unlikely to occur. When a patient is on a perfusion machine, as during open-heart surgery, most cardiovascular alarms from the patient monitoring system are disabled to avoid false alarms.

Paper materials. Separate sheets for Day 1 and Day 2 contained the instructions provided by the experimenter at the beginning of each session. Participants could refer to the instruction sheets at any point. Questionnaires probed participants' musical and nursing background and their views about the alarms so as to provide convergent evidence for objective performance findings. Finally, a debriefing sheet provided the rationale and motive for the study.

Procedure

The participant sat in front of a laptop computer with a mouse located on his or her preferred side. Computer speakers were placed 52 cm apart behind and symmetrically on either side of the computer, approximately 75 cm away from the participant's ears.

On Day 1, participants were introduced to the goal of the experiment. They then proceeded to the learning and test cycles. For the learning phase, participants were seated in front of a computer displaying eight buttons, each labeled with the parameter corresponding to a melodic alarm. Participants clicked the buttons to hear the alarms in any order, but they could hear a maximum of only 24 alarms per learning phase. In this experiment, participants were not provided with the IEC 60601-1-8 mnemonics.

When each learning phase was completed, participants proceeded to the test phase. A new screen contained a button labeled "play alarm" at left and buttons corresponding to the eight alarms at right. Participants listened to the alarm and then clicked what they determined was the correct button. The goal was to complete two successive test phases of the eight alarms with 100% correct. After every test phase participants received feedback on which alarms, if any, they had gotten wrong. Learning was halted when the learning goal was reached or when 50 min had passed.

On Day 2 participants first performed a long-term memory test by completing two successive test phases with no intervening learning phases. They could then review the alarms in four final learning and test cycles, like those on Day 1.

For the remainder of Day 2, participants transferred to a real-time test of their ability to recognize single, sequential, nearly overlapping, and partially overlapping alarms, with and without the concurrent arithmetic task. For the arithmetic task, participants pressed a space bar to see each arithmetic expression. A single-digit arithmetic expression was displayed on the computer screen (e.g., $9 + 1 = 10$, $5 - 7 = 3$). The participant pressed the P key if the expression was correct or the Q key if the expression was incorrect. First, participants became familiar with performing the arithmetic task for around 5 min. Then they transferred to a task in which they identified alarms either with or without the concurrent task.

In the transfer task, an alarm or alarm pair sounded at random intervals between 14 and 18 s long. At the right of the screen were two sets of seven buttons corresponding to the seven high-priority alarms used. If one alarm had sounded, only one column of alarm buttons became active. If two alarms had sounded, then two columns of alarm buttons became active. Participants clicked a button in the left column for the first alarm and (if needed) a button in the right column for the second alarm.

Design

The transfer task was a mixed design with one between-subjects factor (musical training) and two within-subjects factors (kind of alarm pattern, presence or absence of the concurrent task). Of the eight blocks of experimental trials, there were four in which the arithmetic task was present and four in which it was absent. All 108 alarm pairs/alarms were tested once under each level of the concurrent task, with 1 randomly selected pair being repeated to make 28 alarms/pairs per block. The order of concurrent task conditions was counterbalanced in AANNNNAA and NNAAAANN orders (A = arithmetic and N = no arithmetic) with participants assigned to orders in an alternating fashion. Each block was around 7 min in duration.

RESULTS

Learning

Learning was assessed by calculating nurses' speed and accuracy at four phases in learning: the first two tests of Day 1, the last two tests of Day 1, the long-term memory tests at the start of Day 2, and the last two relearning tests on Day 2 before transfer. Phase of learning was a within-subjects factor and musical training a between-subjects factor.

Results for accuracy are shown in Figure 1. Accuracy differed across the four phases of learning, $F(3, 36) = 20.31$, $MSE = 0.016$, $p < .001$. Tukey HSD tests with a familywise alpha level of .05 indicated that nurses' learning improved within each day but not across days. Overall, nurses with musical training performed significantly more accurately than did those without it, $F(1, 12) = 5.68$, $MSE = 0.086$, $p = .03$, with accuracy levels reaching around 80% for those with musical training and 50% for those without. Only 2 of the 14 nurses achieved the 100% accuracy criterion in two successive tests.

Figure 2 shows the pattern of confusions during Day 2 relearning. Percentages next to nodes indicate the average percentage correct identifications for that alarm. Percentages on links indicate the percentage of nurses who 50% or more of the time identified the alarm at the start of the arrow as the alarm at the end of the arrow. For example, more than one third of nurses identified the cardiovascular alarm as the temperature alarm 50% or more of the time, and more than one third identified the power failure alarm as the perfusion alarm 50% or more of the time. The fact that all nurses could correctly identify the general alarm indicates that the basic audibility of alarms was not the source of the confusion.

Transfer

A MANOVA was conducted with accuracy and response time as the criteria, arithmetic task (present or absent) and alarm sequence (nearly overlapping, partially overlapping, sequential, and single) as within-subjects factors, and musical training (musically trained vs. not musically trained) as a between-subjects factor. When two alarms were presented, participants had to correctly identify both alarms in correct order for the response to be scored correct.

In the multivariate tests musical training (Wilks's $\Lambda = .542$), $F(2, 11) = 4.64$, $p = .035$, alarm sequence (Wilks's $\Lambda = .019$), $F(2, 11) = 61.134$, $p < .001$, and arithmetic task (Wilks's $\Lambda = .442$), $F(2, 11) = 6.931$, $p = .011$, were all significant. Follow-up univariate analyses of the significant factors revealed that musically trained participants were significantly more accurate in identifying the alarms, $F(1, 12) = 8.09$, $MSE = 0.135$, $p = .015$, but did not have faster response times (see Figure 3).

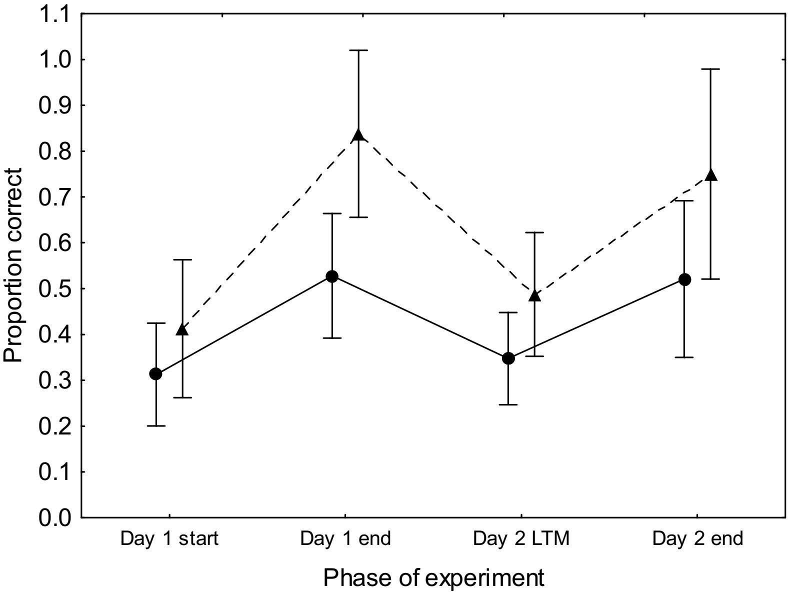

Figure 1. Accuracy of musically trained (▲) and not musically trained (●) participants at the start and end of each day of learning. Error bars are 95% confidence intervals. LTM = long-term memory test at start of Day 2.

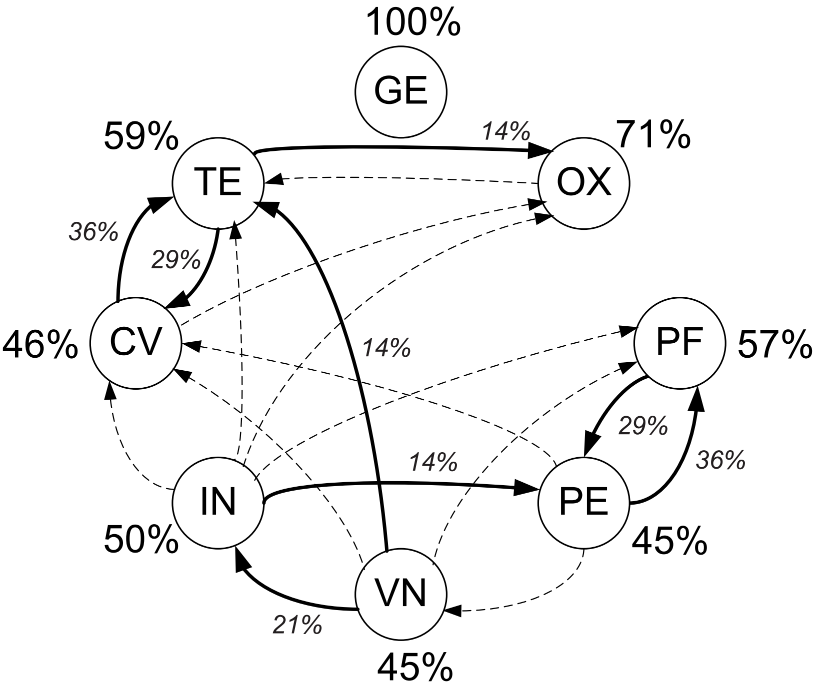

Figure 2. Pattern of confusions during Day 2 relearning. Alarms are GE = general, OX = oxygenation, PF = power failure, PE = perfusion, VN = ventilation, IN = infusion, CV = cardiovascular, and TE = temperature. Large numbers are average percentage correct identification for each alarm. Arrows indicate that the alarm at start of the arrow is confused with the alarm at the end of the arrow. Small numbers in italics are the percentage of participants who showed the confusion indicated on 50% or more occasions.

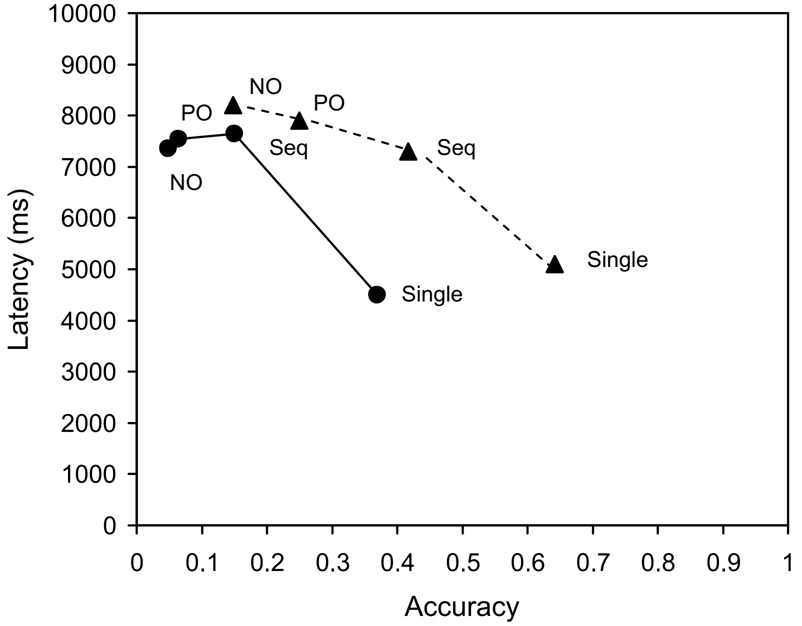

Figure 3. Speed and accuracy of musically trained (▲) and not musically trained (●) participants during transfer to real-time identification of alarms and alarm pairs. NO = nearly overlapping, PO = partially overlapping, Seq = sequential. Responses are scored correct if nurses correctly identified both alarms and reported them in the sequence in which they sounded.

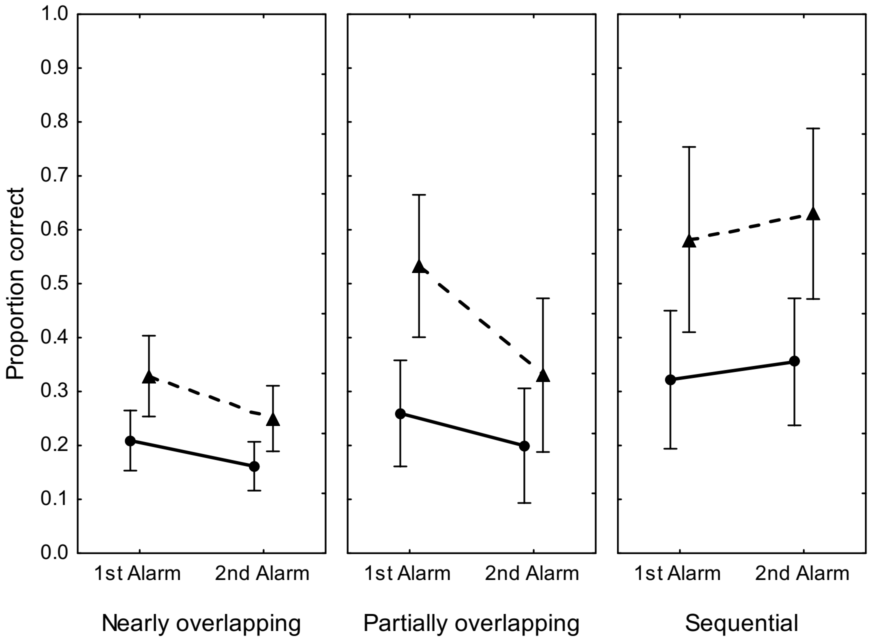

Figure 4. Accuracy of musically trained (▲) and not musically trained (●) participants when responding to the first and second alarm in the nearly overlapping, partially overlapping, and sequential conditions. Responses are scored correct for each alarm individually. Error bars are 95% confidence intervals.

The arithmetic test significantly slowed response times, $F(1, 12) = 14.333$, $MSE = 1414019.103$, $p = .003$, but did not influence accuracy of alarm identification. Both response time, $F(3, 12) = 54.023$, $MSE = 48328948.283$, $p < .001$, and accuracy, $F(3, 12) = 64.126$, $MSE = 0.838$, $p < .001$, differed according to the degree of overlap of the alarms. Tukey HSD tests using a familywise alpha level of .05 showed that single alarms showed faster and more accurate responding than did the other alarm types. Furthermore, sequential alarms were more accurately identified than overlapping alarms. Responses to the two kinds of overlapping alarms were equally slow and inaccurate (see Figure 3).

A further ANOVA compared accuracy of identifying the first alarm versus the second alarm for the nearly overlapping, partially overlapping, and sequential alarm combinations (see Figure 4). The effects of musical training and sequence observed in the first ANOVA were repeated. A main effect of alarm position indicated that the first alarm was generally more accurately identified than the second, $F(1, 12) = 12.91$, $MSE = 0.004$, $p = .004$. There was an interaction between alarm position and alarm sequence, $F(2, 24) = 23.49$, $MSE = 0.002$, $p < .0001$, with the partially overlapping condition showing the greatest benefit for the first alarm, followed by the nearly overlapping condition, whereas the sequential condition showed the greatest benefit for the second alarm. A three-way interaction of musical training, alarm position, and alarm sequence, $F(2, 24) = 5.13$, $MSE = 0.002$, $p < .05$, indicated that musically trained participants were disproportionately accurate with the first alarm on the partially overlapping condition.

Questionnaires

At the end of each block, the nurses were asked how distracted they were by other things happening apart from the alarms. Even though the question did not specify the arithmetic distractor task as a potential distractor, participants reported significantly higher levels of distraction with the arithmetic task, $t(13) = -3.125$, $S_D = 1.68$, $p < .01$.

At the end of the experiment, the nurses were asked what they liked and disliked about the alarms. For likes, only 2 nurses responded unequivocally positively, 6 had qualified positive responses, and the remainder made either irrelevant or no comments. For dislikes, 11 nurses noted that all or at least some alarms sounded too similar, 1 nurse said it was difficult to discriminate between alarms, and 6 nurses said the alarms were not urgent enough.

DISCUSSION

The results of this experiment replicate and extend previous findings that suggest there is cause for concern with the IEC 60601-1-8 melodic alarms (Sanderson et al., 2006; Williams & Beatty, 2005). First, nurses learning the IEC 60601-1-8 high-priority melodic alarms without mnemonic support performed no more accurately than nonnurses learning both medium- and high-priority alarms without mnemonic support (Sanderson et al., 2006). Only 2 nurses among 14 could accuracy identify all alarms by the end of the experiment. Second, nurses confused certain pairs of alarms that nonnursing participants also confused with or without mnemonic support. Some confusions may be dangerous because the melodic alarms may instill a false sense of confidence in the identity of alarms. For example, temperature changes generally happen more slowly than cardiovascular changes. If a nurse mistakes a cardiovascular alarm for a temperature alarm, then the nurse may be slower to respond than if she or he believed it was a cardiovascular alarm. Confusion between the power failure and perfusion alarms was equally high. Overall, these findings suggest that nurses cannot reliably learn to distinguish the eight high-priority IEC 60601-1-8 alarms under the learning conditions most likely to be encountered, in which workers learn the alarms through exposure on the job. Moreover, nurses' comments that the IEC 60601-1-8 alarms were too similar reflect the well-known fact that if alarms or earcons are to be discriminable they should vary on timbre, pitch, register, and rhythm rather than on melody alone (Edworthy & Hellier, 2005; McGookin & Brewster, 2004).

Nurses' ability to identify more than one alarm at a time during transfer was severely limited. If the second alarm arrived after the first note of the first alarm (nearly overlapping condition) or after the third note of the first alarm (partially overlapping condition), accuracy was around chance level. This finding indicates a severe failure of auditory stream segregation (Bregman, 1990). If the criterion of reporting the two alarms in the correct order is relaxed or if corrections for chance correct responding are used, the results do not improve greatly. Nurses benefited from hearing the first three notes of the first alarm in the partially overlapping condition, especially if they were musically trained. This supports Schulkind's (2004) finding that hearing the first few notes of a melody can be sufficient for identification. Perceptual interference caused by the onset of the second alarm usually prevents a full identification being made. When alarms arrive sequentially, however, performance is much better, and responding to the first alarm is no longer more accurate than responding to the second. Overall, the difficulty appears to lie in the initial perceptual discrimination of the two alarms, rather than in retaining their order of arrival in working memory and reporting it accurately. Unless the melodic alarms can be differentiated via timbre or register to support auditory streaming (McGookin & Brewster, 2004), the directive of IEC 60601-1-8 to distribute alarms so that they do not overlap should be taken very seriously, underscoring the importance of developing reliable alarm management techniques (Imhoff & Kuhls, 2006).

Responding during transfer was slower with the concurrent arithmetic task than without it, but the arithmetic task did not worsen accuracy at identifying alarms. Alarms were usually heard while the arithmetic task was being performed, but because both the arithmetic task and the alarm task required a manual response, participants had to suspend the arithmetic task briefly to respond to the alarm. Although the most typical response to an alarm in a hospital would be a similar motor response – turning to view the alarm, to silence it, or to treat the cause – further laboratory tests might use a vocal response to provide a stronger test of the effect of possible competition for the articulatory loop on accuracy at identifying alarms (Baddeley, 1986).

As found previously (Sanderson et al., 2006), musical training is associated with better identification of alarms. Nurses with musical training identified the single alarms more accurately than did nurses without musical training during learning (64% vs. 46% correct overall) and identified the different combinations of alarms more accurately during transfer (37% vs. 16% correct overall) than did nurses without musical training. The low absolute level of performance of participants without musical training is a concern. Alarms should be designed so that participants do not need musical training to reach acceptable levels of alarm identification in the training time typically provided.

There are at least two limitations of this study. First, because of the constraints of our allocated time with nurses and the need to test as many combinations of alarms as possible in the transfer test, we could test performance with only the high-priority alarms. Learning the simpler medium-priority alarms, which play only the first three notes of the alarm at a slower rate, may help participants learn the high-priority alarms. Second, because we chose to investigate learning without mnemonics in this experiment, which is how many health care workers will learn the alarms, the impact of mnemonics on nurses' performance is still unknown. These issues are the subject of further investigations in our laboratory (Wee & Sanderson, 2006).

In conclusion, it would be premature to introduce the IEC 60601-1-8 melodic alarms into health care settings. The poor learnability and discriminability of the alarms, the association between musical training and better identification accuracy, and the difficulty of identifying the alarms when they overlap all suggest that further development and testing are needed. Tests such as those performed in the present study and earlier studies (Sanderson, et al., 2006; Williams & Beatty, 2005) could have played a formative role during development of melodic alarms so that the set of melodies suggested would have avoided the confusions seen here with their possible dangers.

ACKNOWLEDGMENTS

The authors thank Alexandra Wee and Phil Cole for help with programming, Dr. Marcus Watson for bringing the McGookin and Brewster (2004) paper to our attention, and Dr. Kersi Taraporewalla of Royal Brisbane and Women's Hospital for providing access to investigate the intraoperative acoustic environment. We also thank Dr. Chris Thompson of Royal Prince Alfred Hospital for perspectives on the work of the IEC 60601-1-8 standards committee.

REFERENCES

Baddeley, A. (1986). *Working memory.* Oxford, U.K.: Oxford University Press.

Benson, K. B. (1986). *Audio engineering handbook.* New York: McGraw-Hill.

Block, F. E., Rouse, J. D., Hakala, M., & Thompson, C. L. (2000). A proposed new set of alarm sounds which satisfy standards and rationale to encode source information. *Journal of Clinical Monitoring and Computing, 16,* 541–546.

Bregman, A. S. (1990). *Auditory scene analysis: The perceptual organization of sound.* Cambridge, MA: MIT Press.

Edworthy, J., & Hellier, E. (2005). Fewer but better auditory alarms will improve patient safety. *Quality and Safety in Health Care, 14,* 212–215.

Imhoff, M., & Kuhls, S. (2006). Alarm algorithms in critical care monitoring. *Anesthesia and Analgesia, 102,* 1525–1537.

International Electrotechnical Commission. (2005). *IEC 60601-1-8: Medical electrical equipment – General requirements, tests and guidance for alarm systems in medical electrical equipment and medical electrical systems.* Geneva, Switzerland: Author.

Logie, R. H., Gilhooly, K. J., & Wynn, V. (1994). Counting on working memory in arithmetic problem solving. *Memory and Cognition, 22,* 395–410.

McGookin, D. K., & Brewster, S. A. (2004). Understanding concurrent earcons: Applying auditory scene analysis principles to concurrent earcon recognition. *ACM Transactions on Applied Perception, 1,* 130–155.

National Occupational Health and Safety Commission. (1991). Control guide: Management of noise at work. Canberra, ACT: Commonwealth of Australia.

Sanderson, P., Wee, A., & Lacherez, P. (2006). Learnability and discriminability of melodic medical equipment alarms. *Anaesthesia, 61,* 142–147.

Schulkind, M. D. (2004). Serial processing in melody identification and the organization of semantic memory. *Perception and Psychophysics, 66,* 1351–1362.

Wee, A., & Sanderson, P. (2006). Effects of mnemonics in learnability of melodic alarms with registered nurses. In *Proceedings of the Human Factors and Ergonomics Society 50th Annual Meeting.* (pp. 1039–1043). Santa Monica, CA: Human Factors and Ergonomics Society.

Williams, S., & Beatty, P. C. W. (2005). Measuring the performance of audible alarms for anaesthesia. *Physiological Measurement; 26,* 571–581.

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Date received: November 23, 2005
Date accepted: June 7, 2006