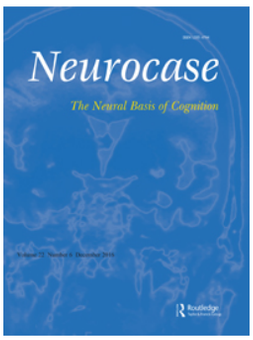

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ISSN: 1355-4794 (Print) 1465-3656 (Online) Journal homepage: http://www.tandfonline.com/loi/nncs20

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To cite this article: Jessica Gillard & Michael Schutz (2016) Composing alarms: considering the musical aspects of auditory alarm design, Neurocase, 22:6, 566-576, DOI: 10.1080/13554794.2016.1253751

To link to this article: http://dx.doi.org/10.1080/13554794.2016.1253751

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NEUROCASE, 2016
VOL. 22, NO. 6, 566–576
http://dx.doi.org/10.1080/13554794.2016.1253751

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Composing alarms: considering the musical aspects of auditory alarm design

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ABSTRACT

Short melodies are commonly linked to referents in jingles, ringtones, movie themes, and even auditory displays (i.e., sounds used in human–computer interactions). While melody associations can be quite effective, auditory alarms in medical devices are generally poorly learned and highly confused. Here, we draw on approaches and stimuli from both music cognition (melody recognition) and human factors (alarm design) to analyze the patterns of confusions in a paired-associate alarm-learning task involving both a standardized melodic alarm set (Experiment 1) and a set of novel melodies (Experiment 2). Although contour played a role in confusions (consistent with previous research), we observed several cases where melodies with similar contours were rarely confused – melodies holding musically distinctive features. This exploratory work suggests that salient features formed by an alarm's melodic structure (such as repeated notes, distinct contours, and easily recognizable intervals) can increase the likelihood of correct alarm identification. We conclude that the use of musical principles and features may help future efforts to improve the design of auditory alarms.

ARTICLE HISTORY
Received 28 March 2016
Accepted 4 October 2016

KEYWORDS
Auditory alarms in medical devices; human computer interface design; auditory perception; music cognition; melody perception

Introduction

Bidirectional associations between sight and sound are important in many aspects of music. For example, when hearing a familiar piece, some listeners might picture the notation and/or imagine the corresponding movements required for its performance. Likewise, while reading a notated score, musicians will often try to "hear" the written notes and even envision the correct fingering or movements required for their production. These processes rely in part on associative memory – our ability to make arbitrary cognitive links between cues either within or across modalities.

We make associations involving sound often and with ease in a variety of endeavors, including music, and this skill known as *associative memory* is a well-researched topic. Explorations of word-sound (Godley, Estes, & Fournet, 1984; Keller & Stevens, 2004; Wakefield, Homewood, & Taylor, 2004), image-sound (Bartholomeus & Doehring, 1971; Klingberg & Roland, 1998), and object-sound (Morton-Evans & Hensley, 1978) pairings indicate broad interest in the role of sound in associative memory. However, associative memory studies involving sound are far less frequent than studies of other associations, such as word–word pairings. For example, reviews of word–word studies exploring issues such as concreteness (Paivio, 1971, 1986), structural models (Taylor, Horwitz, Shah, Fellenz, & Krause, 2000), and paired associate learning paradigms in the larger study of memory (Roediger, 2008) dominate the literature. The limited focus on sound in associative memory paradigms is surprising, given the importance (and our frequent use) of associations involving sounds in everyday situations.

Sound associations are useful in identifying unseen objects, making appropriate decisions to react (or not) to events around us, and reducing our cognitive load (i.e., resources put toward different tasks). Sounds are also effective in conveying information, which may be why musical motifs are frequently used in advertising (i.e., jingles) and telecommunications (i.e., ringtones), in order to create cognitive links between sounds and products, corporations, or people. Additionally, music plays an important role in movies, operas, and plays where associations offer insight into a character's mood (Tan, Spackman, & Bezdek, 2007), or a deeper interpretation of a scene (Vitouch, 2001), such as Wagner's use of leitmotifs or John Williams' use of character themes. Clearly, sound can be an effective medium for conveying information, whether it helps us identify the caller on a phone, announces the arrival of an approaching train, informs us that our email has been sent, or foreshadows an important plot development.

Associations in auditory alarms

In applied contexts, short musical melodies can serve as the basis for *auditory displays* – sounds used in human–computer interactions. For example, to assist manufacturers, the International Electrotechnical Commission (IEC) designed a standardized set of melodic auditory alarms for use in hospitals (i.e., the IEC 60601-1-8 standard).[1] These alarms consist of three- or five-note melodies for medium-priority and high-priority alarms, respectively, and are used to signal patient-related and machine-related issues to medical practitioners. Unfortunately, problems with the IEC alarms are numerous and well documented. They require extensive exposure to learn (Sanderson, Wee, & Lacherez, 2006; Wee & Sanderson, 2008), are poorly retained (Edworthy & Hellier, 2006; Sanderson et al., 2006), and are frequently confused with one another (Edworthy & Hellier, 2005; Lacherez, Seah, &

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Sanderson, 2007; Sanderson et al., 2006; Wee & Sanderson, 2008). However, in these studies, participants with at least 1 year of musical training were better at learning and recalling the IEC Alarms (Sanderson et al., 2006; Wee & Sanderson, 2008). Within each priority level, the IEC alarms have the same length, the same rhythm and span a narrow pitch range (262–523 Hz or C4–C5) – characteristics likely contributing to problems in learning and retention (Edworthy, 1994; Edworthy & Hellier, 2006; Edworthy, Hellier, Titchener, Naweed, & Roels, 2011; Edworthy & Stanton, 1995; Sanderson et al., 2006).

The poor discriminability of the IEC alarms has prompted several suggested improvements based on guidelines put forth by alarm deign pioneer, Roy Patterson (Patterson, 1990). These suggested improvements include increasing the heterogeneity of alarms within a set (Edworthy et al., 2011; Phansalkar et al., 2010), varying their contours (Edworthy & Hellier, 2006), and differentiating their rhythms (Edworthy, 2011; Edworthy et al., 2011; Edworthy & Hellier, 2006). However, to the best of our knowledge, attempts to apply musical principles to improving their effectiveness have not been widely explored. This is surprising considering that they seem inspired by musical melodies (i.e., most exclusively employ diatonic pitches from a single major scale) and could benefit by research conducted in the field of music cognition.

Associative memory and music cognition

Consulting the music cognition literature, melody recognition, and subsequent identification has been suggested to follow the Cohort Theory of spoken word identification (Bartlett & Dowling, 1988; Schulkind, Posner, & Rubin, 2003) originally proposed by Marslen-Wilson and Tyler (1980). This theory suggests that the initial sound (or notes in the case of music) activates a cohort of possible matches in memory, which is narrowed as the sound (or melody) progresses. Identification occurs once all other candidates are eliminated and a single match is made. Contour plays a fundamental role in melody recognition and recall (Cuddy & Lyons, 1981; Dowling, 1978, 1991; Dowling & Bartlett, 1981; Dowling & Fujitani, 1971; Edworthy, 1985; Schulkind et al., 2003), and similarity judgments are largely based on pitch contour, pitch content, and inter-onset note patterns (Ahlback, 2007). Together these findings help explain problems with the IEC alarms: since several of the alarms begin on the same note, have the same general contour, contain many of the same pitches, and do not differ in inter-onset note patterns (medium-priority alarms are depicted in Figure 1(a) with supporting musical notation in Figure 1(b)).

Within the music cognition literature, it has been suggested that studies of melody recognition tend to focus on novel versus familiar stimuli and performance between musicians versus non-musicians (Müllensiefen & Wiggins, 2011). Consequently, as Schulkind et al. (2003) pointed out, there is little research describing what specific contour patterns actually *facilitate* melody identification. Additionally, Müllensiefen and Wiggins (2011) note that even fewer studies employ paired-associate learning paradigms using melodies. As such, we believe that research combining approaches and stimuli from music cognition (melody recognition) and human factors (alarm design) might offer helpful insights that are relevant to both fields.

Here, we describe an exploratory study examining the role of melodic structure in increasing the heterogeneity of alarm design – one common suggestion for improving their efficacy (Edworthy, 2011). One factor of initial interest included amplitude envelope – the shape of a sound over time. Our research team has documented that sounds with natural envelopes (i.e., exponentially decaying "percussive" sounds) lead to superior performance in an associative memory task over sounds with the artificial sounding flat (i.e., abrupt onset, period of sustain, and abrupt offset) envelopes used by the IEC alarms (Schutz, Stefanucci, Baum, & Roth, in press). Although amplitude envelope did not appear to play a role in the context of learning and recalling auditory alarms, our exploration did offer useful information regarding the role of melodic structure in confusions. Although the useful insights from this experiment come from *post-hoc* analysis rather than a priori predictions, we believe that these results can help inform ongoing efforts to improve the effectiveness of auditory displays by providing insights in the relationship between melodic structure (separate from contour) and confusions.

Experiment 1

In our first experiment, we manipulated the amplitude envelope of the IEC 60601 alarms to be either flat (i.e., the original alarms), or percussive (i.e., the original alarms with reshaped, exponentially decaying envelopes). Based on our team's previous findings, we were interested in investigating whether this parameter might be of use in improving alarm effectiveness. This also allowed us to replicate previous findings regarding patterns of confusion amongst the IEC alarms that differed between experiments using undergraduate students (Sanderson et al., 2006) and experiments using medical professionals (Lacherez et al., 2007; Wee & Sanderson, 2008). This included infrequent confusions of alarms that were phonetically similar (i.e., Perfusion and Power Failure, as well as Perfusion and Infusion) amongst undergraduate students, which in contrast were frequently confused amongst medical professionals in previous studies (Lacherez et al., 2007; Wee & Sanderson, 2008).

Method

Participants

Participants consisted of undergraduate students enrolled in an introductory Psychology course at McMaster University. Forty participants partook in the study for course credit[2] and had on average 3.5 years (SD = 3.7, range = 0–14 years) of musical training.

Stimuli and apparatus

We used the medium priority IEC 60601 alarms and associated referents as stimuli (Figure 1(a)) in a between-subjects design. As the original alarms possess a flat temporal structure, we used the original recordings for our flat condition. To generate percussive versions of the alarms, we reshaped each tone with exponentially decaying envelopes using a MAX/MSP patch previously developed by the MAPLE

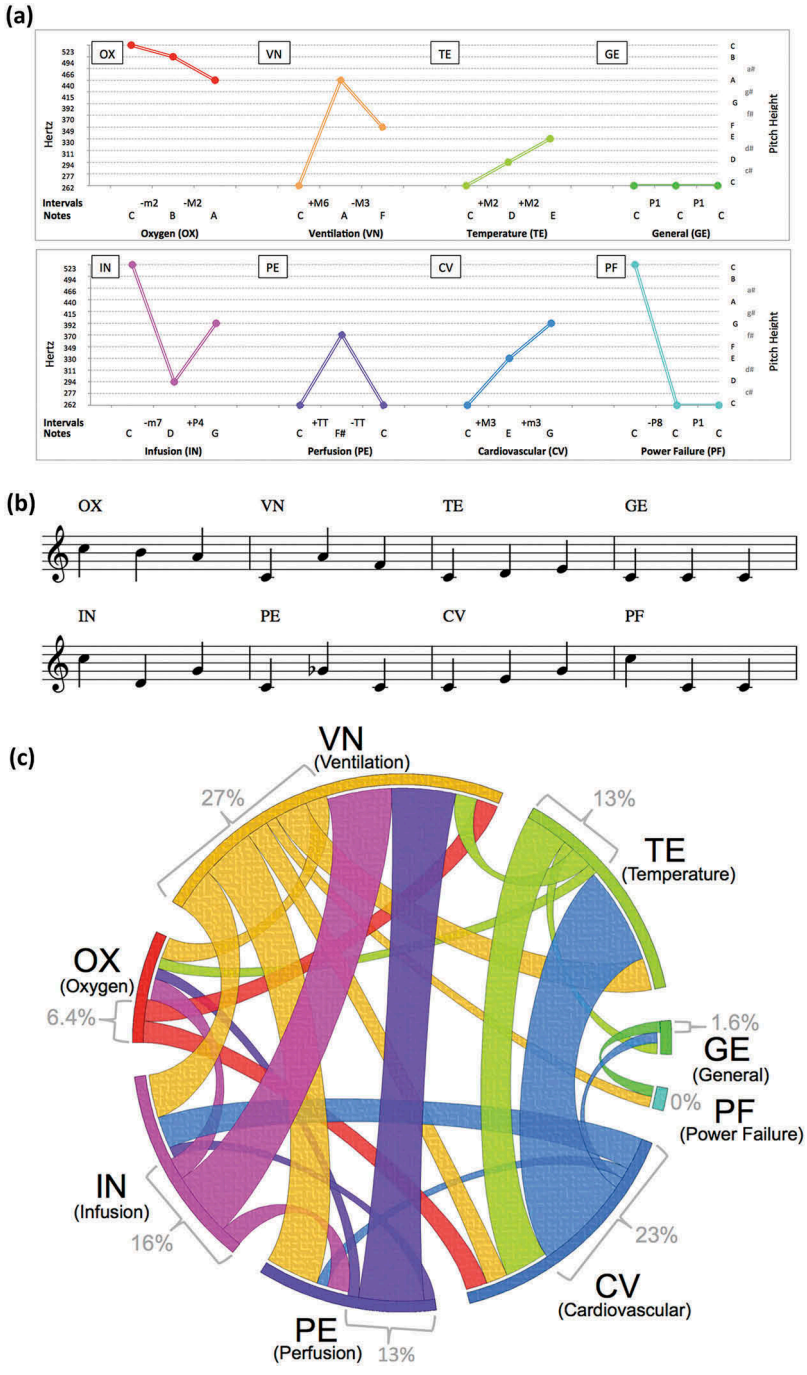

Figure 1. Contours of the eight IEC 60601 alarms (a), notation (b), and Confusions in the evaluation phase of Experiment 1 (c). Alarms are represented by colors: Oxygen (OX) = Red, Ventilation (VN) = Orange, Temperature (TE) = Olive, General (GE) = Green, Power Failure (PF) = Cyan, Cardiovascular (CV) = Blue, Perfusion (PE) = Purple, and Infusion (IN) = Pink. In panel (a), M = Major, m = Minor, P = Perfect, TT = Tritone, + = Ascending, − = Descending. In panel (c), thicker exterior segments and inner bands (connecting two segments) indicate higher rates of confusion. Inner bands in the same color as the exterior segment indicate the times when the alarm in question is confused with another (i.e., outbound confusions). Inner bands of different colors than the exterior segment indicate the times when other alarms are confused with the alarm represented by the exterior segment (i.e., inbound confusions).

Lab.[3] We stored the tone sequences on an iMac computer and presented them over Sennheiser HDA 200 headphones at a comfortable listening level held constant for all participants. Prior to beginning the experiment, we administered a short survey including questions regarding demographics, musical training as well as musical practice and listening behaviors.

Procedure

To engage participants, we read them a script asking them to imagine himself or herself as a surgeon and received one of two lists of the eight medical alarm referents (i.e., "Cardiovascular," "Perfusion," "Temperature," etc.), counterbalanced between participants. The experimenter explained that the task was to learn to identify eight medical alarms and

defined each of them briefly. The experiment then consisted of four phases: (1) study phase, (2) training phase, (3) distracter task, and (4) evaluation phase, which are described individually below. We randomized the order in which the alarms were presented for each participant.

Study phase. Participants heard each of the eight alarms twice in a random order along with a verbal statement of the correct alarm referent. We then played a "masking sound" (white noise through a low-pass filter) for a duration of 6 s between different alarms presentations. This blocked out extraneous noise and ensured even spacing between trials to control for individual differences in rehearsal time.

Training phase. We asked participants to identify the correct alarm referent after hearing each of the alarms once in a randomized order. Participants received feedback on their correctness after which we replayed the alarm and reminded them of the correct referent (regardless of their answer). We played the masking sound between sequences once again. Each training block included all eight alarms (played once each). We continued to present training blocks until participants correctly identified 7 out of 8 alarms in 2 consecutive blocks or completed a maximum of 10 blocks. To help avoid frustration, we offered positive reinforcement every other block (e.g., "You're doing very well!") regardless of performance.

Distracter task. Upon completion of the training phase, participants performed a silent distracter task (an online mini-golf game[4]) for 5 min.

Evaluation phase. We presented each alarm (randomizing the order for each participant) and asked participants to identify the correct alarm referent. Additionally, we asked participants to indicate how confident they felt about their answer on a scale from 1 (*Not confident at all*) to 6 (*Very confident*). We did not give participants feedback during the evaluation phase but relayed their final score upon completion.

Results

Our main manipulation of envelope had no significant affect on performance ($p > .05$), therefore, we collapsed across envelope to analyze the confusion data. On average, participants correctly identified 6.4 (out of a possible 8) alarms in the evaluation phase ($SD = 1.57$). The patterns of confusion (i.e., when one alarm was "confused" with another) in the evaluation phase are plotted using the graphics tool Circos[5] in Figure 1(c) (additionally, they are summarized in table form in Appendix A). The plot depicts the total number of confusions ($n = 62$) around the circumference of the circle, with each of the eight alarms represented by different colored segments according to the following mapping: Oxygen (OX) = Red, Temperature (TE) = Orange, Ventilation (VN) = Olive, General (GE) = Green, Power Failure (PF) = Cyan, Cardiovascular (PE) = Blue, Perfusion (CV) = Purple, and Infusion (IN) = Pink.

Longer exterior segments indicate alarms that were highly confused. For example, the long exterior segments for the Ventilation (Olive) and Cardiovascular (Blue) alarms indicate the highest levels of confusion, encompassing 27% ($n = 17$) and 23% ($n = 14$) of total confusions, respectively. The medium exterior segments for the Temperature (Orange), Perfusion (Purple), and Infusion (Pink) indicate moderate confusion, accounting for 13% ($n = 8$), 13% ($n = 8$), and 16% ($n = 10$) of total confusions, respectively. The relatively short exterior segments for the Oxygen (Red) and General alarms (Green) indicate the least confusion, accounting for only 6.4% ($n = 4$) and 1.6% ($n = 1$) of total confusions, respectively, and the Power Failure (Cyan) alarm was not confused at all ($n = 0$). Like-colored connecting inner bands (i.e., in the same color as the exterior segments) indicate "outbound" confusions – the times when the alarm in question is confused with another. Different colored inner bands indicate "inbound" confusions – the times when other alarms are misidentified as the alarm of interest. The length of each alarm's exterior segment reflects both its outbound and inbound confusions (smaller segments represent the least-confused alarms). However, as one alarm's inbound confusions are another's outbound, we will confine our discussion to the latter to avoid redundancy.

Shorter exterior segments indicate that alarms were confused less frequently. For example, the General alarm (Green) is one of the least confused as indicated by its relatively short exterior segment and thin inner bands of alarm-to-alarm confusion. The like-colored (i.e., green) inner bands indicate when participants misidentified the General alarm as another, with that band's thickness reflecting confusion prevalence. For example, only one participant misidentified the General alarm as the Power Failure alarm (Cyan, $n = 1$). The General alarm is one of the least confused (i.e., most successful), for as indicated by its short exterior segment it accounted for only 1.6% ($n = 1$) of the total confusions.

In contrast, the relatively large exterior segment of the Ventilation alarm (Orange) indicates significant confusion. Misidentifications (orange inner bands) include almost *all* other alarms: Oxygen (Red, $n = 2$), Temperature (Olive, $n = 3$), Power Failure (Cyan, $n = 1$), Cardiovascular (Blue, $n = 2$), Perfusion (Purple, $n = 5$), and Infusion (Pink, $n = 4$), accounting for 27% ($n = 17$) of total confusions. Additionally, participants frequently misidentified the Ventilation alarm as the Perfusion alarm, indicated by the thick inner orange band spanning across the graph to the Purple (Perfusion) section.

Participants misidentified the Perfusion alarm (Purple) moderately, falling between the extremes of the General and Ventilation alarms, with 13% ($n = 8$) of the total confusions. These included the Oxygen (Red, $n = 1$), Ventilation (Orange, $n = 6$), and Infusion (Pink, $n = 1$) alarms, with the majority stemming from the Ventilation alarm (thick purple inner band extending to the orange Ventilation alarm).

In past investigations, highly confused alarms have been represented by the number of participants that confused one alarm consistently with another on at least 25% of the trials during learning-test cycles (Lacherez et al., 2007; Sanderson et al., 2006; Wee & Sanderson, 2008). This approach is ill suited for our purposes, since we are only looking at performance during the evaluation phase, and not during the training phase (which is comparable to the learning-test cycles). Therefore, to determine which alarms were "highly confused," we looked for cells that fell at or above two standard deviations about the mean. In the current dataset, any alarm

misidentified five or more times consistently with another alarm was considered highly confused (M = 1.1, SD = 1.88). This included confusions between Ventilation and Perfusion (n = 5; thick orange band), Cardiovascular and Temperature (n = 9; thick blue band), Perfusion and Ventilation (n = 6; thick purple band), and Infusion and Ventilation (n = 6; thick Pink band).

Musical training

A t test revealed that participants with musical training (i.e., one or more years)[6] required significantly fewer training blocks (M = 6.4, SD = 2.78) to learn the alarms than participants without musical training (M = 8.3, SD = 2.30), t(38) = −2.18, p = .036. However, in the evaluation phase, musical training did not significantly affect alarm recall (some training M = 6.7, SD = 1.40; no training M = 5.8, SD = 1.72), t(38) = 1.77, p = .068.

Discussion

We successfully replicated several of the confusions reported in previous studies (Lacherez et al., 2007; Sanderson et al., 2006; Wee & Sanderson, 2008). Many stemmed from similarities in contour, consistent with previous research on contour's role in melody recognition (Cuddy & Lyons, 1981; Dowling, 1978, 1991; Dowling & Bartlett, 1981; Edworthy, 1985; Edworthy & Hellier, 2006; Massaro, Kallman, & Kelly, 1980; Schulkind et al., 2003) For example, Temperature (Olive) and Cardiovascular (Blue) both have two ascending intervals; Ventilation (Orange) and Perfusion (Purple) both have an ascending followed by a descending interval. However, we observed a few confusion patterns not explained on the basis of contour.

For example, we observed significant confusions between Ventilation (Orange) and Infusion (Pink) – which differ in contour. A previous study finding similar patterns of confusion attributed this to the fact that the Ventilation and Infusion alarms are often heard together in a medical context (Sanderson et al., 2006). While this has been reported amongst medical professionals (Lacherez et al., 2007; Wee & Sanderson, 2008), this is unlikely to explain our findings here using an undergraduate population lacking exposure to the alarms in medical settings [Sanderson et al. (2006) reported similar findings in a population of students without medical training]. This suggests that these confusions might in fact stem from the design of the alarm sequences themselves, rather than the alarm's meaning for medical professionals. We suspect that these alarms might be confused due to "contour inversion" as opposed to the medical context, as they are essentially mirror images of one another with respect to contour and occupy the same contour space (Dowling, 1971; Marvin & Laprade, 1987).

As with previous studies, we observed low levels of confusion among some alarms. This is consistent with results indicating that distinctive features led to better performance. For example, the Oxygen alarm (Red) is the only melody with two descending intervals in the set and the General alarm (Green) is composed of three repeated notes, making them both easily identifiable and consequently less confusable. Similarly, participants never misidentified the Power Failure alarm (Cyan), consisting of a descending octave followed by a repeated note (i.e., combining two musically salient intervals). These results and insights into the IEC alarm set are consistent with previous observations in both alarm design (Edworthy, 2011; Edworthy et al., 2011) and music cognition (Müllensiefen & Halpern, 2014; Schulkind et al., 2003).

Despite this consistency, it is also worth mentioning that we failed to replicate several patterns of confusion reported previously amongst medical professionals. For example, the Perfusion and Power Failure alarms were frequently confused by nurses (Lacherez et al., 2007; Wee & Sanderson, 2008), yet they were never confused here. Additionally, one study reported a high prevalence of confusion between the Perfusion and Infusion alarms (Wee & Sanderson, 2008), yet here, we found only a mild confusion. These do not appear to be a result of the alarms themselves (i.e., melodies) since they differ in contour and are not frequently confused by undergraduate students reported here and previously (Sanderson et al., 2006) but may rather stem from the alarm referents. We suspect that these confusions may be due to contextual cues relevant to medical professionals or even phonetic similarity. Future studies might shed light on this issue by randomizing the IEC alarm sounds and alarm referents.

As suggested by Edworthy et al. (2011), varying other aspects such as rhythm, timbre, and tempo can help reduce misidentification and optimize alarm effectiveness. In other words, increasing heterogeneity among alarms can reduce confusions. Our findings suggest that carefully arranging the pitches according to musical principles can also help to reduce confusion amongst alarms. Similarly, alarms with similar musical characteristics may still be confused even if they differ in contour (i.e., the Ventilation and Infusion alarms).

Experimental design and musical training

Past investigations have suggested that participants with at least 1 year of musical training are better at learning and recalling the IEC alarms (Sanderson et al., 2006; Wee & Sanderson, 2008). Similarly, we found that participants with at least 1 year of musical training were able to learn the alarms in fewer training blocks compared to participants with no musical training. However, here, participants performed equally well on alarm recall in the evaluation phase regardless of whether or not they met the threshold for classification as musically trained (i.e., 1 year in the alarm literature). In previous studies, participants completed learning-test cycles until they reached 100% accuracy in two consecutive tests or reached a specified time limit ranging from 35 to 50 min and would receive a list of the alarms they identified incorrectly at the end of each test (Lacherez et al., 2007; Sanderson et al., 2006; Wee & Sanderson, 2008). Here, we used a slightly different approach in which participants completed training blocks until they scored at least 7/8 (or 87.5%) in 2 consecutive blocks or completed a maximum of 10 blocks.

One potentially insightful difference between our design and designs employed previously (showing strong effects of musical background) is that here we replayed the alarm and restated the referent after each response in the training phase, regardless of correctness. This approach may have been particularly helpful to those with less musical exposure, leading to similar performance in the evaluation phase.

Future efforts to improve learning and retention of alarms might benefit from exploring these kinds of strategies for those without musical training. Additionally, it suggests that previously reported disadvantages for those without formal musical training may be overcome by changes to the training routine used. Experiment 2 explores this idea and additionally addresses potential confounds stemming from unvarying melody–referent pairings.

Experiment 2

To further explore whether (a) distinct features help improve correct alarm identification and (b) what aspects appear to group melodies with dissimilar contours as cognitively similar, we looked at confusions in another set of stimuli. Here, we paired the same eight IEC alarm referents with eight novel melodies from previous work by our team. This allowed us to determine whether the types of confusions observed with the IEC alarms appear with other melodies. Additionally, we varied the pairings of melodies and alarm referents – an important factor when trying to determine whether confusions stem from melodic structure (i.e., the alarms) or phonetic similarity (i.e., the alarm referents). As previous studies always used set pairings of alarms and referents matching the IEC proposals, this offers a novel chance to disambiguate potential confounds inherent in using the same pairings of sounds and referents for all participants.

Method

Participants

Participants consisted of undergraduate students enrolled in either an introductory Psychology or Linguistics course at McMaster. Forty participants (14 male, 25 female, 1 transgendered) ranging in age from 17 to 24 (M = 19.1 years, SD = 1.56) participated in the study for course credit. Additionally, participants had on average 2.2 years of musical training (SD = 3.07, range = 0–12 years).

Stimuli and apparatus

We selected eight tone sequences consisting of tones drawn from a one octave chromatic scale (A4 – A5) from a set used in a previous study conducted by Schutz et al. (in press). Each sequence consisted of a sound file with four sine wave (pure tone) notes, roughly 4 s in length. Although we manipulated the temporal structure of individual notes within these melodies[7] (as in Experiment 1), here, we used a within-subjects design with each participant hearing four melodies with each amplitude envelope. We enumerated the tone sequences (shown in Figure 2(a), notation provided in Figure 2(b)) from 1 to 8 and stored them on a MacBook Air laptop. We presented the tone sequences over Sennheiser HDA 200 headphones at a comfortable listening level held constant for all participants. Prior to beginning the experiment, participants completed the survey described in Experiment 1.

Procedure

The procedure for Experiment 2 is similar to that of Experiment 1, with the exception of the use of novel melodies. Additionally, here, we randomized the pairings of melodies and alarm referents for all participants rather than maintaining consistent melody–alarm referent pairings, as in the first experiment. In other words, Melody 1 may be paired with the referent "Ventilation" for one participant, but a paired with a different referent such as "Power Failure" for another participant. This allowed us to control for potentially confusing properties of the referents themselves (i.e., "Perfusion"/"Infusion").

Results

Once again, the envelope manipulation had no significant effect on performance ($p > .05$), and we again collapsed across this parameter to analyze the confusion data. Participants correctly identified 5.9 (SD = 1.59) melody–referent pairings in the evaluation phase on average. The patterns of confusion within the evaluation phase are plotted using the graphics tool Circos in Figure 2(c) (and summarized in detail in Appendix B). The plot depicts the total number of confusions (n = 85) around the circumference of the circle, with each of the eight melodies represented by different colored exterior segments according to the following mapping: 1 = Red, 2 = Orange, 3 = Olive, 4 = Green, 5 = Cyan, 6 = Blue, 7 = Purple, and 8 = Pink. The most highly confused melodies (i.e., the largest exterior segments on the Circos graph) include Melodies 3 (Olive), 6 (Blue), and 7 (Purple) representing 22.3% (n = 19), 15.3% (n = 13), and 21.2% (n = 18) of total confusions, respectively. Moderately confused melodies include Melodies 1 (Red) and 4 (Green) accounting for 12.9% (n = 11) and 11.8% (n = 10) of total confusions, respectively. The least confused included Melodies 2 (Orange), 5 (Cyan), and 8 (Pink), accounting for 5.9% (n = 5), 5.9% (n = 5), and 4.7% (n = 4), respectively. Once again, the thickness of the inner bands between melody segments corresponds to the prevalence of their confusion.

Again, to determine which alarms were highly confused, we looked for cells that fell at or above two standard deviations about the mean. Here, any melody misidentified five or more times consistently as another alarm was considered highly confused (M = 1.5, SD = 1.77). This included confusions between Melody 3 and Melody 6 (n = 10; thick olive band), as well as confusions between Melody 7 and Melodies 3 and 4 (n = 5 each; thick purple bands).

Musical training

In contrast to the previous experiment, participants with at least 1 year of musical training did not learn the melody–referent associations any faster (M = 7.2, SD = 2.387) than participants without musical training (M = 8.2, SD = 2.34), $t(38) = -1.38$, $p = .175$. Additionally, their performance in the evaluation phase did not differ significantly (some training M = 6.2, SD = 1.58; no training M = 5.6, SD = 1.57), $t(38) = 1.281$, $p = .208$. Furthermore, in comparison to Experiment 1, participants in Experiment 2 had significantly fewer years of musical training (Experiment 1: M = 3.5, SD = 3.70; Experiment 2: M = 2.2, SD = 3.03), $t(39.597) = 2.19$, $p = .034$.

Discussion

Overall, these melodies yielded greater confusions (85) than the alarms used in Experiment 1 (62). This may be attributed

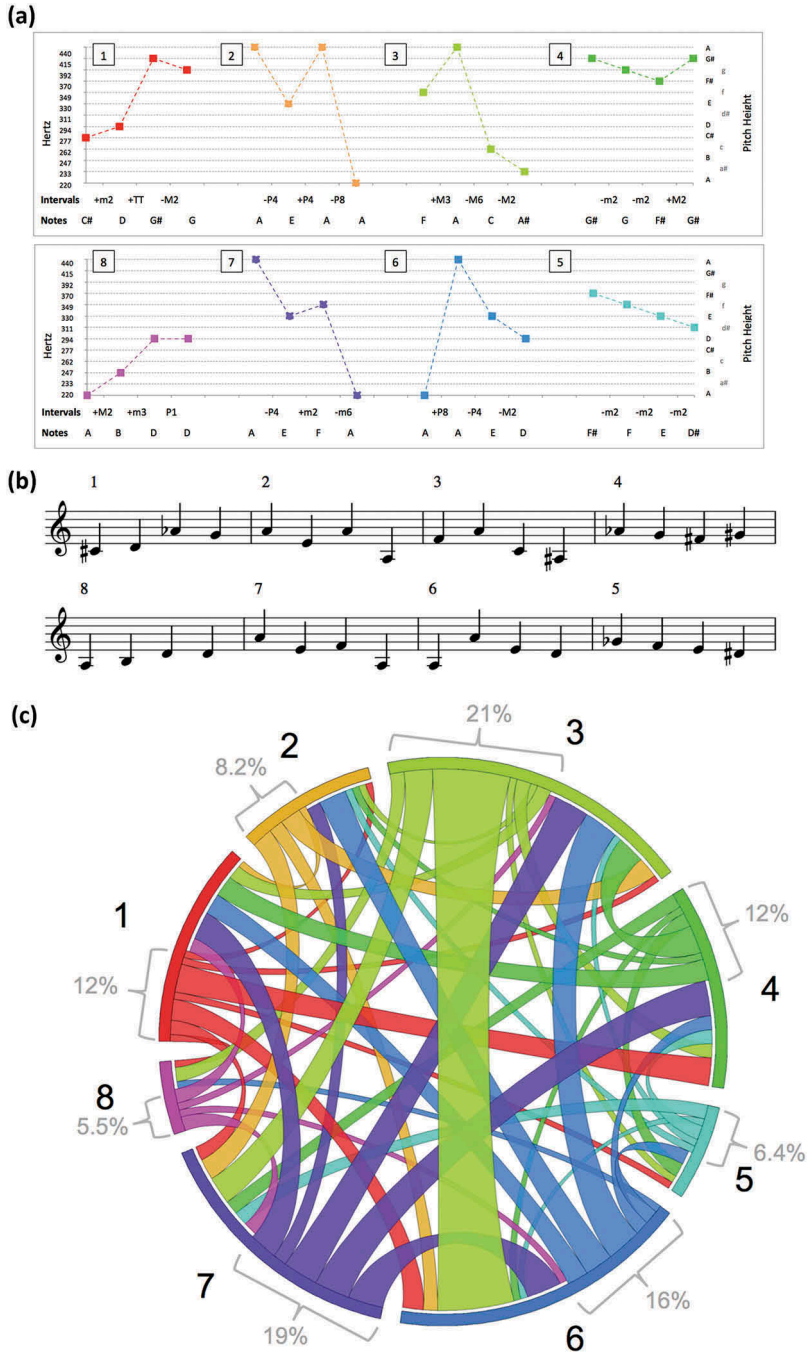

Figure 2. Contours of the eight melodies (a), notation (b), and Confusions in the evaluation phase of Experiment 2 (c). In panel (a), M = Major, m = Minor, P = Perfect, TT = Tritone, + = ascending, − = Descending. In panel (c), melodies are distinguished by color: 1 = Red, 2 = Orange, 3 = Olive, 4 = Green, 5 = Cyan, 6 = Blue, 7 = Purple, and 8 = Pink. Thicker exterior segments and inner bands indicate higher rates of confusion. Inner bands in the same color as the exterior segment indicate the times when the melody in question is confused with another (i.e., outbound confusions). Inner bands of different colors than the exterior segment indicate the times when other melodies are confused with the alarm represented by the exterior segment (i.e., inbound confusions). Colors are for clarifying individual alarms/melodies within an experiment. There is no intended correspondence between colors within the two experiments (i.e., Oxygen in Experiment 1 and alarm 1 in Experiment 2 are both Red but are not necessarily related in any way.

to their increased length (4 notes rather than 3) and the greater variety of intervals used. In Experiment 1, the IEC alarms consisted of three note melodies, composed almost entirely from the Major scale. In Experiment 2, the to-be-learned melodies consisted of four notes that are less strictly diatonic in their structure. Previous research has shown a decrease in contour judgment performance with increasing melody length (Edworthy, 1982, 1985) as well as poorer recognition of atonal versus tonal melodies (Mikumo, 1992).

Again, it appears that contour plays an important role in explaining this pattern of confusions. The most highly confused melodies (3 and 6) share a contour consisting of an ascending interval followed by two descending intervals. Interestingly, the final interval in both melodies is a

descending major second. Several participants (25%) misidentified Melody 3 as Melody 6, which accounted for over *half* of its total confusions (53%). However, once again, there are systematic results that are not explained by contour.

Curiously, other melody pairs with similar contours – arranged vertically in Figure 2(a) (i.e., 1 with 8, 2 with 7, and 4 with 5) – were *not* frequently confused. Moreover, we found high rates of confusion between alarms differing substantially in contour. As in the first experiment, we suspect that this reflects the importance of musically distinctive features (i.e., a repeated note in Melody 1 vs. Melody 8, prominent octave interval in Melody 2 vs. Melody 6, and a salient change in contour in Melody 4 vs. Melody 5).

For example, Melody 7 contains a descending interval followed by an ascending and then descending interval (Figure 2(a)). Participants confused this melody with Melodies 1, 2, 3, 4, and 6. Despite their dissimilarities, the contours of all five melodies contain changes of direction. It is possible that melodies that contain one or multiple changes in direction with no other defining features are more easily confused. This might also explain why participants confused Melody 7 less often with Melody 2. Although these melodies are very similar in contour, the repeated note in Melody 2 may have acted as a distinct feature allowing participants to better differentiate the two. Additionally, the descending octave – an interval that is very salient even to an untrained ear (Krumhansl & Kessler, 1982) – may have helped differentiate Melody 2.

Of the melodies that contain changes in direction, Melodies 1 and 4 seem to be less confused than their counterparts, despite having one change of pitch direction each. This may be due to more subtle yet still distinct features. For example, Melody 1 contains a tritone, likely making it sound sadder (Huron, 2008) and less stable (Krumhansl & Kessler, 1982) than the other melodies. Some participants, particularly those with significant musically training, may have been able to identify this and use it in their learning. Likewise, Melody 4 consists of two descending intervals followed by an ascending interval, beginning, and ending on the same note. This return back to the initial note, or the "tonic" of these four note melodies, has been shown to improve melody recognition (Dowling, 1991) and may have helped differentiate Melodies 4 and 5, which have exactly the same contour with the exception of the last interval.

These salient intervals may help minimize confusion. The same can be said for Melodies 5 and 8 in that distinctive features, such as an overall descending contour (as in Melody 5), or a successively repeated note (as in Melody 8) are highly salient and can easily be differentiated from other alarms.

Melody–referent confusions

In this experiment, we randomized the melodies and alarm–referents, allowing us to address confusions caused by the referents themselves (i.e., phonetic similarity). As with previous studies, we saw modest confusions between Perfusion and Power Failure as well and Perfusion and Infusion referents. This suggests potential problems with the alarm names independent of the alarm sequences – a possibility that to the best of our knowledge has not been reported, as most studies tend to associate the alarms only with their recommended referent commands, confounding interpretations of confusions. Additionally, if phonetically similar alarm referents are paired with melodies that are also very similar, confusions could be additive and subsequently compound the problem.

Musical training

In Experiment 1, we found that musically trained participants required significantly fewer training blocks than musically untrained participants. Using the same criteria to define musical training, here, we found no such effect. Musically trained and untrained participants performed similarly in both the training and evaluation phases. We further explored this relationship by assessing the correlation between years of training and performance, which did not reach significance. This lack of a training effect may be attributed to the fact that participants in Experiment 2 had significantly fewer years of musical training overall than participants in Experiment 1. Consequently, musically trained participants took on average 6.4 blocks in Experiment 1 to learn the association, but 7.2 blocks in Experiment 2 (musically untrained participants did not differ between the two experiments – requiring 8.3 blocks in the first and 8.2 in the second experiment). It is possible that a certain level of training is required to affect performance on this task.

Conclusion

IEC alarm confusions

Ensuring that alarm sets are efficient and memorable is a significant and timely issue in human factors and alarm design, the subject of intensive studies offering a plethora of ideas for improvements (Edworthy, 2011; Edworthy et al., 2011; Phansalkar et al., 2010; Sanderson, Liu, & Jenkins, 2009). However, these studies rarely focus on the musical structure of auditory alarms, such as how particular combinations of musical intervals contribute to confusions. This is somewhat surprising, given that melody recognition is a rich topic within the field of music perception. To contribute toward efforts bridging these areas of research, here, we explored alarm learning using both a standard alarm set (i.e., the IEC alarms) in Experiment 1 and a novel alarm set in Experiment 2. By randomizing the melody–referent pairings in Experiment 2, we were also able to avoid potential confounds inherent when using the same alarm–referent pairs (unavoidable in previous experiments for obvious reasons). Furthermore, this design decision shed some light on the fact that alarm identification can also be influence by verbal confusions – a topic that requires further exploration and is highly relevant to alarm design.

Additionally, our results suggest that the superior performance of musically trained participants (i.e., having at least 1 year of formal musical training) reported in previous studies may be attributed to the training structure of the task. Unlike previous investigations where participants received a list of alarms they identified incorrectly (Lacherez et al., 2007; Sanderson et al., 2006; Wee & Sanderson, 2008), we reinforced the alarm/melody and referent after every trial, regardless of response correctness. Furthermore, we believe that this directly affected performance in the evaluation phases,

where we found no significant difference in performance between participants with some musical training versus no musical training.

Although more research is required to fully explore the ideas raised by our findings, they suggest that the accuracy of identifying melodic alarms may be improved by varying the tonal qualities of alarms and including salient features such as repeated notes, distinct contours, and distinctive intervals (i.e., by avoiding focusing exclusively on notes from within a major scale, which can limit opportunities for heterogeneity). Consequently, attention to the melodic structure of auditory alarms offers another technique for increasing heterogeneity in alarm sets – a factor relevant to ongoing efforts to improve alarm design. These principles could be used to build more robust redundancy into alarm cues by covarying interval quality and tone durations, for example.

It is important to note that even small improvements in auditory alarm design could lead to potentially large improvements in patient care. For example, one observational study in an Intensive Care Unit found that on average, two critical alarms are missed per day *per hospital* (Donchin et al., 2003). Consequently, in the United States with approximately 5720 registered hospitals servicing a population of 315 million, this rate corresponds to roughly 4.2 million errors per year. We recognize that medical professionals respond to many more alarms than they miss, and also that there are problematic aspects of alarms beyond their structure. However, we mention this issue here to underscore both the magnitude of the problem as well as the powerful potential public health benefits of even incremental improvements in alarm design by any means – such as through attention to basic principles of melodic structure.

Broader implications for music cognition research

While it is clear that we are able to easily make associations with music (as in the case of jingles, ringtones and musical motifs in operas, plays, or movies), it is less clear which specific features facilitate (or hinder) melody identification and the subsequent retrieval of these associations. Our exploratory data provide some insight on this issue, suggesting that distinctive features (i.e., repeated notes, distinctive contours, variations in tonality, etc.) are important factors in helping to distinguish melodies. Although future research is needed to further test some of the ideas arising from our data, we believe that this work holds value in improving our understanding of associative memory involving sounds, as well as informing research on melody identification. This also provides a unique opportunity in which music cognition research may be used in an applied setting to inspire future efforts to improve the design of auditory alarms – an issue of broad relevance to public health.

Acknowledgements

We would like to thank Janet Kim, Fiona Manning, Glenn Paul, Olivia Podolak, Matthew Poon, and Jonathan Vaisberg for their assistance in data collection, and Jeanine Stefanucci for her assistance in exploring the ideas leading to this project.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the Natural Sciences and Engineering Research Council of Canada [Grant Numbers NSERC RGPIN/386603-2010 and ER10-07-195]; McMaster University Arts Research Board, and the Canadian Foundation for Innovation: [Grant Number CFI-LOF 30101].

Notes

1. http://itee.uq.edu.au/%7Ecerg/auditory/alarms.htm.
2. Demographic information could not be provided due to an unfortunate lab flooding in which we lost all hardcopies of participant information collected for this experiment before it could be saved electronically.
3. Flat alarms consisted of three tones 244 ms in length (including 25 ms rise/fall times) separated by 156 ms. The general structure of percussive alarms was the same with the exception of the individual tones having a rise time of 25 ms, followed by an immediate exponential decay for the remaining duration of the tone.
4. http://www.addictinggames.com/sports-games/miniputt3.jsp.
5. http://circos.ca/circos_online/.
6. Previous explorations of IEC alarm learning classified individuals with least 1 year of musical training as "musically trained."
7. We used SuperCollider (http://supercollider.github.io/) to shape pure tones (i.e., sine waves) into flat and percussive envelopes for 13 different pitches forming the one octave chromatic scale. These sequences used pitches iteratively selected (with replacement) from the original 13 tones. We then arranged these individual tones into sequences using Audacity (http://www.audacityteam.org) – a free sound-editing program. All tone sequences consisted of four 1-s sound clips, either all percussive or all flat, concatenated together to create a 4-s melody. Percussive tones were approximately 800 ms in length separated by approximately 150 ms. Flat tones were 745 ms in length separated by 200 ms. For additional technical details, see Schutz et al. (in press).

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Appendix A

Summary of Experiment 1 Alarm Confusions

	Oxygen (Red)	Ventilation (Orange)	Temperature (Olive)	General (Green)	Power Failure (Cyan)	Cardiovascular (Blue)	Perfusion (Purple)	Infusion (Pink)
OX	-	2 (3.2%)	1 (1.6%)	0	0	0	1 (1.6%)	2 (3.2%)
VN	2 (3.2%)	-	2 (3.2%)	0	0	0	6 (9.7%)	6 (9.7%)
TE	0	3 (4.8%)	-	0	0	9 (14.5%)	0	0
GE	0	0	1 (1.6%)	-	0	1 (1.6%)	0	0
PF	0	1 (1.6%)	0	1 (1.6%)	-	0	0	0
CV	2 (3.2%)	2 (3.2%)	4 (6.5%)	0	0	-	0	0
PE	0	5 (8.1%)	0	0	0	1 (1.6%)	-	2 (3.2%)
IN	0	4 (6.5%)	0	0	0	3 (4.8%)	1 (1.6%)	-
	Total = 4 (6.4%)	**Total = 17 (27%)**	**Total = 8 (13%)**	**Total = 1 (1.6%)**	**Total = 0 (0%)**	**Total = 14 (23%)**	**Total = 8 (13%)**	**Total = 10 (16%)**

Note. Total confusions for Experiment 1, n = 62.

Appendix B

Summary of Experiment 2 Melody Confusions

	1 (Red)	2 (Orange)	3 (Olive)	4 (Green)	5 (Cyan)	6 (Blue)	7 (Purple)	8 (Pink)
1	-	1 (1.2%)	2 (2.4%)	2 (2.4%)	0	3 (3.5%)	3 (3.5%)	1 (1.2%)
2	0	-	0	1 (1.2%)	0	3 (3.5%)	2 (2.4%)	0
3	1 (1.2%)	2 (2.4%)	-	3 (3.5%)	1 (1.2%)	4 (4.7%)	5 (5.9%)	1 (1.2%)
4	4 (4.7%)	0	1 (1.2%)	-	1 (1.2%)	1 (1.2%)	5 (5.9%)	0
5	1 (1.2%)	0	1 (1.2%)	2 (2.4%)	-	1 (1.2%)	0	0
6	3 (3.5%)	0	10 (11.8%)	0	1 (1.2%)	-	3 (3.5%)	1 (1.2%)
7	2 (2.4%)	2 (2.4%)	3 (3.5%)	2 (2.4%)	1 (1.2%)	0	-	2 (2.4%)
8	0	0	2 (2.4%)	0	0	1 (1.2%)	0	-
	Total = 11 (12.9%)	**Total = 5 (5.9%)**	**Total = 19 (22.3%)**	**Total = 10 (11.8%)**	**Total = 4 (4.7%)**	**Total = 13 (15.3%)**	**Total = 18 (21.2%)**	**Total = 5 (5.9%)**

Note. Total confusions for Experiment 2, n = 85.