MEDICAL ALARMS AND AUDITORY MASKING: THE ROLE OF AMPLITUDE ENVELOPE

By

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Abstract

Auditory alarms are essential for updating healthcare workers about patients. However, standard medical alarms are susceptible to auditory masking, which occurs when one sound renders another inaudible. Masking leads healthcare workers to miss alarms, putting patients at risk. Here, we investigated whether the risk of masking is affected by an alarm's change in energy over time, called amplitude envelope. Although the current standard of medical alarms relies on sounds with constant "flat" envelopes, past research shows perceptual advantages in incorporating sounds with decaying "percussive" envelopes. Using the *Medical Alarm Audibility System Checker* (MAASC)—a computer modelling software developed by Hasanain et al. (2017)—we identified a configuration of standard medical alarms where one target alarm could theoretically be masked by two masker alarms. We synthesized flat and percussive versions of the alarms for comparison. In a 3AFC experiment, we asked participants to identify which of three presentations of the maskers also contained the target. The target volume varied according to a three-down one-up adaptive staircase model so that the target volume eventually converged on the masking threshold at which the target was barely audible over the masker. We compared thresholds between combinations of target and masker envelopes. Alarms were most resistant to masking when target and masker envelopes were heterogeneous, especially when a percussive target was paired with flat maskers. We recommend implementing envelope heterogeneity into medical alarm design to minimize masking, which will make alarms safer and more effective.

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I—Introduction

i. Background

Auditory alarms are essential in safety-critical workplaces, notably healthcare (Edworthy, 2013; Foley et al., 2022). Medical alarms keep healthcare workers informed of patient status while they perform tasks that require visual attention. The design of medical alarms is regulated by the International Electrotechnical Commission (IEC) 60601-1-8 standard (henceforth the IEC standard) such that each alarm uses a melodic pattern to indicate a specific patient need (e.g., Oxygen, Drug Delivery) and priority level (i.e., low, medium, or high) (IEC, 2006).

Medical alarm designers follow a “better safe than sorry” philosophy by maintaining high numbers and volumes of alarms, ensuring detectability but generating high false alarm rates (Block et al., 1999; Schlesinger et al., 2018). With approximately 350 alarms sounding per patient per day, both patients and healthcare workers suffer from annoyance and sensory overload (Schlesinger et al., 2018; Sendelbach & Funk, 2013). The perpetual din of alarms creates a stressful environment that disrupts patient rest, impeding recovery (Topf, 2000). Similarly, alarms exacerbate stress among healthcare workers, especially during times of mass hospitalizations like the COVID-19 pandemic that placed overburdened healthcare workers at dire risk for mental health crisis (Asadi et al., 2022; Lee & Friese, 2021). To cope with the sheer number of medical alarms, healthcare workers often lower alarm volumes (Sendelbach & Funk, 2013). Moreover, since 99.5% of alarms are non-urgent—meaning they do not indicate life-threatening events (O’Carroll, 1986)—combined with the sheer number of alarms, healthcare workers experience a desensitization to alarms known as alarm fatigue (Sendelbach & Funk, 2013). When healthcare workers tune out alarms or lower alarm volumes, the small percentage of alarms that *are* critical go unnoticed, which on occasion can lead to catastrophic consequences (Cvach, 2012; Sendelbach & Funk, 2013).

These pressing issues have galvanized research to improve sound design of medical alarms. For instance, past research tested differences in the distribution of acoustic energy over time, known as amplitude envelope. In healthcare and other safety-critical industries that rely on auditory alarms, flat amplitude envelopes—synthesized beeps with constant energy—are standard (Foley et al., 2022; Schutz & Gillard, 2020). In contrast, many natural sounds—like the strike of a drum or the clink of two drinking glasses—have percussive amplitude envelopes that decay in energy over time. Although flat and percussive alarms are similarly easy to learn and remember, percussive alarms are perceived as far less annoying (Sreetharan et al., 2021) and more detectable without compromising simultaneous speech comprehension (Foley et al., 2022, 2023). Incorporating percussive tones into medical alarm design holds immense promise as a solution to limit alarm fatigue.

However, a relatively unaddressed problem with medical alarms is auditory masking. Masking occurs when one sound renders another simultaneous or near-simultaneous sound inaudible due to physiological limits of the human auditory system—specifically, interference between sound waves on the basilar membrane (Oxenham & Wojtczak, 2010). Whether masking will occur depends on many factors, most importantly the volumes and frequency components of the target (inaudible sound) and the masker (audible sound). The signal-to-noise ratio (SNR) at which a masker just renders a target inaudible is called the masking threshold. In hospitals, where alarm volumes are perpetually high and alarms often sound simultaneously, masking presents a sizeable risk. Hasanain et al. (2017) developed the *Medical Alarm Audibility System Checker* (MAASC), a model checking software that applies psychoacoustic theory to identify combinations of IEC standard alarms that cause masking. Given the volumes and frequency components of multiple alarms, MAASC predicts how the alarms would stimulate the basilar membrane if played simultaneously and evaluates whether the target volume falls above or below a calculated masking threshold. Bolton et al. (2020) experimentally validated MAASC with a signal detection experiment using IEC alarms. Then, Bolton et al. (2022) used MAASC to demonstrate that within the 10 dB range of alarm volumes permitted by the IEC, many alarms are subject to total masking when only three other alarms play simultaneously. As mentioned, with roughly 350 alarms sounding per patient per day, multiple alarms sounding simultaneously is surely a frequent occurrence (Bolton et al., 2022; Schlesinger et al., 2018). This raises great concern that masking regularly presents a danger of missed alarms, putting the lives of patients in jeopardy.

The IEC alarms may be concerningly prone to tone-on-tone masking due to their acoustical homogeneity (Bolton et al., 2022). Each alarm has a different melody to denote its type and priority level, but each melody is derived from the same set of nine pitches with fundamental frequencies between 262 and 523 Hz and four minimum additional harmonic frequencies (IEC 2006). Alarms of the same priority level also have identical temporal structures. Rayo et al. (2019) demonstrated that alarms with greater acoustical heterogeneity than IEC alarms were more identifiable to healthcare workers in a real (though inactive) hospital unit. The authors speculated that alarm heterogeneity may minimize masking from background noise. Similarly, heterogeneity may also minimize tone-on-tone masking between alarms themselves. When Bolton et al. (2022) introduced temporal variation to the sequences of IEC alarms by randomizing the durations of tones and pauses, MAASC indicated that the alarms became more resistant to masking. These studies provide considerable evidence that implementing acoustical heterogeneity into alarm design improves problems with masking, making alarms safer and more effective. However, Rayo et al. (2019) did not directly test masking between alarms, and Bolton et al. (2022) used a computer modelling approach rather than an experimental one. Thus, there is an urgent need to experimentally evaluate the influence of acoustical heterogeneity on resistance of IEC alarms to auditory masking.

ii. Current Study

Amplitude envelope can play a major role in sound perception, influencing duration discrimination (Vallet et al., 2014), audio-visual integration (Chuen & Schutz, 2016) and learning and memory (Schutz et al., 2017). However, differential masking of tones based on amplitude envelope remains an unexplored topic. Bolton et al. (2022) showed improved resistance to masking between alarms with irregular tone spacing, introducing temporal heterogeneity to the structure of the alarm sequences. We wonder if a similar improvement could be achieved by varying amplitude envelopes between alarms, introducing temporal heterogeneity to the structure of the tones themselves. The purpose of this study is to investigate whether amplitude envelope impacts susceptibility of IEC alarms to tone-on-tone simultaneous masking. We hypothesize that including both flat and percussive tones in alarms sets introduces temporal heterogeneity to the structure of the tones, lowering masking thresholds and better enabling healthcare workers to hear simultaneous alarms. Additionally, this study aims to test how accurately the predictions of MAASC align with observed thresholds of flat and percussive alarms. MAASC is currently designed to predict masking thresholds of flat tones implemented in the IEC standard (Bolton et al., 2020, 2022; Hasanain et al., 2017). This study presents a unique opportunity to assess the accuracy of MAASC with respect to the IEC standard and show a direct comparison to variations on the standard that incorporate percussive tones. Our findings have the potential to directly inform alarm designers about the efficacy of alarm sets that incorporate percussive tones and the influence of amplitude envelope heterogeneity.

II—Methods

i. Stimuli

We tested tone-on-tone masking of medium-priority IEC alarms due to their greater susceptibility to masking compared to those of low- or high-priority (Bolton et al., 2022). Using MAASC, we determined combinations of alarm melodies for which total masking is theoretically possible (Bolton et al., 2020, 2022; Hasanain et al., 2017). According to the MAASC software, total masking of the General alarm occurs when it plays at –29 dB relative to the Temperature and Drug Delivery alarms playing at the same time. Figure 1 shows the melodies and timing of the three alarms that produce total masking. These three alarms were more melodically distinct from each other than other combinations of alarms that produce total masking, which we anticipated would enable participants to distinguish between alarms during the experiment. Hence, we chose the General alarm as the target with the combined Temperature and Drug Delivery alarms as the masker.

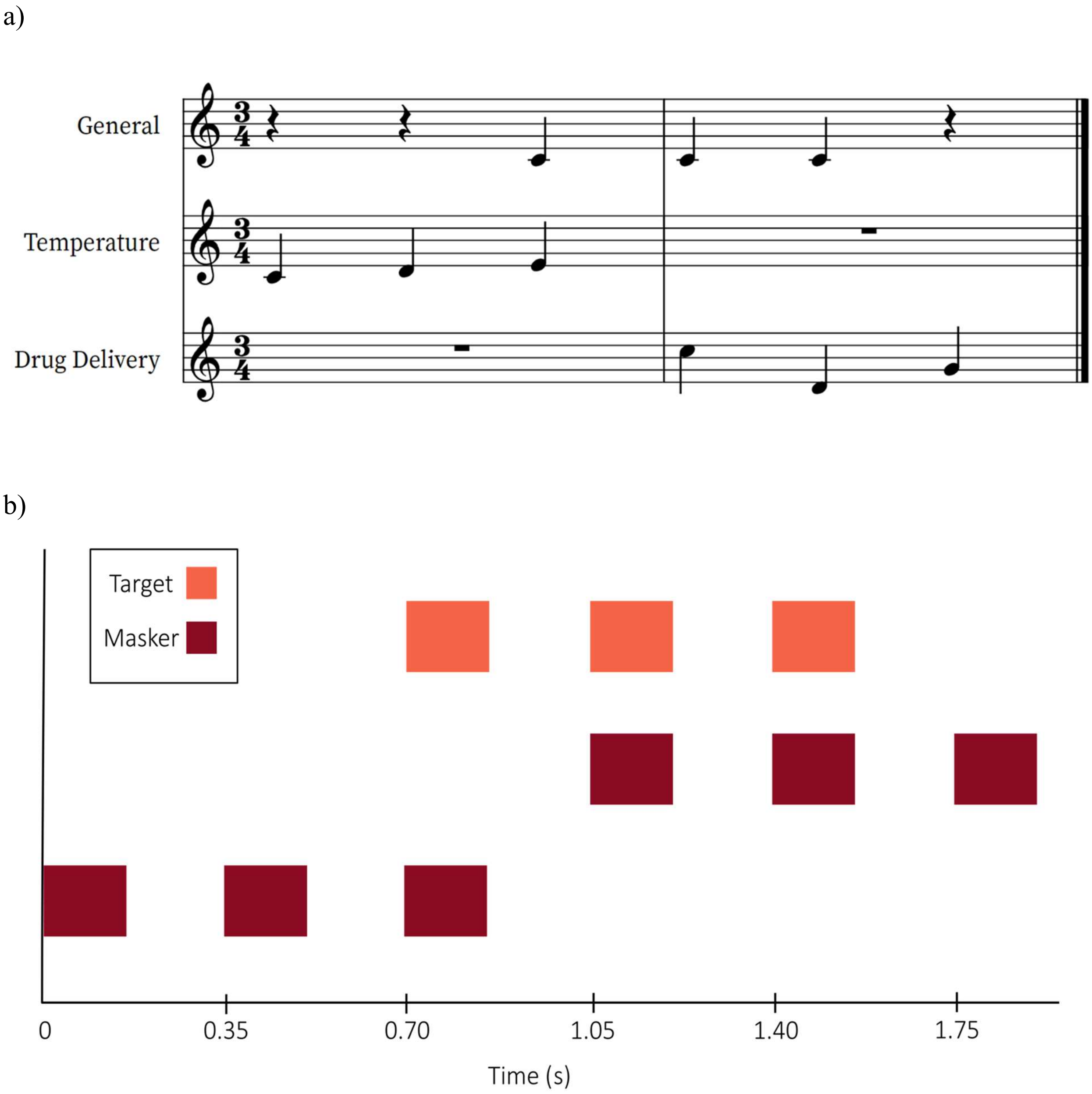
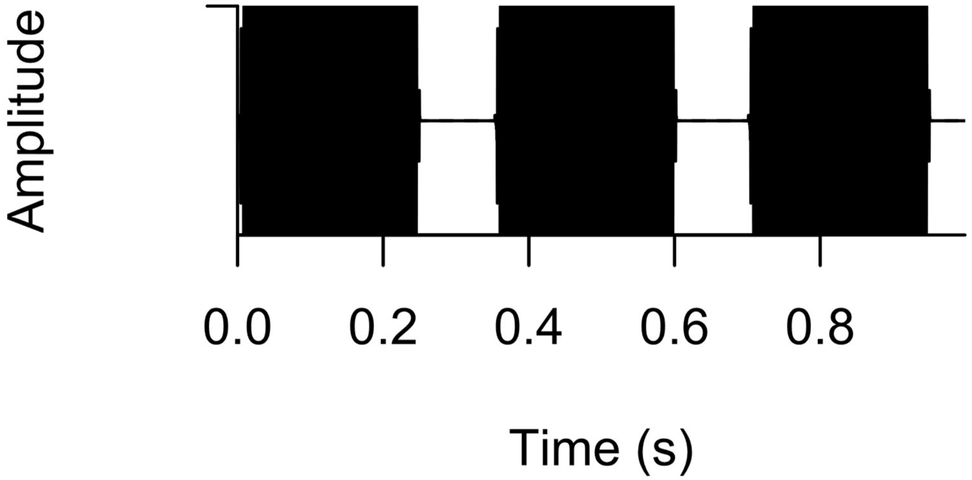


Figure 1: Two equivalent visual representations of the alarm stimuli. a) The melodies in musical notation of the General, Temperature, and Drug Delivery alarms and their relative timing that produces total masking of the General alarm. b) The precise tone onset timing of the alarm stimuli we synthesized for the experiment. The target corresponds to the General alarm and the masker corresponds to the Temperature and Drug Delivery alarms. The durations and offsets of

the tones shown here do not reflect those of the tones used in the experiment because they vary between flat and percussive amplitude envelopes.

a)



b)

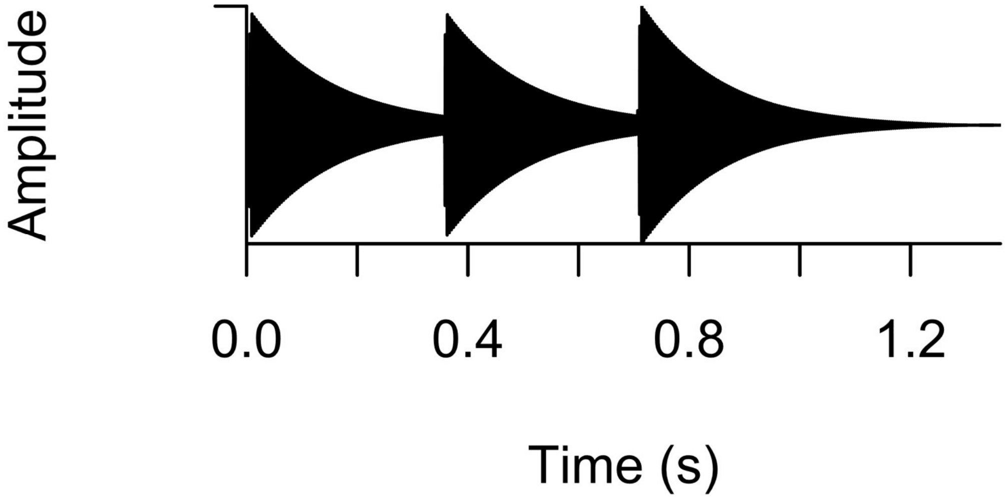
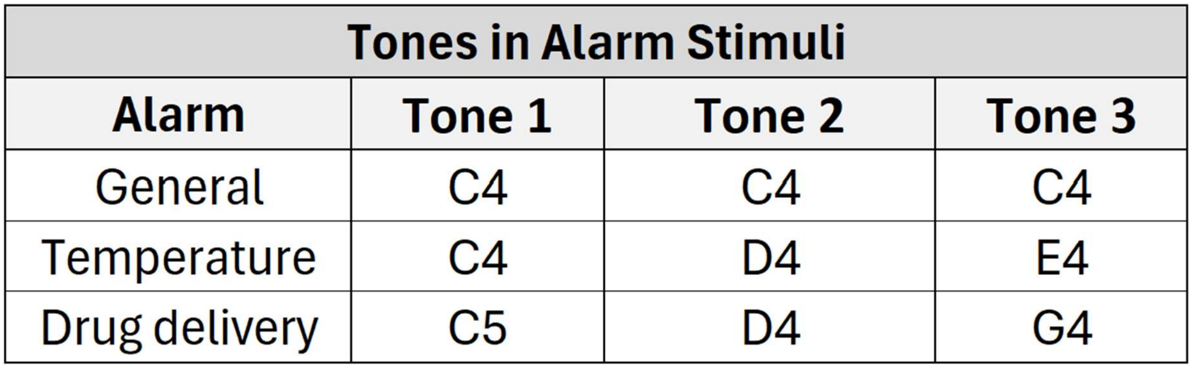


Figure 2: The amplitude envelopes and tone spacing of a) flat and b) percussive versions of the General IEC alarm we synthesized. Our flat and percussive versions of the Temperature and Drug Delivery alarms had identical temporal structures to the General alarm shown here.

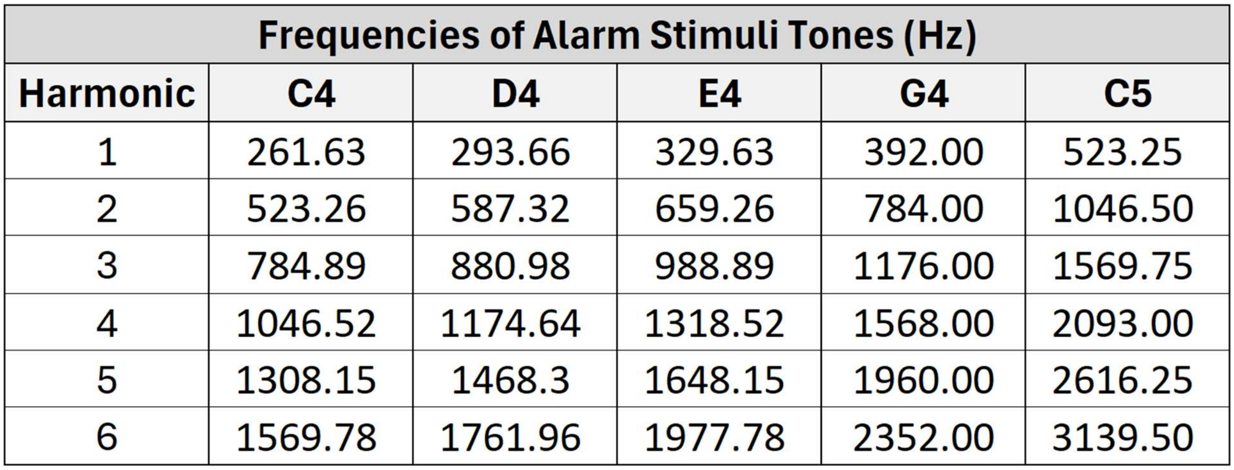
Using MAESTRO (Ng & Schutz, 2017), a tone generator graphical user interface built on top of the programming language *Supercollider* (McCartney, 2002), we synthesized flat and percussive versions of the three alarms (Figure 2). Following the IEC guidelines for medium-priority alarms, each consisted of three tones (Table 1), with each tone containing a fundamental frequency plus five harmonics (Table 2). Each flat tone had an attack of 5 ms, a sustain of 240 ms, a release of 5 ms, and on- and off-curves of 0. Each percussive tone had a 5 ms attack, no sustain, a 595 ms exponential decay, an on-curve of 0, and an off-curve of –4 (Foley et al., 2022, 2023). We made the percussive tones longer than the flat tones to roughly equate perceived duration because listeners perceive percussive tones as shorter than flat tones of equal duration (Vallet et al., 2014).

Table 1: Tones comprising each of the three alarms used as stimuli in the masking experiment.



Tones in Alarm Stimuli			
Alarm	**Tone 1**	**Tone 2**	**Tone 3**
General	C4	C4	C4
Temperature	C4	D4	E4
Drug delivery	C5	D4	G4

Table 2: Component frequencies (in Hz, rounded to two decimal places) of each tone used to create the alarm stimuli.



Frequencies of Alarm Stimuli Tones (Hz)

Harmonic	C4	D4	E4	G4	C5
1	261.63	293.66	329.63	392.00	523.25
2	523.26	587.32	659.26	784.00	1046.50
3	784.89	880.98	988.89	1176.00	1569.75
4	1046.52	1174.64	1318.52	1568.00	2093.00
5	1308.15	1468.3	1648.15	1960.00	2616.25
6	1569.78	1761.96	1977.78	2352.00	3139.50

We used the audio software *Audacity*® version 3.3.3 (Audacity Team, 2014) to space the onsets of each tone comprising an alarm by 350 ms, and to configure the timing of the three alarms so that the general alarm could be masked. We adjusted the masker's volume to –25 decibels root mean squared (dB RMS) and created 51 copies of the target with intensities ranging from –15 to –65 dB RMS in even 1 dB increments.

ii. Participants

McMaster University undergraduate psychology students were recruited through *Sona Systems* (https://www.sona-systems.com/) to participate in our study in exchange for course credit (Sona Systems, n.d.). All participants were required to have normal hearing and vision (including vision corrected to normal with glasses or contact lenses). The McMaster University Research Ethics Board approved all experimental procedures, and all participants gave informed consent before the study.

iii. Procedure

We generated the paradigm using *Psychopy* version 2023.1.3 and deployed it on *Pavlovia*, *Psychopy*'s online platform for hosting experiments (Peirce et al., 2019). Participants accessed the experiment using their own laptops and headphones. First, the screen displayed a message asking participants to set their computer volume to a comfortable level based on a repeating sample tone, and to keep the volume the same for the whole experiment. Next, the screen displayed, *"In this task, you are required to listen for a specific melody. This target will play among noise that you should ignore."* Upon pressing the spacebar, the screen displayed the word "Target" while the flat target and the percussive target played one after the other. Then, the screen displayed, *"In addition to the target, a different melody acting as noise will play."* Upon pressing the spacebar again, the screen displayed "Noise" while the flat masker and the percussive masker played one after the other. Next, the screen displayed, *"During this experiment, you will hear three different collections of sounds. You must identify which collection of sounds presented had the target melody by pressing "1", "2", or "3"."* Participants pressed the spacebar again once ready to begin the masking task.

The masking task used a three-alternative forced choice (3AFC) paradigm (Leek, 2001). In each trial, three sounds played consecutively and in random order: the masker alone, twice, and the masker plus the target, once. The screen then displayed *"Which sound contained the target tone?"* and participants were prompted to select sound 1, 2, or 3 on their keyboard (Figure 3). Between trials, the masker stayed at a fixed volume of –25 dB RMS. The target's volume began at –15 dB RMS and varied between –15 and –65 dB RMS according to a three-down one-up adaptive staircase (Levitt, 1971). When participants correctly selected the sound containing the target three times in a row, the target's volume decreased for the next trial. Every time the participant responded incorrectly, the target's volume increased. An incorrect response followed by three correct responses or vice versa reversed the direction of the staircase. The target's volume initially varied in 8 dB steps, which reduced to 4 dB steps after the first two reversals, then to 2 dB steps after the next two reversals, then to 1 dB steps after another two reversals for the rest of the experiment. Each staircase ended after eight total reversals or after reaching the maximum of 200 trials (Boebinger et al., 2015).

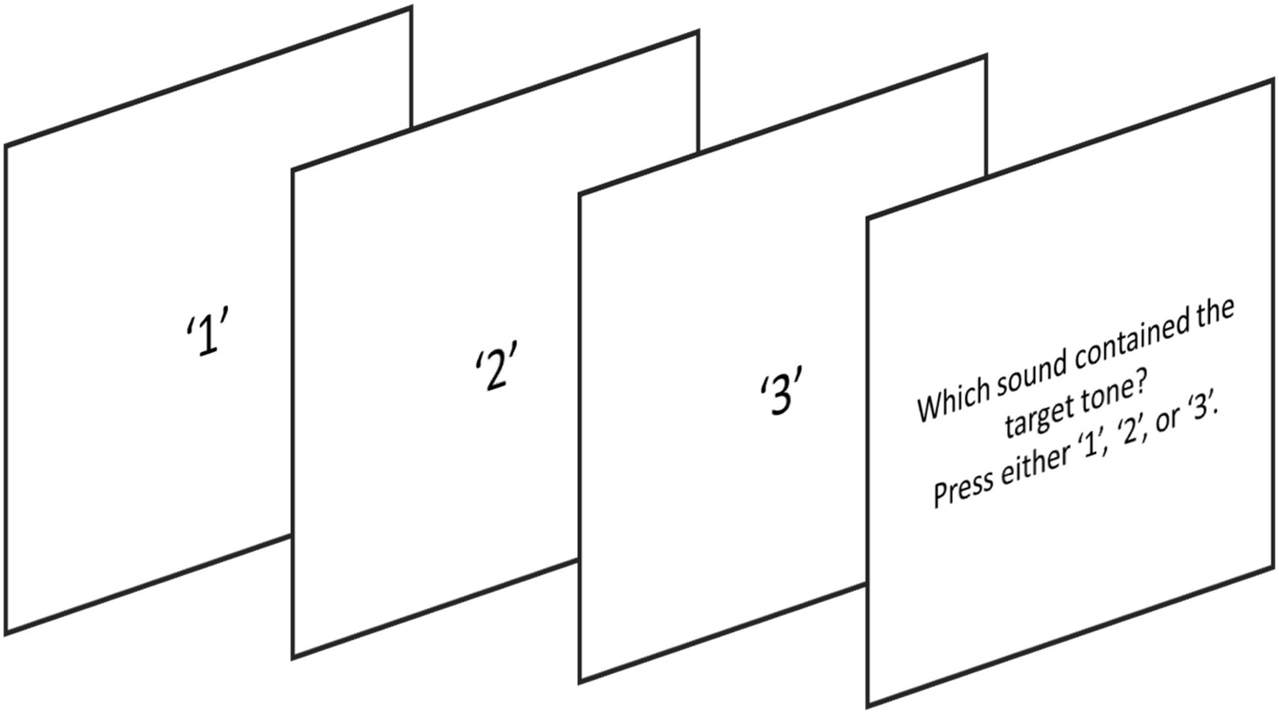


Figure 3: The onscreen display shown to participants during a trial.

The step size gradually decreased so that the staircase would converge on the target's volume where a participant was equally likely to cause a step up or a step down. For a three-down one-up staircase, this target's volume corresponds to 79% performance on the psychometric function (i.e., a 79% chance of a correct response on a single trial), which we defined for this experiment as the masking threshold at which the target was barely audible (Levitt, 1971). We determined the masking threshold using the mid-run estimates method by calculating the target's average volume on all except the first two reversals (Boebinger et al., 2015; Leek, 2001; Levitt, 1971).

We created four independent staircases by combining each masker amplitude envelope (flat or percussive) with each target amplitude envelope (flat or percussive). As a result, the masker and target of two staircases (Flat masker/Percussive target and Percussive masker/Flat target) were heterogeneous and those of the other two (Flat masker/Flat target and Percussive masker/Percussive target) were homogeneous. Participants were randomly assigned to either the heterogeneous or homogeneous condition, in which trials from the two corresponding staircases were presented in random order. We compared masking thresholds within the heterogeneous condition, within the homogeneous condition, and between conditions to assess whether the amplitude envelopes of the target and masker impacted masking.

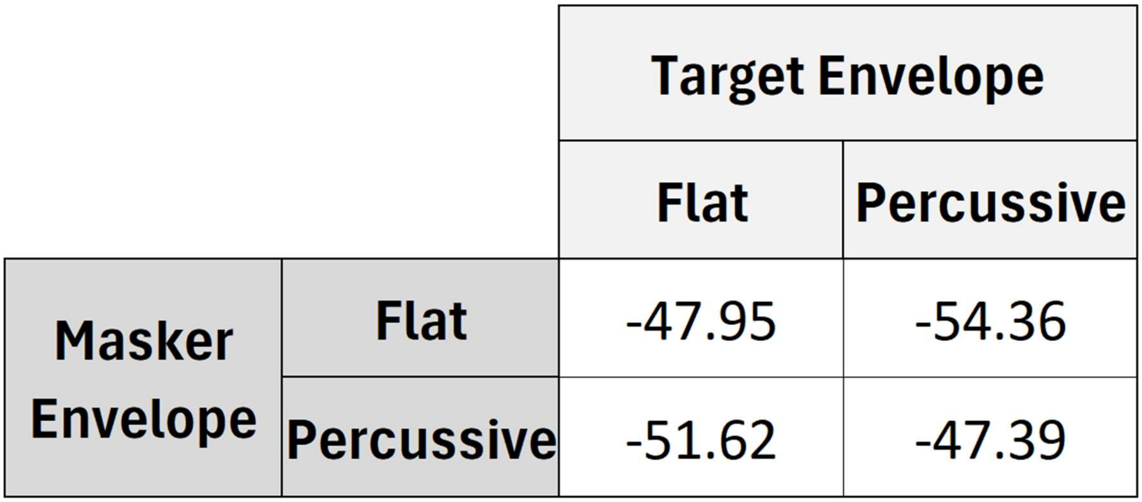
III—Results

We obtained results from 103 participants, with 40 in the heterogeneous group and 63 in the homogeneous group. 36 participants (10 in the heterogeneous group and 26 in the homogeneous group) were excluded from statistical analysis because they had masking thresholds greater than the masker volume (–25 dB RMS), reflecting lack of engagement or poor understanding of the task. Thus, we analyzed masking thresholds from 67 participants (30 heterogeneous, 37 homogeneous).

Table 3 shows the masking thresholds (i.e., mean target levels in dB RMS on all but the first two reversals) for each of the four envelope conditions. We used two-tailed independent sample t-tests to evaluate three masking threshold comparisons. First, we compared thresholds of heterogeneous staircases: Flat masker/Percussive target ($M = -54.36$, $SD = 7.03$) against Percussive masker/Flat target ($M = -51.62$, $SD = 8.12$). Second, we compared thresholds of homogeneous staircases: Flat masker/Flat target ($M = -47.95$, $SD = 10.40$) against Percussive masker/Percussive target ($M = -47.39$, $SD = 9.61$). Third, we compared thresholds of heterogeneous against homogeneous staircases overall.

Based on the results of Levene's test for homogeneity of variance, we assumed equal variance for the within group t-tests but not for the between group t-test. There was a significant threshold difference within the heterogeneous group (t (1, 357) = 3.41, $p < 0.01$) and between heterogeneous and homogeneous groups (t (1, 806) = 8.55, $p < 0.01$). The difference between thresholds within the homogeneous group was non-significant (t (1, 448) = 0.59, $p = 0.56$). All three comparisons are shown in Figure 4.

Table 3: Masking thresholds in dB RMS for each of the four envelope conditions.



		Target Envelope	
		Flat	**Percussive**
Masker Envelope	**Flat**	-47.95	-54.36
	Percussive	-51.62	-47.39

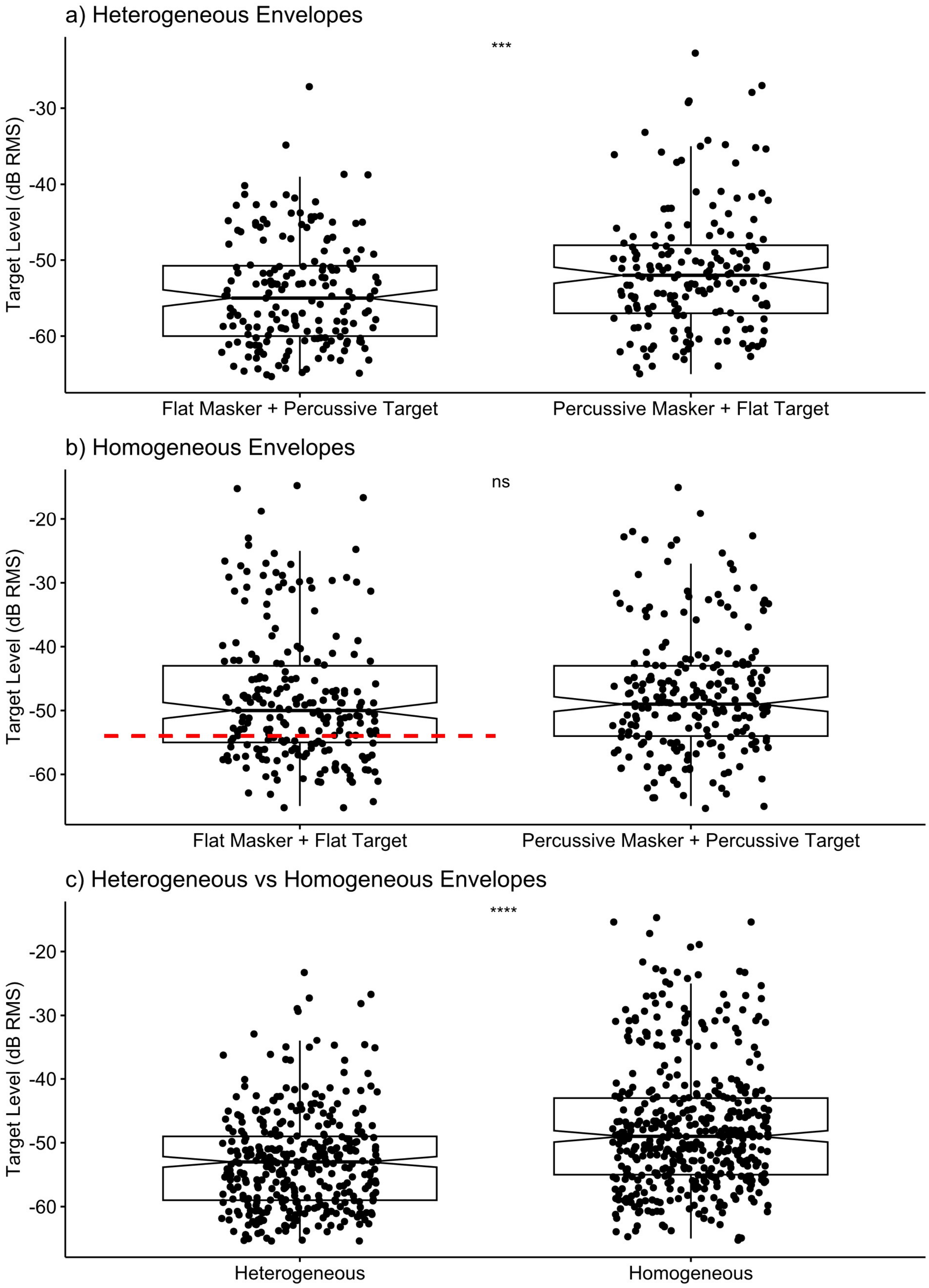

a) Heterogeneous Envelopes
***
Target Level (dB RMS)
-30
-40
-50
-60
Flat Masker + Percussive Target
Percussive Masker + Flat Target
b) Homogeneous Envelopes
ns
Target Level (dB RMS)
-20
-30
-40
-50
-60
Flat Masker + Flat Target
Percussive Masker + Percussive Target
c) Heterogeneous vs Homogeneous Envelopes
****
Target Level (dB RMS)
-20
-30
-40
-50
-60
Heterogeneous
Homogeneous

Figure 4: Box plots comparing masking thresholds a) within the heterogeneous group, b) within the homogeneous group, and c) between heterogeneous and homogeneous groups. Each point represents the target level at a reversal in an adaptive staircase, excluding the first two reversals of each staircase. The black horizontal line on each box represents the median, with the notches indicating the confidence interval of the median. The red dashed line indicates the MAASC theoretical masking threshold between a Flat masker/Flat target of –54 dB RMS, which is –29 dB relative to the masker level of –25 dB RMS (Hasanain et al., 2017).

IV—Discussion

i. Summary of Findings

These findings reveal that amplitude envelope impacted the susceptibility of IEC alarms to tone-on-tone simultaneous auditory masking. As anticipated, heterogeneous envelope combinations had significantly lower masking thresholds (–54.36 dB RMS for Flat masker/Percussive target and –51.62 dB RMS for Percussive masker/Flat target) compared to homogeneous combinations (–47.95 dB RMS for Flat masker/Flat target and –47.39 dB RMS for Percussive masker/Percussive target), suggesting enhanced resistance to masking. Both homogeneous combinations showed approximately equal susceptibility to masking. However, the Flat masker/Percussive target combination displayed the highest resistance to masking, with a significantly lower masking threshold than even the other heterogeneous combination of Percussive masker/Flat target.

A possible explanation of masking resistance between percussive targets paired with flat maskers may have been due to the amplitude envelope of percussive tones. Flat tones have constant amplitude over time, whereas percussive tones are characterized by high-energy peaks followed by a rapid exponential decay. As a result, the peak energies of percussive tones exceed those of flat tones at equivalent RMS levels. Foley et al. (2022) highlighted this property of percussive tones as a possible explanation of high detectability amid speech compared to flat tones. Indeed, a percussive target's high energy peak may promote detectability against a flat masker even at lower signal-to-noise ratios (SNRs), whereas a percussive masker's high energy peak may contribute to a relatively higher masking threshold of a flat target. Additionally, heterogeneous envelope combinations overall are likely more resistant to masking than homogeneous combinations because heterogeneity between target and masker introduces opportunities for detection when a target peaks in energy or a masker dips in energy (Buus, 1985; Hall & Grose, 1988). When target and masker have homogeneous envelopes, whether flat or percussive, the proportion of target to masker energy remains constant over the whole duration of the sound. Thus, homogeneous envelope combinations should show no envelope advantage and should have higher masking thresholds than heterogeneous combinations, as supported by our results.

ii. Implications for Alarm Design

These findings have profound implications for improving alarm efficacy. Rayo et al. (2019) and Bolton et al. (2022) advocate for greater acoustical heterogeneity of alarms to minimize masking. Our results strongly support this recommendation. As no envelope combination was significantly more vulnerable to masking than the Flat masker/Flat target combination, implementing envelope heterogeneity in future alarm design will not raise masking thresholds between alarms. In fact, implementing alarms with a variety of envelopes appears to elicit resistance to masking.

Our findings also add to the growing body of evidence supporting the implementation of percussive tones in medical alarm design. Though the IEC standard does not specify a required amplitude envelope, medical alarm designers have long used flat tones by default due to their highly controlled temporal characteristics (IEC, 2006; Schutz & Gillard, 2020). However, emerging research shows many advantages to using percussive tones as alarms. Compared to their flat counterparts, percussive tones are not only perceived as less annoying (Sreetharan et al., 2021), but they are also more detectable amid simultaneous speech without compromising speech comprehension (Foley et al., 2022, 2023). Moreover, because changing the amplitude envelopes of IEC alarms preserves their melodic and rhythmic structures, implementing percussive tones in alarm design does not impair learning and memory of alarms (Sreetharan et al., 2021). In addition to these benefits, our current study demonstrates that combining flat and percussive tones in alarm sets effectively creates temporal heterogeneity, promoting resistance to masking. Our study also revealed that fully percussive alarm sets were just as vulnerable to masking as fully flat alarm sets representative of the current standard. Alarm designers, then, should not interpret the advantages of percussive tones as evidence to replace flat alarm sets with entirely percussive ones. Instead, our findings support implementing percussive tones into medical alarm design alongside flat tones to reduce annoyance, improve detectability, and limit masking, improving alarm efficacy overall.

iii. Validation of MAASC Software

Our calculated masking thresholds for all four envelope conditions were within +/- 3 dB of the theoretical MAASC threshold of –29 dB relative to masker volume (Hasanain et al., 2017). Interestingly, thresholds for both heterogeneous combinations were closer to the MAASC threshold than the Flat masker/Flat target threshold. Although MAASC was designed to predict thresholds of exclusively flat alarms concurrent with the IEC standard, the theoretical MAASC threshold appeared to better align with observed thresholds in the Percussive masker/Percussive target condition and both heterogeneous conditions. However, the lack of experimental control resulting from online testing and high variance in masking thresholds across all conditions could have influenced these results—as will be discussed further in the limitations. Replicating this experiment in a more controlled environment, such as a sound attenuating booth, may yield an observed threshold for the Flat masker/Flat target combination that more closely aligns with MAASC's predicted threshold. Such a replication could further verify MAASC's accuracy in predicting thresholds for flat alarms concurrent with the IEC standard, assessing MAASC's potential to critically inform alarm designers about the efficacy of proposed alarms.

iv. Limitations and Future Directions

Our use of online data collection may have influenced the results. Although we excluded data from participants who were obviously disengaged from the task, we cannot evaluate how participants' attention and engagement varied throughout the experiment—a challenge characteristic of adaptive staircase paradigms (Levitt, 1971). Asking participants to provide confidence ratings with their answers could address this problem in future. Moreover, we measured data from homogeneous and heterogeneous envelope conditions from separate participants as a between-group variable. This was necessary to keep the experiment to a reasonable length while measuring enough trials in each condition for each staircase to converge. However, it created variability between heterogeneous and homogeneous conditions that may have originated from differences between samples rather than between conditions.

Although we instructed participants to use headphones and to avoid changing their computer volumes during the experiment, we cannot guarantee they did so. There may also have been considerable variability in the sound volumes that participants considered comfortable for the task, which could have impacted participants' masking thresholds. However, lack of control over headphone use and other factors may grant ecological validity to the results (Foley et al., 2022). Studying how listeners perceive alarms outside of highly controlled laboratories proves useful for applications in hospitals where alarm design varies tremendously between implementations. Replicating a version of this study in a sound-attenuating booth or even an inactive hospital unit (Rayo et al., 2019) would clarify potential influences of online testing.

We recommend adapting this paradigm to assess the impacts of amplitude envelope on non-simultaneous (i.e., forward and backward) masking (Oxenham & Wojtczak, 2010). Given the sheer number of alarms in realistic hospital environments, some alarms may play simultaneously whereas many others play in rapid succession, presenting a risk of non-simultaneous masking. We predict that compared to flat tones, percussive tones would be less vulnerable to non-simultaneous masking because their high-energy onsets would be salient amid other alarms, then their rapid decay would allow healthcare workers to hear incoming alarm onsets. In contrast, the currently implemented IEC standard flat tones maintain constant energy over time. Any partially overlapping sequence of flat alarms would likely be heard as a continuous sound, presenting a risk of masking.

V—Conclusion

This study adds to increasing evidence that masking between IEC standard medical alarms presents more than a theoretical risk of missed alarms (Bolton et al., 2020, 2022; Rayo et al., 2019). Fortunately, our findings demonstrate that it is possible to reduce masking between alarms by manipulating a simple acoustic property: amplitude envelope. Previous research suggests that introducing temporal heterogeneity to the sequences of alarms using irregular tone spacing can promote resistance to masking (Bolton et al., 2022). Our study builds on this idea, showing lowered masking thresholds of alarm sets with heterogeneous amplitude envelopes. Implementing percussive tones in alarm design alongside flat tones is another effective way to create temporal heterogeneity that could be used in conjunction with irregular tone spacing to limit masking. In hospitals, where missed alarms can delay patient recovery and even result in fatalities (Cvach, 2012; Sendelbach & Funk, 2013), such improvements to medical alarm design hold great potential to support audibility without exacerbating stress among patients and healthcare workers (Foley et al., 2022, 2023; Sreetharan et al., 2021). The applications of our findings may even extend beyond hospitals. Auditory alarms are fundamental to many other safety-critical industries, including aviation (Bliss, 2003), automotive (Marshall et al., 2007), railways (Edworthy et al., 2011), and industrial processing (Laberge et al., 2014). As in healthcare, the auditory alarms in these industries primarily use flat tones by default (Foley et al., 2022; Schutz & Gillard, 2020). Although research is needed to determine if masking presents a sizeable risk in these industries as it does in healthcare, implementing acoustical heterogeneity in alarms through varying amplitude envelopes appears to come at no compromise (Sreetharan et al., 2021). Therefore, our findings have the potential to inform safer, more effective alarm design in healthcare and safety-critical industries more broadly.

VI—References

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