2021

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Parker, C. (2021) 'Can you hear it? Identifying the priority and function of overlapping auditory medical alarms', The Plymouth Student Scientist, pp. 639-657.
http://hdl.handle.net/10026.1/17317

The Plymouth Student Scientist
University of Plymouth

Can you hear it? Identifying the priority and function of overlapping auditory medical alarms

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Abstract

This paper presents an experimental study that exhibits the differences seen between the recognition of high and moderate priority auditory alarms when played simultaneously. Past research has demonstrated that the current IEC-60601-1-8 alarms used in clinical settings are challenging to identify and learn, and that newly developed auditory icons are easier to discriminate. The current research compares these two types of alarms and measures participant ability to recognise both the *function* and *priority* of single sounding and combination sounding alarms. Participants were either assigned to listen to IEC alarms or auditory icons and had to determine the function and priority of each alarm for both single and combination trials. Results display a significant difference between alarm priority and function identification in participants in the auditory icon condition, compared with those in the IEC alarms condition. Participants showed greater overall identification accuracy with auditory icons, for both single sounding and combination sounding trials. A significant difference was also found in priority identification in participants exposed to single sounding IEC alarms, where participants were better at identifying the *priority* of the IEC alarms but not the function. Explanations for this result are discussed with concern to alarm efficacy. Overall, findings from this study show that auditory icons outperform the current IEC alarms on both function and priority identification, proving to be the superior of the two. Results imply the importance of priority and function recognition in auditory icons when placed in a medical environment, and suggestions for further research are made.

Keywords: auditory comparisons, priority auditory alarms, IEC-60601-1-8 alarms, clinical settings, auditor icons, identification accuracy, alarm efficacy, hearing, psychology

Introduction

Auditory alarms are an integral component within all medical environments. They are crucial to monitor patients' vital information by alerting medical staff about health status, changes to medical equipment and potential adverse events. The International Electrotechnical Commission (IEC) has a published standard (IEC 60601-1-8:2006) which includes a specification of requirements to which the basic safety of medical equipment must be upheld at a global level. A 'reserved' set of alarms is included in the standard which contains information about the different alarm categories that should be present: these include a General alarm, Cardiovascular, Ventilation, Drug administration, Oxygen, Perfusion, Power down and Temperature (Edworthy & Baldwin, 2016).

Each of the eight alarm categories retains a unique sound which represents the function, a high and moderate priority version of each alarm is also included to indicate event severity. Though the function sound of each category remains constant, priority is represented through the number of pulses present in the sound. High priority alarms are presented as a five-pulse rhythmic unit, twice in succession, whereas moderate priority is presented as a single three-pulse unit (Edworthy *et al*., 2017). The construction of the high and moderate priority alarm sequences are demonstrated in Table 1. Understanding an alarm's level of priority is a crucial ability and aids healthcare workers to respond appropriately. Moreover, the priority does not just serve as a form of acoustic information for event severity but communicates the order in which the listener must attend to each alarm, should two sound at the same time; hence, the need for both the high and moderate priority alarms.

However, the current set of IEC standard alarms has shown to lack efficacy. Williams and Beatty (2005) have demonstrated the restrictions to the learnability of the current IEC alarms and show a 97.5% misidentification rate in participants after training. Current IEC alarm learnability and discriminability were also examined by Sanderson, Wee and Lacherez (2006). They also found similar results where participants displayed confusion and low accuracy rates when attempting to identify the functions of the IEC alarms. Furthermore, this study also found that participants were faster to react to the alarms indicating a moderate level of priority, despite rating high priority alarms as more urgent. This result suggests that even though participants recognised which alarm was more urgent, there appears to be confusion in interpreting which alarm to react to first. Wee and Sanderson (2008) have further extended these findings to a more applicable demographic, where a reduction in response-time to high priority alarms was found in a sample of critical care nurses, despite understanding the urgency of the high priority alarm. Therefore showing that these IEC alarms are challenging to learn, interpret and identify even for those with extensive medical training and medical familiarity. It is therefore clear from these studies that IEC alarms are already difficult to identify in a laboratory study, let alone in the fast-paced setting of a clinical environment.

Moreover, due to the nature of medical settings, it is highly unlikely that staff will find themselves in a position where only one alarm is heard at a time. Therefore interpreting two alarms at the same time is incredibly important and should be done as accurately as possible, something which the IEC alarms have also presented limitations to. Research by Lacherez, Seah and Sanderson (2007) has demonstrated that when two or more IEC alarms are to play at the same time, alarm identification accuracy decreases even amongst those who are familiar with the sounds and their function, i.e. medical staff. Lacherez *et al*. (2007) also revealed that nurses and non-nurses both confused alarm pairs at a similar rate, displayed poor learning, and performed alarm function identification no differently from each other when listening to IEC alarms. This result implies that even with the copious amounts of training associated with this profession, when two alarms sound simultaneously, it is a challenging task to identify either of them.

Problems regarding the melody of the IEC alarms are believed to be the foundations of these issues and, although the melodic tone of each alarm varies slightly, each alarm is composed of similar rhythms and keys. However, if alarms are to be discriminable, they need to vary on more than just rhythm and melody alone (McGookin & Brewster, 2004). Consequently, because of the homogeneity of the IEC alarms, the likelihood of identification decreases when two alarms are heard simultaneously, due to the inability to separate one sound from the other (Lacherez *et al*., 2007). This problem in identification lends a considerable cause for concern regarding IEC alarm contribution to the fatal matter of alarm fatigue in the medical industry (Cvach, 2012).

It is in these melodic issues that limitations to our cognitive system have been outlined. Lacherez *et al.* (2007) have drawn theoretical explanations using evidence from Bregman (1990) to explain the inability of multiple IEC alarm comprehension, suggesting that a lack of processing comes from a deficit in 'auditory scene analysis' (Bregman, 1990): a process in the auditory system which separates the input of auditory streams. IEC alarms do not possess the features required to segment these auditory streams, resulting in confusion and an inability to separate one alarm from the other when heard at the same time (Lacherez *et al*., 2007). Moreover, hearing the first few notes of a melody is a necessary component of identification, and blocking this with the sounds of other overlapping alarms will make this much more difficult (Schulkind, 2004). It has also been thought that the IEC alarms pose limits to the human perceptual system as it's not fully equipped enough to hold the pitch values of a long tone, and the use of smaller melodic intervals make tone retention easier (Deutsch, 1978). Furthermore, overexposure to the sound of multiple alarms causes our auditory system to become overused, especially with consistent false-alarms which cloud our perceptual system (Edworthy & Hellier, 2005).

In light of the issues caused by the IEC alarms, advances have been made to update the IEC alarms. Petocz, Keller and Stevens (2008) have explained that the melodies of the current IEC alarms share minimal relationships with the function they represent due to their abstractness, so any associations needed to recall the alarm function have to be learned at a great effort. Due to this IEC alarm limitation, a novel class of alarms known as "auditory icons" have made their way to the forefront of new research (Edworthy *et al.*, 2017). Auditory icons are audible metaphors for the function which they represent, for example, the icon for the deletion of a file on a computer is the sound of crumpling paper. Auditory icons also possess a priority element for each category of alarm which is represented in the form of a priority pointer; a different sound which is embedded within the icon to represent high or moderate priority. Edworthy *et al*. (2014) previously established the efficacy and learnability of these alarms by demonstrating that participants can learn metaphoric icons at a significantly better rate than random abstract alarms *and* the current IEC alarms, which suggests that the current standard is outdated, and new alarms are available which facilitate enhanced alarm learning and identification.

With this in mind, Edworthy *et al*. (2017) and subsequent researchers have become part of a move on behalf of the relevant standards committees that stand to update the reserved alarms specified in the IEC standard and to provide empirical evidence on their performance, or lack thereof. Edworthy *et al*. (2017) have experimented with other types of metaphoric alarms which match the criteria specified in the IEC, in attempt to make comparisons with IEC alarm learnability. Results show that when participants were introduced to four alternative alarm sets, not only did all four alternatives outperform the current IEC alarms on recognisability but the auditory icons were the most easily recognised of the four conditions. Therefore, not only showing that metaphoric alarms are generally better than the current IEC alarms, but that auditory icons are best suited in terms of performance.

Furthermore, McNeer, Horn, Bennet, Edworthy and Dudaryk (2018) have extended this body of research to anaesthetists, of whom have knowledge and familiarity of a clinical environment. Participants were assigned to either the standard IEC alarms or auditory icon condition and were tested on identification accuracy and response time. Participants in the icon group were 26.1 times more likely to correctly identify the function of the alarm than those in the standard IEC condition; response times were also much faster in the icon condition. In addition to these results, participants were more likely to experience fatigue and have perceptions of a higher task load when exposed to the IEC standard alarms. Therefore, not only do auditory icons prove themselves to be of faster learnability and discriminability, but also appear to reduce the effects of perceived workload and alarm fatigue.

Subsequently, auditory icons have shown superior accuracy over the IEC alarms on recognisability and localisability in a lab setting (Edworthy *et al.*, 2017). As well as greater identification accuracy in a clinical setting, with auditory icons outperforming IEC alarms on response time and perceived fatigue (McNeer *et al*., 2018). However, despite the use of a clinically simulated environment, some of these previous studies have failed to include essential factors which affect alarm identification, such as background noise and divided attention. Edworthy *et al.* (2018) have presented findings which compare the localisability of IEC alarms and auditory icons while performing a secondary task in the presence of background noise. Results from this study have shown that participants were able to localise auditory icons while completing a secondary task at the same rate as localising IEC alarms with no other tasks. Demonstrating the extent to which the design of the alarm can ease the workload on the listener in a challenging medical environment. Bolton, Zheng, Li, Edworthy and Boyd (2019) have also demonstrated that a further limitation to the IEC alarms is the minimal level of background noise required to mask other alarms. Results from Bolton *et al.* (2019) show that background noise that is loud enough to mask the alarm's primary harmonic is enough to make the alarm indistinguishable. This finding explains the cause of alarm fatigue through psychoacoustics and how medical staff are incapable of recognising and responding to these alarms even after copious amounts of training, through no fault of their own.

Ergo, the 'top-performing' auditory icons have been sought after by Bennett, Dudaryk, Crenshaw, Edworthy and McNeer (2019) who used medical staff to test alarm identification and masking in a clinical simulation. Results demonstrate that most of the auditory icon alarms were still audible at volumes ¼ of the level of background noise. Moreover, the embedded priority pointer should allow audibility to become highly distinguishable from background noise and other icon alarms, unlike IEC alarms that mask each other (Bolton *et al.*, 2019). Therefore auditory icons are still more distinguishable than the current IEC alarms, even with louder background noise and distraction. Thus, Bennet *et al.* (2019) have formatively tested 38 auditory icons, of which eight have been proposed as the 'best performing' concerning audibility and identification. This set of eight alarms has been put forward for recommendation to the IEC as replacements for the current alarms in the standard.

With the use of these newly proposed alarms, research needs to establish the efficiency of the auditory icons when two are heard at overlapping intervals. It is critical at this stage that the auditory icons outperform the current IEC alarms on a matter of function and priority identification. The rate of function identification has previously been established in past research; therefore priority identification needs to be measured to understand if the priority pointers in the auditory icons are still distinguishable when heard with an overlapping second alarm. Therefore, this research aimed to examine these factors in a laboratory study where participants were either assigned to listen to the current IEC standard alarms or the newly recommended auditory icons. Participants heard two different alarms with differing priorities, which overlapped each other in sound. Participant accuracy was recorded based on priority and function identification.

It was predicted that auditory icons would outperform IEC standard alarms on function identification at least, due to the supporting evidence in past literature. Priority identification accuracy was also measured as it was predicted that participants would be better at identifying high priority and moderate priority alarms in the auditory icon condition, compared to the current standard IEC alarms condition. This prediction was grounded on the premise that auditory icons possess two different components of sound (function and a priority pointer), and the icons will be processed as different auditory streams when heard together, making them easier to identify (Bregman, 1990). In consequence, it is therefore predicted that overall (priority and function) performance is more accurate when listening to the new auditory icons compared with the current IEC standard alarms.

Method

Participants

66 participants (60 female, 6 male, M_{age}=20.86, age range: 18-49 years) from the University of Plymouth took part in this study investigating auditory alarms. All participants were psychology students from the university and were recruited from the University's Psychology Participation Pool. Participants were required to have normal or corrected-to-normal hearing in order to complete the study.

Materials

Equipment:

Throughout the experiment a standard sized computer monitor was used, along with a set of over-head headphones which were set to a comfortable listening volume of 25. A computer mouse was also used to indicate answer choice.

Stimuli:

The program used in this study was specifically designed for this experiment. Four main alarm functions were present during this study: cardiovascular, oxygenation, ventilation and drug administration. The alarms used were selected from the current IEC 60601-1-8 standard of reserved alarms and from the new set of recommended auditory icons that are to be implemented in the updated IEC 60601-1-8, occurring in 2020. Both high and medium priorities were selected for use in this experiment.

IEC alarms (old):

The current IEC alarms consist of a 10-pulse basic unit (2x 5-pulse unit) for the four high priority alarms and a 3-pulse basic unit for the moderate priority sounds, of which meet the requirements if the standard. Table 1. illustrates the melodies of which formulate the current IEC alarms, including the four used in the current study.

Table 1: Melodies of current IEC 60601-1-8 alarms, including the four chosen functions for this study and their priority tones.

Cause	**Medium Priority**	**High Priority**
Cardiovascular	c e g	c e g - g C
Ventilation	c a f	c a f - a f
Oxygen	C b a	C b a - g f
Drug administration	C d g	C d g - C d

NOTE 1: The characters c, d, e, f, g, a, b, C refer to relative musical pitches and C is one octave above c.
NOTE 2: A high priority alarm signal is generated with the five pulses shown, repeated once, for a total of ten pulses

Auditory Icons (new):

Auditory Icons are termed to describe any sound that has an obvious connection to its function, its metaphorical (Edworthy *et al.,* 2017). Each of the four alarms consisted of two separate components: an auditory icon (metaphorical sound) and either a high or moderate priority pointer- a sound which is abstract in quality, shorter than the auditory icon and used to indicate the priority of the alarm. The pointers used in the icons are harmonically improved versions of the rhythmic structure which make-up the old IEC alarms. The high priority pointer consists of a 10- pulse unit (2x 5-pulse), similar in sound to the IEC high priority alarm but much faster. The moderate priority pointer is a 3-pulse unit, again, similar but faster than the IEC medium priority tone. Table 2. illustrates the descriptions for each of the new IEC alarms, including the four which are included in this study.

Table 2: Descriptions of the new/updated IEC alarms including icon metaphor and sound description.

Category of the source of the alarm condition	Auditory Icon metaphor	Auditory Icon description
Cardiovascular	‘Lup-dup'; heartbeat sound	A stylized, square/triangle wave-based 'heartbeat' sound with no discernible frequency. Six pulses formed from three 2-pulse 'lup-dup' sequences
Ventilation	A single inhale followed by an exhale	A 1s inhaling sound (like white noise), followed by a 0.5s gap, followed by a slow exhale with a long tail
Oxygenation	Irregular, stylized dripping/saturation	Stylized irregular temporal pattern with some discernible pitch; a two-tone sequence superimposed on the six-tone pattern
Drug Administration	Shaking pill bottle	Two 0.8s sequences of a 4-rattle shaking sound

The four selected alarms were tested in both single and combined form.

<u>Single alarms:</u>
On trials with a single alarm sound, each of the alarms (high and moderate priorities, old IEC and new auditory icons) were heard as their individual forms.

<u>Combination alarms:</u>
Combination alarms consisted of an initial high priority alarm followed by a moderate priority alarm. For both old (IEC) and new (auditory icon) conditions the moderate priority alarm always followed the high priority by a gap of 1.2 seconds. This allowed the first alarm to almost finish before the second alarm was heard, in attempt to avoid participant confusion but still simulate the sound of overlapping alarms. As it was not possible to generate all possible combinations of alarms for both old and new conditions, a set list of pairings was used for both conditions. A table of all used alarm combinations is illustrated in Table 3.

Table 3: High and moderate alarms played as combinations during the trial phase.

		High priority alarm			
		Ventilation	Oxygenation	Drug Administration	Cardiovascular
Moderate priority alarm	Ventilation				
	Oxygenation	✓		✓	✓
	Drug Administration		✓		✓
	Cardiovascular	✓	✓	✓	

Thus, each high priority alarm was paired with two of the three possible moderate priority alarms. And, no alarms of the same function were paired together.

Procedure

Participants were randomly allocated to either the old or new condition upon arrival to the experiment and were seated in front of the computer monitor at a comfortable viewing distance. Instructions of the study brief were visible on the monitor for the participant to read. After reading the brief (Appendix A) and completing their informed consent (Appendix B), participants were instructed to put on their headphones and begin the study.

Participants allocated to the ‘old’ condition listened to the current IEC-60601-1-8 alarms whereas those in the ‘new’ condition listened to the auditory icons. Prior to the trial phase of the study, participants were given a 10-minute training phase where they listened to each of the four alarms and viewed their function on the computer monitor three times each. Participants were then given four practice alarms where they were presented with two single and two combination alarms.

Participants had the opportunity to listen and respond as if in the trial phase, in order to become familiar with the nature of the study. Once the training phase was completed, the program was paused by a screen detailing that the next stage of the study would be the trial phase.

The trial phase included listening to a mixture of the high and moderate priority alarms presented alone or presented as a combination. For trials which included a single alarm, participants had to listen to the sound and then a) select the level of priority (Figure 1.), and b) identify the function of the alarm (Figure 2.)

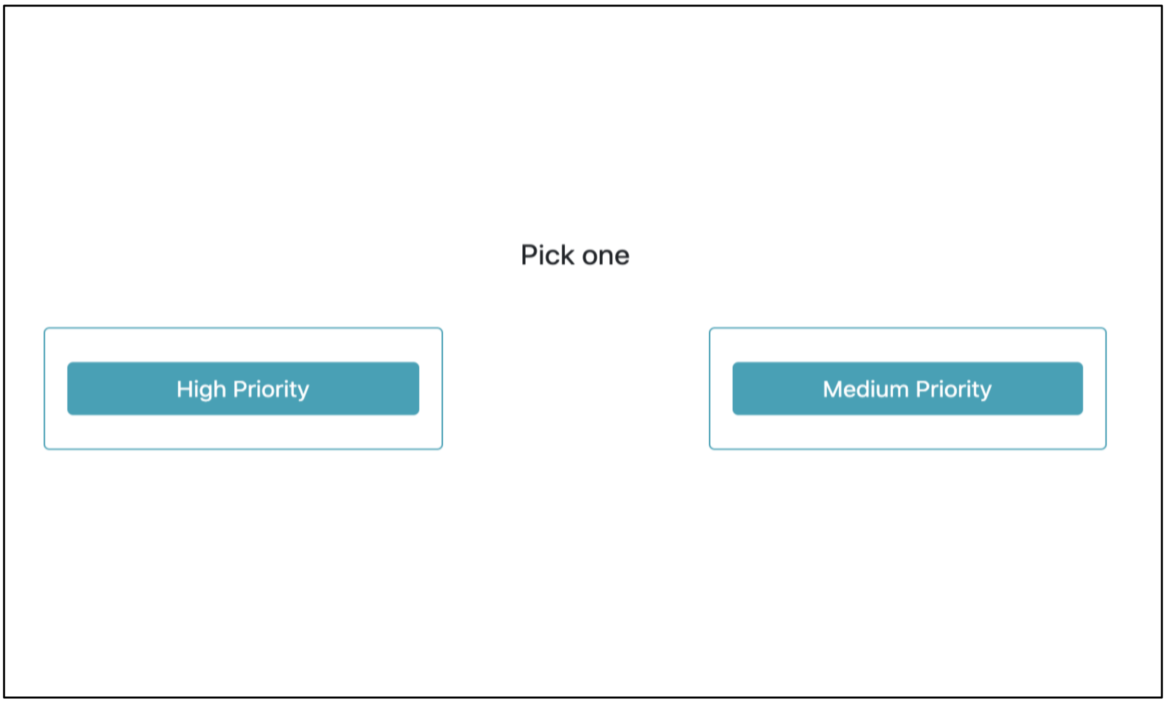

Figure 1: A copy of the first on-screen option presented to participants after listening to a single sounding alarm, listing the options of alarm priority.

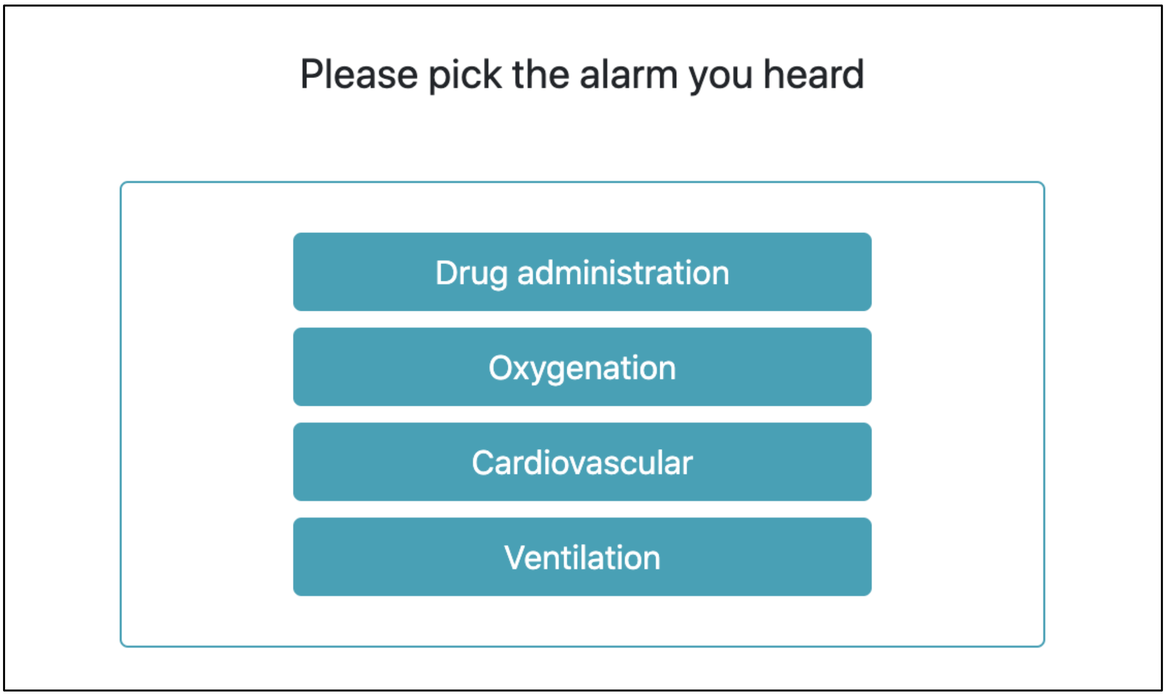

Figure 2: A copy of the second on-screen option, presented to participants after listening to a single sounding alarm, listing the options of alarm function.

For trials which included a combination alarm, participants were presented with an on-screen option to which they were instructed to select what they thought was the high priority alarm and then select which they thought was the moderate priority alarm. The high priority alarm was always heard first and then followed by the moderate priority alarm. Thus, the high priority options always appeared to the left of the screen as a 'first choice' option and moderate priority always appeared to the right of the screen. An example of the on-screen option given to participants is presented in Figure 3.

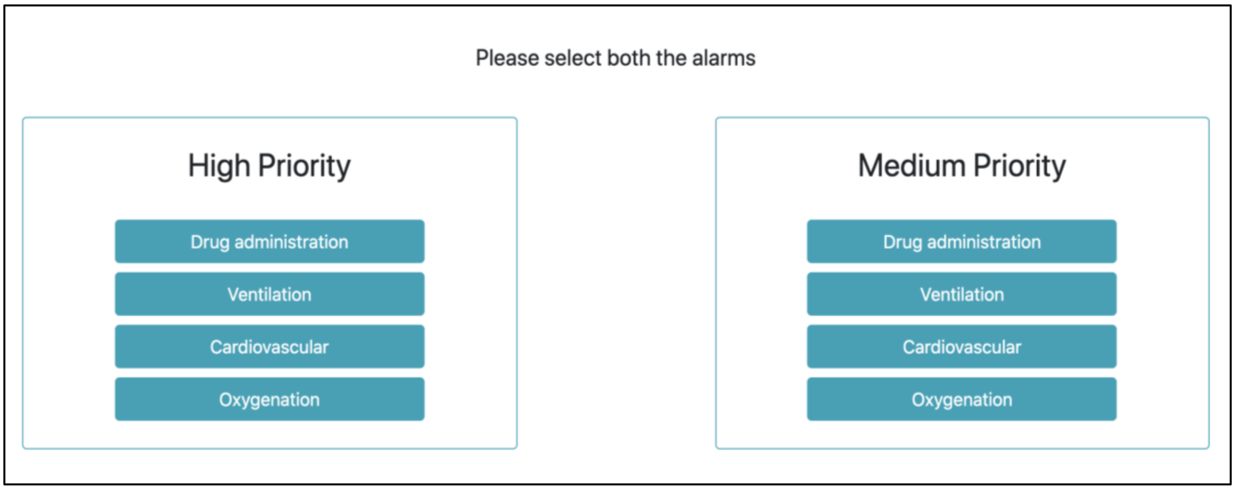

Figure 3: A copy of the on-screen option presented to participants after listening to a combination alarm sound.

The test phase consisted of 32 trials, which consisted of 16 single sounding alarm trials and 16 combined alarm trials. Throughout the study, data for the single and combination sounding alarms was collected in reflection of: correct/incorrect *priority* identification, correct/ incorrect *function* identification and an overall priority/function identification score. Participants were only marked as being overall correct if both the function and priority identification was correct. Priority and function data were recorded in isolation to the overall score for more detailed analysis. After completion, participants were given a debrief (Appendix C) and given all the appropriate contact details should they have wished to withdraw their data.

Results

2x2 ANOVA:

A two-way analysis of variance was conducted using the two variables 'condition' and 'stimulus' to establish the accuracy of alarm-priority and alarm-function identification. The condition variable included two levels, signifying the current IEC alarms (old) and the auditory icons (new). The stimulus variable included two levels to depict the type of alarm trial participants listened to (single, combination). Mean scores were calculated using data scored as being 'overall correct', meaning that if participants accurately identified both the priority and the function of the alarm(s) they would be scored as '1' but if either of the identifications were incorrect, they would be scored as a '0' for 'overall correct'.

All effects were statistically significant where the 'condition' variable yielded an F value of $F(1, 2108) = 375.78$, $p < .001$, showing a significant difference between the two conditions; old alarms (*M*= .30, *SD*= .46) and new alarms (*M*= .68, *SD*= .47) and the 'stimulus' variable yielding an *F* value of $F(1, 2108)= 108.49$, $p < .001$, also showing a significant difference for single (*M*= .60, *SD*= .49) and combination (*M*= .39, *SD*= .49) alarms. The interaction effect was not significant $F(1, 2108) = .46$, $p = .50$, suggesting no interactions between variables took place. Differences between means can be seen in figure 4.

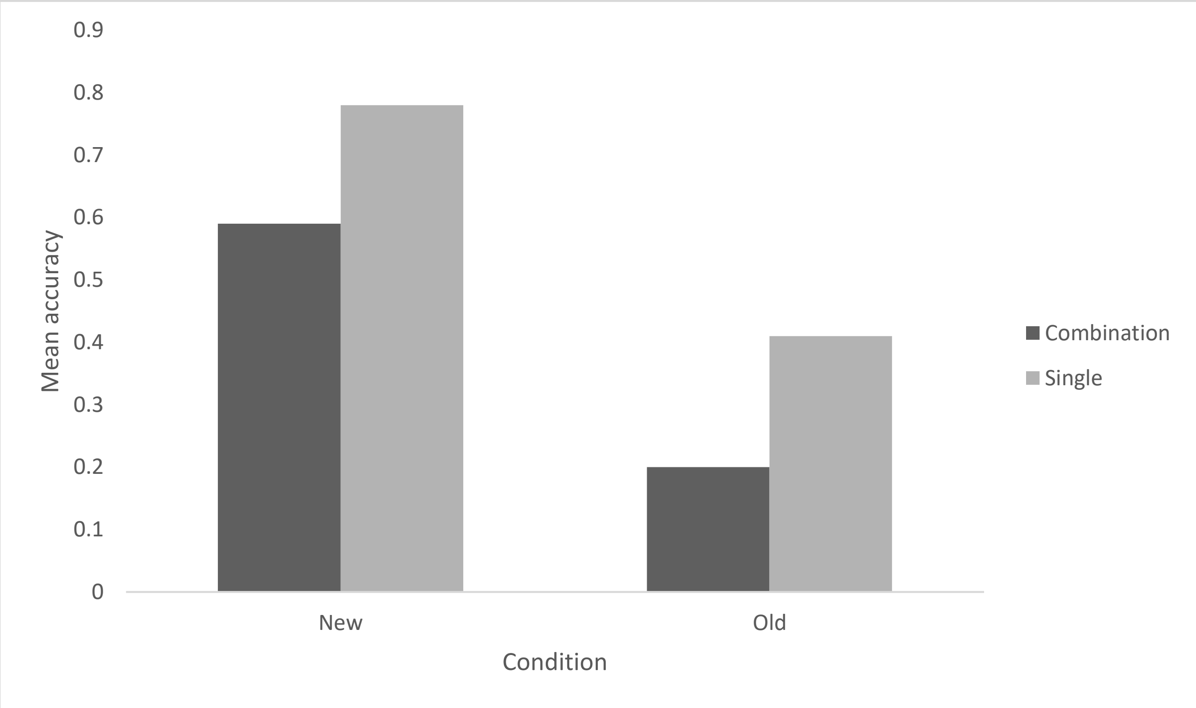

Figure 4: A bar chart comparing the differences between means of single and combination alarm function and priority identification accuracy in old and new conditions where 'old' represents the IEC alarms and 'new' represents auditory icons.

t-tests:

Four *t*-tests were also run to establish differences in means between all four levels of comparison (single, combination, old, new).

An independent-samples *t*-test comparing participants listening to single alarms found a significant difference between participants in the old condition (*M*= .41, *SD*= .49) and participants in the new alarms condition (*M*= .78, *SD*= .41), $t(1023.88)= 13.11$, $p< .001$, where equal variances were not assumed. Participants listening to single sounding alarms show greater identification accuracy in the new condition compared to the old condition.

An independent samples *t*-test comparing participants listening to combination alarms found a significant difference between participants in the old alarms condition (*M*= .20, *SD*= .40) and participants in the new condition (*M*= .59, *SD*= .49), $t(1008.21)= 14.32$, $p< .001$ where equal variances were not assumed. Participants listening to combination sounds were more accurate at identification in the new condition, compared to the old alarms condition.

A paired samples *t*-test was conducted to compare the accuracy of alarm identification among participants in the old alarm condition with single alarms (*M*= .41, *SD*= .49) and combination alarms (*M*= .20, *SD*= .40), *t*(527)= 9.08, *p*< .001. Where single old alarms are more accurately identified than combination old alarms.

A further paired samples t-test was conducted to compare the accuracy of alarm identification among participants in the new alarm condition with single alarms (*M*= .78, *SD*= .41) and combination alarms (*M*= .59, *SD*= .49), *t*(527)= 7.89, *p*< .001, where single new alarms were also more accurately identified than combination new alarms.

One-way ANOVAs:

Throughout data collection, results were taken to record correct and incorrect responses to priority and function identification as separate entities. An overall score was calculated using these and participants were only marked as being correct if both identifications were accurate ('1'), of which this data has been represented in the previous 2x2 ANOVA statistical tests. This overall score only represents the sample of participants who managed to correctly identify the priority and the function of the alarm. However, this does not accurately represent the participants who managed to identify one but not the other, i.e. accurately identified priority, but mixed up the functions, or visa versa. Therefore, several one-way between-subjects ANOVAs have been conducted to establish any differences between the number of correctly identified priorities and the number of correctly identified functions in single and combination stimuli, in isolation to the overall score.

Priority Identification:

Data from participants who managed to accurately identify priority *only* are represented in this section of statistical analyses. Data was taken from participants who scored '1' for priority identification but '0' for function identification for both single alarm trials and combination alarm trials.

A significant difference was found between the number of correctly identified *priorities* in single old alarms (*M*= .96, *SD*= .19) and single new alarms (*M*= .84, *SD*= .37), *F*(1, 1054)= 48.51, *p*< .001, where participants had better accuracy for identifying single alarm priorities in the old condition than the new condition. Possible explanations for this are discussed. Differences between means can be seen in Figure 5.

A second one-way ANOVA has shown a significant difference, between combination alarms where *priority* identification in old alarms (*M*= .41, *SD*= .49) was significantly different from new alarms (*M*=.63, *SD*= .48), *F*(1,1054)= 51.65, *p*< .001. But, unlike the last, participants exposed to the new condition were more accurate than participants in the old condition on identifying the priority of combination alarms. Differences in means can be seen in Figure 6.

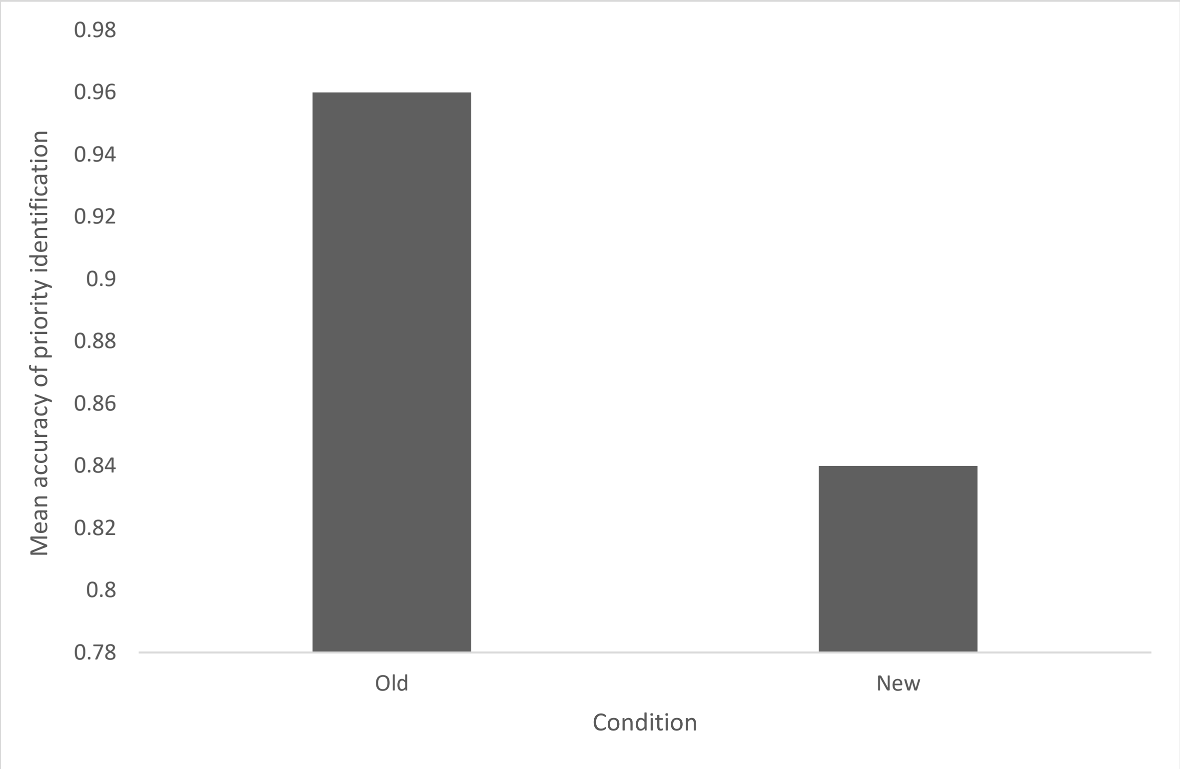

Figure 5: A bar chart of means, showing priority identification accuracy of single alarms in old (IEC) and new (auditory icons) conditions.

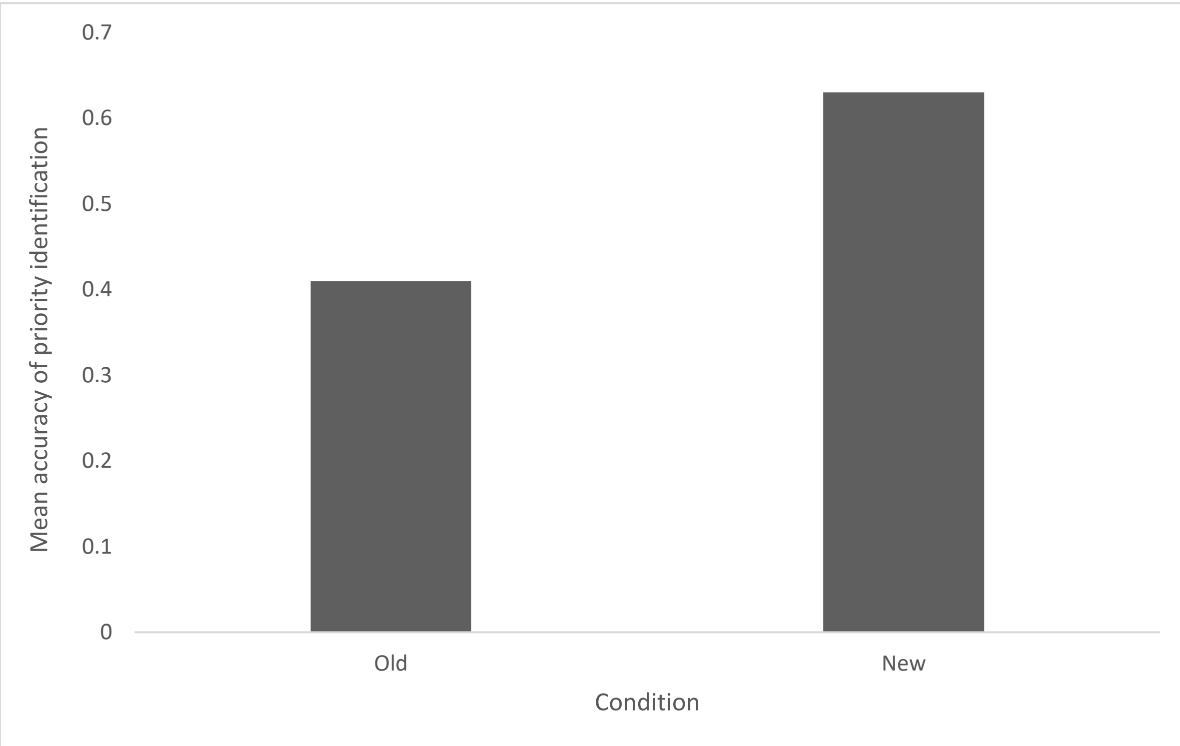

Figure 6: A bar chart of means, showing priority identification accuracy of combination alarms in old (IEC) and new (auditory icons) conditions.

Function Identification:
Data from participants who managed to accurately identify function *only* are represented in this section of statistical analyses. Data was taken from participants who scored '0' for priority identification but '1' for function identification for both single alarm and combination alarm trials.

A significant difference was found between the number of correctly identified alarm *functions* of single alarms in the old alarm condition (*M*= .43, *SD*= .50) and new alarm condition (*M*= .91, *SD*= .28), *F*(1,1054)= 385.27, *p*< .001, where participants were more accurate at identifying the function of new single alarms, compared to old single alarms. Difference between means can be seen in Figure 7.

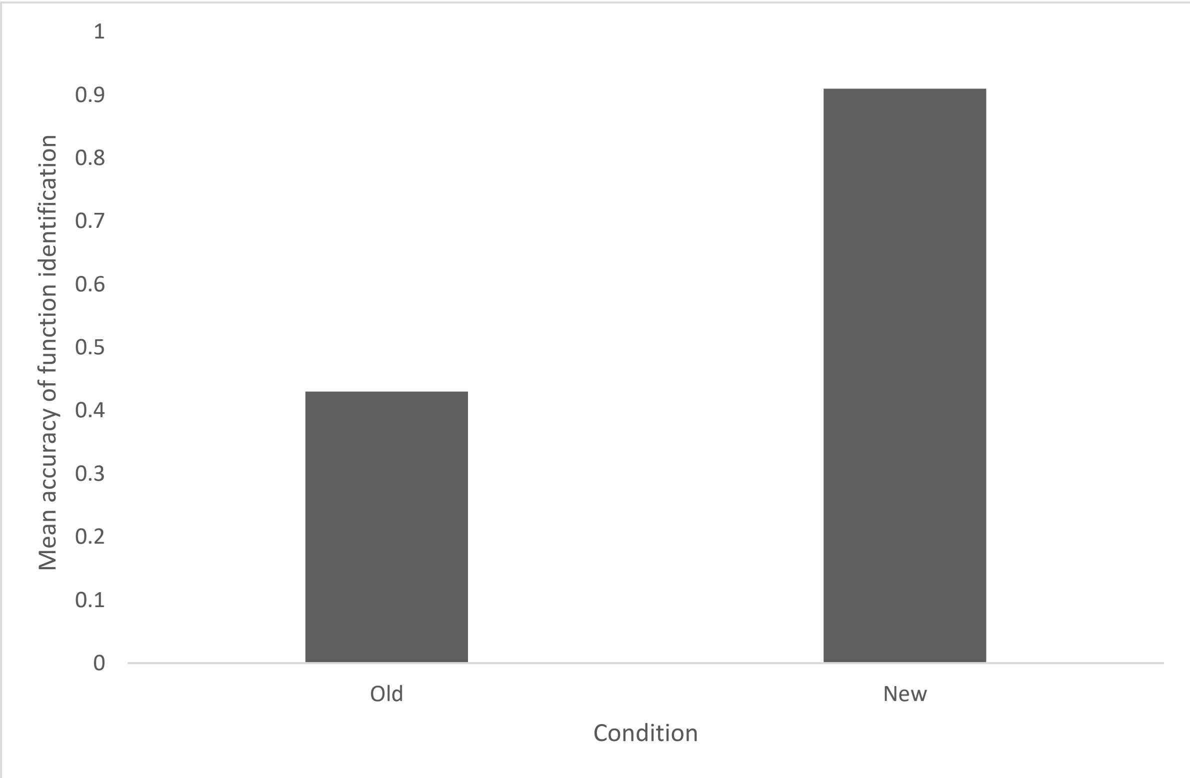

Figure 7: A bar chart of means, showing function identification accuracy of single alarms in old (IEC) and new (auditory icons) conditions.

A further significant difference was also found between the number of correctly identified alarm *functions* of combined alarms in the old alarm condition (*M*= .37, *SD*= .48) and new alarm condition (*M*= .69, *SD*= .47), *F*(1,1054)= 120.66, *p*< .001, where participants were more accurate at identifying the function of new combined alarms than old combined alarms. Differences between means can be seen in Figure 8.

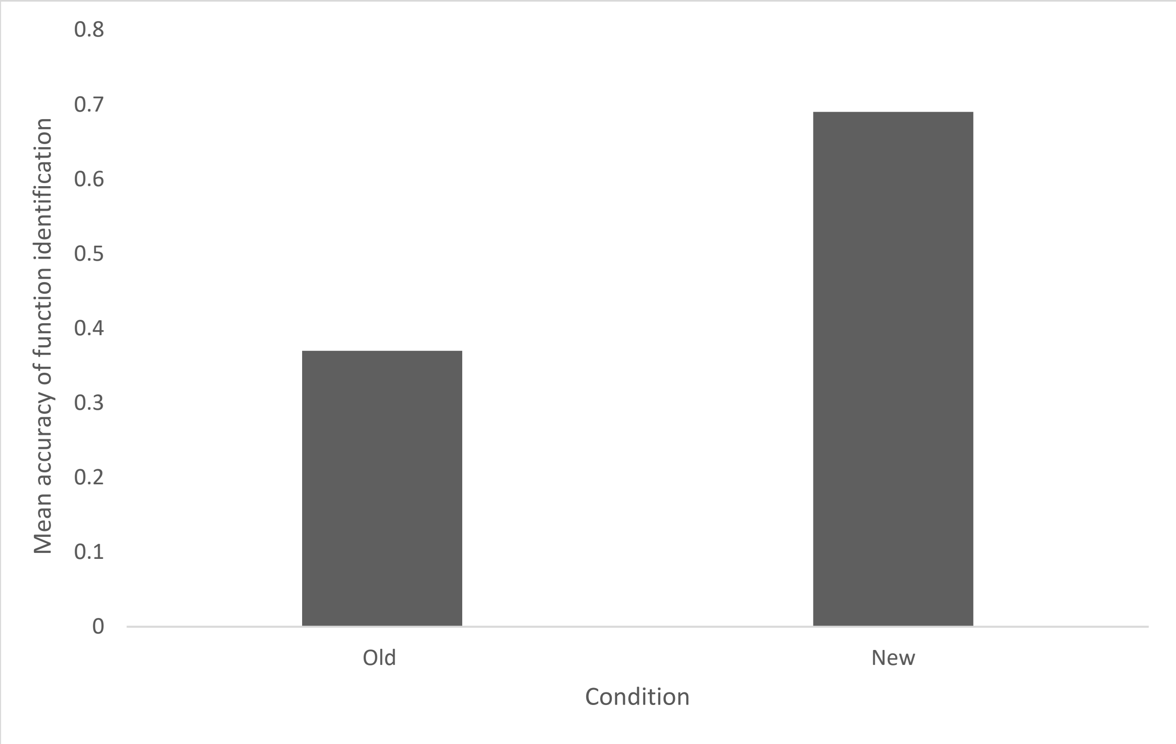

Figure 8: A bar chart of means, showing function identification accuracy of combination alarms in old (IEC) and new (auditory icons) conditions.

Discussion

The current study set out to gather data in support of the recent research regarding auditory icons and their enhanced identifiability, in comparison to the current set of IEC standard alarms. This study outlines differences seen within participants when identifying single sounding and combination alarms, which differ in levels of priority, with participants who were either exposed to the current IEC standard alarms or the newly recommended auditory icons. It was predicted that auditory icons would outperform the current IEC alarms on the discriminability of function identification and priority identification when heard alone and when heard in succession of a second alarm.

Overall, the results presented in this paper provide support for past research that indicates that auditory icons are more easily recognisable and learnable than the current set of reserved IEC standard alarms (Edworthy *et al.*, 2017; McNeer *et al*., 2018). Firstly it can be noted from the 2x2 ANOVA that participants were significantly better at identifying the function and priority, as a whole, in single sounding auditory icons, in comparison to the single sounding IEC alarms. This finding is not surprising given the evidence seen in previous research to support this (McNeer *et al.*, 2018); however, this was something we needed to investigate in order to gain a fair comparison between the single and combination data. Nevertheless, similar results were also found for the combination alarms, where participants were also more accurate at the overall identification of combined auditory icons compared to the combined IEC alarms, something which research has not yet established. Furthermore, the subsequent *t*-tests lend further support to this finding, demonstrating that the auditory icons significantly outperformed the IEC alarms in both single and combination conditions. These *t*-tests have also shown that the alarms that were played in singular form were significantly better identified than those played in succession, for both the IEC and auditory icons; but, with the icons proving the superior of the two in terms of function and priority identification. This finding displays the effects a second alarm has on identifiability response time, which is heightened with the use of the IEC alarms; of which, supports the previous findings made by Lacherez *et al.* (2007). Therefore, when examining the overall rate of function and priority identification, it can be said that the new auditory icons significantly outperform the current IEC standard alarms.

In order to assess the accuracy of function and priority identification in isolation to overall performance, several one-way ANOVAs were completed. Almost all of the results were as predicted where the new auditory icons significantly outperformed the IEC alarms on *function* identification for both single and combination alarms. Combined auditory icons also significantly outperformed the opposing IEC combined alarms on *priority* identification, which was also expected.

However, one result from these one-way ANOVAs appeared to show what could be considered as an anomalous finding, where single-sounding IEC alarms were better recognised than the single-sounding auditory icons on *priority* alone; however, while this was not expected, it is not surprising. The IEC alarms differentiate in priority by expressing ten fast pulses (high priority) or three slower pulses (moderate priority) (Edworthy *et al*., 2017). Therefore, discriminating between single sounding high and moderate priority IEC alarms is quite easy to do. However, the new auditory icons express priority through an embedded pointer, which also helps to identify the function. Consequently, the overall identification process for the auditory icons is easier, as the pointers facilitate the identification of function as well as the priority. Hence, the listener needs to listen to two sounds and make a decision, unlike the IEC sounds where priority is the only differing feature about the alarms. So when people are asked to identify both priority and function, they are much better able to do this with the auditory icon alarms than the IEC alarms. However, when asked only to identify the alarm based on priority, this is a straightforward decision to make with the IEC alarms. This explanation rationalises the results seen from this study, but questions the usefulness of this IEC alarm feature.

If people are only able to discriminate between priorities of the IEC alarms and are unable to discriminate the functions, then are these alarms serving their purpose? The ability to identify alarm priority alone is not a useful component to an alarm system as people are also required to be able to identify the function; of which, cannot be achieved with the IEC alarms for single or combined alarms, as per the results. Furthermore, when placed in a medical environment where multiple alarms may sound at any one time, the IEC alarms would prove quite ineffective if staff are only able to identify and locate the alarms based on priority without identifying their function as well. Therefore, with this in mind, the auditory icons remain as the superior system for auditory alarms.

Therefore, the data collected from the current study support the predictions made at the beginning of the paper. Collectively, these results suggest that not only are auditory icons easier to identify when heard singularly but also when heard in the presence of another alarm. Furthermore, the rate of accurate identifications for priority and function in auditory icons suggest that they are unique enough to gauge an accurate alarm-based judgement. Additionally, the limited 10-minute slot given for the initial training phase during the study also suggests that the auditory icons possess qualities that facilitate better alarm-based learning than the current IEC alarms. Both of these findings support earlier research by Edworthy *et al.* (2014) regarding the enhanced discriminability and learnability of the auditory icons.

Moreover, this study has also outlined previously unknown findings. In reference to priority, it can now be understood that identification accuracy of the current IEC alarms is not due to the function, but to the level of priority; of which, is an impractical feature if the function cannot be recognised concurrently. Therefore, although the auditory icons may not outperform the IEC alarms on priority identification alone, the high overall accuracy of icon priority and function identification demonstrates the importance of having an alarm system which facilitates listeners to comprehend both parts.

Furthermore, past research has focussed on the differences seen between the new auditory icons and the current IEC alarms (McNeer *et al*., 2018). But there is limited research into the effects of successive sounding alarms. Lacherez *et al.* (2007) have demonstrated how nurses become confused and lack accuracy when attempting to identify IEC alarms that overlap.

The current paper demonstrates results in support of this finding, in such that participants also lack accuracy in identification when IEC alarms overlap in sound and also have differing priorities. Theories from Bregman (1990) could also be applied to this finding, in support of ‘auditory scene analysis’ as this indicates that there is a lack of auditory stream segregation due to the IEC alarms not holding the features required to make these alarms more distinguishable for the auditory stream. And, as the IEC alarms only possess auditory difference through priority, it is easy for the listener to become confused when hearing two alarms that overlap. In contrast, auditory icons are developed to retain two elements to their alarm: the metaphoric function and a priority pointer, which are very different in sound. Auditory icons would, therefore, facilitate easier segregation into the auditory stream because of these different properties allowing for easier function and priority identification, which supports the findings made by McGookin and Brewster (2004).

Despite the significant findings, the current study does pose some limitations. Firstly, this study was conducted with psychology students from the University of Plymouth. While this demographic provided the predicted results, future research should aim to reproduce these findings in a sample of participants who are familiar with a medical environment in order to boost ecological validity. To further this, future research should also explore these differences in a hospital-based setting, and provide participants with additional tasks to simulate the environment and the reality of a hospital ward that is true to life, something of which the current laboratory study does not reflect.

Conclusion

In respect to the current IEC alarms, this study has demonstrated how auditory icons are easier to learn, and that their priority and function are more accurately identified than the current IEC alarms when heard alone and when overlapped with another alarm. Therefore, data from this paper further supports past research into auditory icons and their enhanced efficiency in the medical industry. Upon consideration of the results, new research should be conducted to deepen our understanding of the *priority* element in an alarm. Given that the IEC alarms outperformed the auditory icons on priority identification alone, research should examine this core element by experimenting with priority identification in isolation to function. This research could then determine an accurate representation of the performance of priority identification in auditory icon alarms, through the elimination of the metaphorical function, and to gather a true understanding of how well participants can identify alarm priority without the need also to process the function.

Acknowledgements

I would like to thank my project supervisor Professor Judy Edworthy for her help and guidance throughout this project. I would also like to thank my tutor Professor Jon May for his supportive advice throughout this project and throughout my time at the University of Plymouth.

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