To Repeat or Not to Repeat? Redesigning Repeating Auditory Alarms Based on EEG Analysis

Yi-Chen Lee
Dept. of Computer Science
National Chiao Tung
University, Taiwan
johnx3x3@gmail.com

Fu-Yin Cherng
Dept. of Computer Science
National Chiao Tung
University, Taiwan
fuyincherng@gmail.com

Jung-Tai King
Brain Research Center
National Chiao Tung
University, Taiwan
jtchin@gmail.com

Wen-Chieh Lin
Dept. of Computer Science
National Chiao Tung
University, Taiwan
wclin@cs.nctu.edu.tw

ABSTRACT

Auditory alarms that repeatedly interrupt users until they react are common, especially in the context of alarms. However, when an alarm repeats, our brains habituate to it and perceive it less and less, with reductions in both perception and attention-shifting: a phenomenon known as the repetition-suppression effect (RS). To retain users' perception and attention, this paper proposes and tests the use of pitch- and intensity-modulated alarms. Its experimental findings suggest that the proposed modulated alarms can reduce RS, albeit in different patterns, depending on whether pitch or intensity is the focus of the modulation. Specifically, pitch-modulated alarms were found to reduce RS more when the number of repetitions was small, while intensity-modulated alarms reduced it more as the number of repetitions increased. Based on these results, we make several recommendations for the design of improved repeating alarms, based on which modulation approach should be adopted in various situations.

CCS CONCEPTS

• **Human-centered computing → Empirical studies in HCI**;

KEYWORDS

Auditory alarms; brain-computer interface; neuroergonomics

CHI 2019, May 4–9, 2019, Glasgow, Scotland Uk

ACM ISBN 978-1-4503-5970-2/19/05…$15.00
https://doi.org/10.1145/3290605.3300743

ACM Reference Format:
Yi-Chen Lee, Fu-Yin Cherng, Jung-Tai King, and Wen-Chieh Lin. 2019. To Repeat or Not to Repeat? Redesigning Repeating Auditory Alarms Based on EEG Analysis. In *CHI Conference on Human Factors in Computing Systems Proceedings (CHI 2019), May 4–9, 2019, Glasgow, Scotland Uk.* ACM, New York, NY, USA, 10 pages. https://doi.org/10.1145/3290605.3300743

1 INTRODUCTION

Auditory alarms are widely used in our daily life, notably in the information-dense environments (e.g., cockpits and operation rooms) where auditory alarms usually are used to assist users to monitor contextual information and alert them when unusual events happen [16, 41, 51]. In this scenario, alarms will keep ringing repeatedly within a short period of time until the events are handled. When they are designed appropriately, such alarms help us to communicate efficiently, keep to our schedules, and react to dangers swiftly. Conversely, poor alarm design may fail to attract users' attention or convey the intended messages clearly. Moreover, in the multitasking scenarios like operation rooms, cockpits or clinical applications where multiple alarms with different levels of urgency and meanings would ring simultaneously, the recognizability of these alarms becomes critical for users to react accurately and timely [16, 41, 51].

Therefore, many studies have investigated various aspects of auditory alarms, including their sound properties (harmonics, tempo, and pitch [10, 13, 49]); how they are generated (auditory icons and earcons [5, 20, 21]); and their higher-level properties (e.g., intuitiveness [19, 20], learnability [20], and perceived urgency [16, 17]). While this has led to some proposed design guidelines for creating better auditory alarms [9, 30], most such studies have regarded each alarm in a series as an independent stimulus, without considering the separate effects of serial delivery or the interactive effects of a series' member alarms. This paper therefore investigates this important, yet rarely addressed issue.

Fundamentally, the purpose of auditory alarms being repeated is to attract more attention from their hearers than a single alarm would. However, when an auditory alarm repeats identically, human brain cells perceive it less and less strongly, due to fatigue and facilitation [22]. Neuroscientists refer to this habituation phenomenon as the repetition-suppression effect (RS). To the extent that we can reduce RS, we can boost individuals' awareness of repeating auditory alarms, and thus improve such alarms' efficiency.

In the case of visual warnings, the habituation problem has been addressed through the use of polymorphic warnings [2] and different attractor designs [7, 8]. Similarly, in the auditory sphere, a simple solution to reducing RS might be to insert a totally different alarm into a succession of identical ones. However, this could induce another problem: the extra effort users would need to expend to memorize the multiple sounds associated with a single alarm. Therefore, the present research adopted a 'middle way' approach to reducing RS, by inserting pitch- or intensity-modulated versions of a alarm into a series of otherwise identical ones.

Prior studies have measured degrees of habituation by observing users' behaviors [7, 8]. However, habituation is a complex cognitive process that cannot be captured via behavioral data alone. Electroencephalography (EEG), in contrast, provides direct, in-depth data on users' cognitive states, unobtrusively and without their conscious participation; and it has been applied to evaluation and usability testing in the field of human-computer interaction (HCI) [12, 13, 28, 50]. We, therefore, conducted an EEG experiment to examine the effects on RS of the modulated alarms.

Prior studies of RS [34, 45, 46] have used the conventional oddball paradigm, and only repeated their deviant sounds twice each. To simulate a more realistic scenario, the present study examined the RS effects of five repetitions against the background noise of a coffee shop. This combination of modulated alarms, rather than totally different alarms, a higher number of repetitions, and a realistic auditory background render this study a unique contribution to the literature.

2 BACKGROUND AND RELATED WORK

EEG-based Evaluation of Auditory Notifications

Auditory notifications are widely used in our daily lives to convey important messages, and many studies have investigated how changes in their musical parameters (e.g., intensity, pitch and tempo [13, 16, 49]) affect their usability (e.g., intuitiveness [19, 20], learnability, memorability [20], and perceived urgency [10, 17, 24]) and users' preferences for some notifications over others [20]. Such research has often relied on questionnaires or measures of users' behavioral performance, such as response time and hit rate [1, 19, 20]. However, since the process of being notified by sounds includes covert aspects of human cognitions (e.g., perception of the notification, and attention shifting), users' behavioral performance is at best an indirect approximation of their cognition, and at worst, highly inconsistent [16, 42, 52].

For these reasons, EEG - an electrophysiological monitoring method using non-invasive electrodes placed on the scalp to record the electrical activity of the brain - has been utilized in the fields of ergonomics and HCI. Burt et al. [10], for example, observed how the three different auditory warning signals they had designed influenced humans' urgency perceptions, reaction times, arousal, relaxed wakefulness and alert attentiveness by analyzing EEG frequencies alongside their behaviors.

Along with frequency domain analysis, event-related potential (ERP) is another EEG analysis method that prior studies have used to capture humans' various cognitive functions [10, 13, 28]. By averaging the EEG waveform according to the onset of different stimuli, the ERPs can directly reflect specific sensory, cognitive or motor events. Different experimental paradigms and tasks can elicit various ERPs in different brain regions [31].

Two ERP components - mismatch negativity (MMN) and P3a - reflect the effects of auditory alarms. MMN is a pre-attention deviance-detection ERP component elicited 150-250 ms after novel stimuli occur [35, 36]. Previous studies have shown that MMN responds to change in pitch, duration, and sound-source location [39, 40].

P3a, meanwhile, occurs 250-300 ms after stimuli onset [18, 44]. It is one of the two subcomponents of P300, which is considered to be a compound cognitive phenomenon that reflects an information processing involved both attentional and memory mechanisms. Polich indicated that high cognitive demand tasks would cause large P300 amplitude [44]. P3a is related to the attention orientation and the other subcomponent P3b is related to working memory updating [44]. P3a's amplitude increases when the stimulus attracts more attention from a participant.

Lee et al. [28] proposed an EEG-based method for measuring the MMN and P3a responses of participants as they passively listened to auditory notifications in a relatively realistic scenario that did not require behavioral responses. Cherng et al. [13] further developed this method as a means of evaluating how the acoustic features of auditory notifications affected their participants' awareness and attention-shifting. Taken together, these findings of these previous studies demonstrate that the use of physiological measures, in conjunction with behavioral and self-report measures, can reveal otherwise hidden cognitive aspects of human perception of auditory alarms; and that this has the potential to drive important refinements in auditory-display design.

Habituation and Repetition Suppression

Though habituation can facilitate human response in the circumstances that require skilled and repetitive actions, it is not usually desirable for users to be habituated to messages that require them to pay attention, such as warning sounds.

Anderson et al. [2] used functional magnetic resonance imaging (fMRI) to examine habituation, and identified huge drops in the brain's visual-processing activities when the same visual warning was presented even for just a second time, reflecting how easily their participants were habituated to such warnings. The same authors also found that when the same warnings were presented in different design formats whenever they appeared, their participants were more resistant to habituation.

In RS, the neuroscience paradigm of habituation [2], deviant sound's MMN and P3a amplitudes both decrease if it occurs repetitively [26, 34, 45, 46]. In other words, when we hear successive identical sounds, our brain cells are activated less and less due to fatigue, sharpening, and/or facilitation [3, 22, 43]. Previous studies of RS have usually used just two consecutive sounds, but nevertheless have indicated that it significantly reduces the MMN amplitude elicited by the second identical sound [34, 46]. Successive deviants with one or more different features (e.g., pitch and duration [14, 34, 37] and source location [34]) can reduce RS's impact, as indicated by their elicitation of full MMN responses. Unlike prior RS studies, however, the present research used five successive sounds rather than two; and employed ambient coffee-shop sound as a background, rather than simply repeating single tones in a setting that was otherwise silent.

3 EXPERIMENT

Research Goal and Questions

This study's goal, of arriving at an effective method for maintaining users' auditory perception of and attention to repeated auditory alarms by reducing RS, was pursued via an experiment guided by two research questions. A detailed explanation of each is provided below.

RQ1. What, if any, are the effects on RS of repeating auditory alarms against realistic background noise rather than standardized tones? Prior studies' experiments often used the oddball paradigm to measure how their participants' MMN and P3a responses changed due to RS [34, 35, 45, 46]. In that paradigm, frequently repeating standard sounds and infrequent deviant sounds are played as stimuli, with the latter type serving as targets that elicit the participants' MMN and P3a. Such studies have, however, only ever used single tones as either the standard or the deviant sounds. To more closely approximate reality, the present experiment followed the methodology proposed by Lee et al. [28], in which the standard sound consists of real-life background noise. Because this study's method differs sharply from those used by prior RS studies, its first research question examines whether we can induce and observe RS in our experimental setting, i.e., whether the amplitudes of MMN and P3a decrease when a sound occurs repetitively [34, 45, 46].

RQ2. Can the proposed modulation method reduce RS? In terms of this research's potential goal, the key questions to be considered are whether the proposed modulation method can reduce RS effect happening when a sound is displayed repetitively, and if so, whether the two variants of this method have different effects. As mentioned in RQ1, since the amplitudes of MMN and P3a are used as the metric of RS effect by prior studies [34, 45, 46], the modulation method could maintain or increase the MMN and P3a amplitude of a series of auditory alarms if it successfully reduces RS effect.

Participants and Devices

We recruited 14 participants (six females and eight males, 21-26 years old), none of whom reported any hearing problems, brain disease, or brain injury. We played a subtitled silent movie on a laptop placed in front of each participant, and used speakers (Altec Lansing 2.0 ch, VS2620) to present the audio stimuli. The movie is used to prevent participants from focusing on the notifications. The participants were instructed to only concentrate on the movie during the experiment. Before the experiment, a decibel meter was used to adjust the intensity of the stimuli to appropriate levels.

Stimuli

We conducted several pilot studies to decide the number of repetitions and intensity of the standard and deviant stimuli. The results of these studies revealed that five repetitions are the smallest unit to induce repetition suppression and increasing the pitch of sound by 1000 Hz or the intensity of sounds by 9 dB enable the modulation to be perceived by general people. Another finding from the pilot studies is that adding rise and fall for each deviant can prevent participants from overly shocking by the sudden appearance of sounds, which would cause unwanted attention-shifting at the beginning and end of stimuli. The method was also adopted by the prior study [25].

Based on the above research questions and the results of the pilot studies, three kinds of auditory alarms were designed. The first, a 1000 Hz sine wave, was the basic alarm (hereafter, "A"). The second , a 1500 Hz sine wave, was the pitch-modulated alarm ("P"). A and P were played with intensity of 70 dB SPL. Lastly, the intensity-modulated alarm ("I") was a 1000 Hz sine wave with an intensity of 79 dB SPL. All three types of auditory alarms were 125 ms long with 5 ms of rise and fall time. We did not test more levels of pitch and intensity in the experiments since the goal of the present research is to evaluate the effectiveness of the pitch and intensity modulation instead of suggesting an exact increment of intensity or pitch for the modulation.

To simulate a noisy real-world environment, the standard stimuli consisted of ambient sound recorded in a coffee shop, with an average intensity of 70 dB SPL and a range of 68-72 dB SPL. All deviants comprised five alarms, and followed one of three patterns: AAAAA (Dev1), APAPA (Dev2), or AIAIA (Dev3). The loudness of the standard stimuli was tuned to 70 dB, and each deviant was 79 dB for all participants.

The inter-stimulus-interval (ISI) between any two alarms was set at 300 ms, based on a previous study's finding [48] that when the time elapsed between the onsets of two successive stimuli was shorter than 150 ms, only one MMN response would be elicited. The onsets of the five alarms within a given deviant were therefore set at 0 ms, 425 ms, 850 ms, 1275 ms, and 1700 ms from the start of the deviant, as shown in Figure 1.

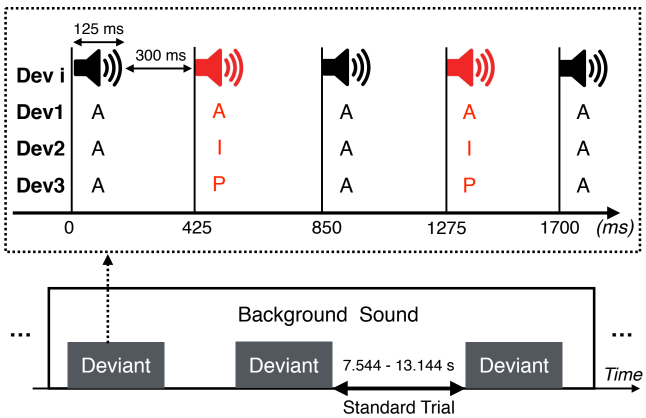


Figure 1: Experiment design. Each occurrence of each type of deviant comprised five 125 ms-long alarms separated by 300 ms intervals. The stimuli were randomly scattered while the background sound played continuously. The intervals between deviants were deemed standard trials.

Procedure and Paradigm

Each participant sat on a chair in a noise-filtered chamber, and was instructed to focus on the silent movie while listening to the stimuli. No voluntary response to either the audio or the video was required. Each person's participation was divided into two sessions: isolated, and mixed. The aim of the isolated session was to observe whether a repeating auditory alarm induced RS in the researchers' modified oddball paradigm (RQ1), so it contained only Dev1. The mixed session, on the other hand, examined the effects of the proposed modulation method on regaining the participants' auditory awareness by reducing the RS effect (RQ2), and hence included Dev1, Dev2 and Dev3.

The order of the two sessions was counterbalanced between participants. A mixed session consisted of four 15 min blocks separated by three 5 min rest periods, while an isolated session comprised two 10 min blocks with one 5 min rest period between them. The order of Dev1-Dev3 in the mixed sessions was random, and in both session types, the inter-stimuli intervals ranged from 7.544 to 13.144 s, 10.344 s on average. Since the alarms were randomly scattered, each participant heard alarms at different times under the same background sound. The EEG data recorded between each pair of consecutive deviants were deemed the standard trials, and those recorded while each audio alarm was playing were deemed the deviant trials (Figure 1).

In all, there were 45 deviant trials per block in the mixed session, and 40 deviant trials per block in the isolated session. Thus, there were 260 deviant trials per participant; a total of 3,640 deviant trials for all 14 participants; and the same overall number of standard trials. The probability of each deviant occurring was the same, and deviants comprised 15% of the total experiment time.

EEG Recording and Data Analysis

A non-invasive 32-channel EEG cap was used to measure the participants' brain activity. Its data was recorded using a NeuroScan system with Ag-AgCl electrodes and a bandpass filter of 0.01-100 Hz with sampling rate of 1000 Hz. All electrodes were gelled to the participants' scalps (Quik-Gel, PJT Project-Tech Ltd.) to ensure that resistance remained below 5 micro Ohm.

An open-source MATLAB toolbox, EEGLAB [15], was used to process the EEG data. To remove electrical noise, a bandpass filter of 1-30 Hz was applied. The epochs used for computing ERP were 2700 ms long, starting 250 ms before and ending 2450 ms after the first stimulus onset. The pre-stimuli period (-250 ms to 0 ms) was set as the baseline. All epochs with voltage variations exceeding 80 μV were automatically rejected to remove artifacts such as DC bias, blinks, and slow eye movements [11]. The data was downsampled to 250 Hz, as this allowed independent component analysis (ICA) to be sped up without the loss of relevant information [4, 6, 32]. Then, ICA was used to remove ocular artifacts, including the noise caused by facial-muscle and eye movements [33]. The procedure of removing artifacts first and then performing ICA is suggested by the prior studies [12, 28], which can purify the input data for ICA.

MMN and P3a magnitudes were calculated by subtracting each participant's EEG response to the standard stimuli from his or her EEG response to each deviant. Based on previous studies' findings that MMN amplitude is maximal at the frontal electrode (Fz), which is generally considered the representative location/source of MMN [35, 38], the current study's statistical analysis utilized Fz ERP. Prior works also used Fz to derive P3a along with MMN, which are often inseparable [35, 36]. Calculation of the amplitude of MMN (P3a) in each trial relied on a 52 ms window centered at the most negative (positive) peak within 150-250 ms (200-300 ms) after stimuli onset, the data within which was averaged to arrive at the amplitude of MMN (P3a). The latency of MMN (P3a) was calculated by subtracting the onset time of the stimulus from the occurring time of the most negative (positive) peak. The MMN/P3a elicited by the j-th alarm of deviant i was denoted as Devi MMNj/P3aj (e.g., the MMN elicited by the third alarm of deviant one was called Dev1 MMN3).

Levene's test was used to confirm the equality of variance of MMN and P3a in the case of each deviant [29]. Repeated-measures analysis of variance (RM-ANOVA) was then applied to the MMN and P3a amplitude and latency results. The independent variable of the RM-ANOVA for the inter-deviant analysis is the number of repetition, and for the intra-deviants analysis, the independent variable is the deviant type, i.e., Dev1 (isolated), Dev1, Dev2, Dev3. Lastly, post-hoc Tukey's HSD test were used to determine which pairs of MMN or P3a exhibited significant differences.

4 RESULTS

Figure 2 shows the ERP curves elicited on the Fz channel by each deviant stimulus. This section first compares the results of MMN and P3a responses of the five alarms of Dev1 across the isolated and mixed sessions, to establish whether RS was induced by the repetition of identical auditory alarms amid natural ambient sound. Then, it compares MMN and P3a responses across the isolated and (entire) mixed sessions, to evaluate whether the designed pitch- and intensity-modulated alarms alleviated RS.

RS Effect

As Figure 3 shows, the average amplitude of the MMN2 elicited by Dev1 in the isolated sessions was significantly greater than that of the MMN3 elicited by the same deviant in the same sessions ($F(1,1120)=78.1231$, $p<.001$, Figure 3a). This suggests that, in those sessions where only sound "A" was played, the participants' pre-attentive auditory detection of that sound decreased when it was repeated a third time. However, there was no significant difference between the latencies of MMN elicited by the alarms in the same sessions. Nor was any RS effect on the participants' attention-shifting identified, insofar as there were no significant differences among the P3a amplitudes of separate alarms or P3a latencies within the isolated sessions.

From Figure 3b, it is clear that there were no significant differences between the MMN amplitude and latency associated with Dev1 in the mixed sessions. This indicates that the participants' pre-attentive auditory detection did not decrease when they received Dev1 under conditions where Dev2 and Dev3 were also present: presumably, because modulation of the latter two sounds (i.e., the second and fourth alarms within a deviant) led them to expect that the deviants in the mixed sessions were characterized by constant change. This change in expectations would also tend to explain the relative stability of MMN amplitudes of different alarms within Dev1 in the mixed session, as compared to the isolated session. No main effect of alarm order on the participants' P3a amplitude and latency was found in either session.

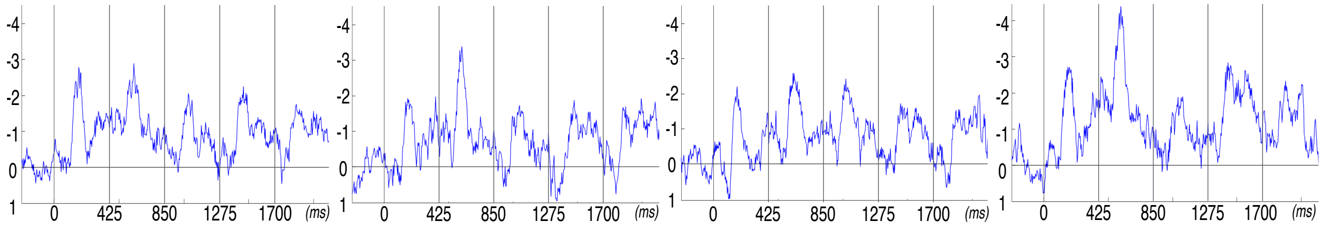
Notably, RS only affected MMN amplitude: the amplitude of MMN3 was significantly decreased compared with the amplitude of MMN2. This finding differs slightly from those of previous studies [34, 45, 46] in which RS appeared to decrease the amplitudes of both MMN and P3a. This discrepancy will be explored in the Discussion section, below. In any case, because the present study only detected RS effects on MMN amplitude, the remainder of this paper will focus mainly on MMN rather than P3a.

Effect of Modulated Alarms

The MMN amplitudes elicited by modulated alarms (i.e., by Dev2 and Dev3) exhibited different patterns from those elicited by non-modulated (Dev1) alarms in the isolated condition. From Figure 3c, it can be seen that within Dev2 (APAPA), there was no main effect of alarm order on the participants' MMN amplitude or latency. This finding indicates that there was no RS effect within Dev2 from the perspective of MMN amplitude.

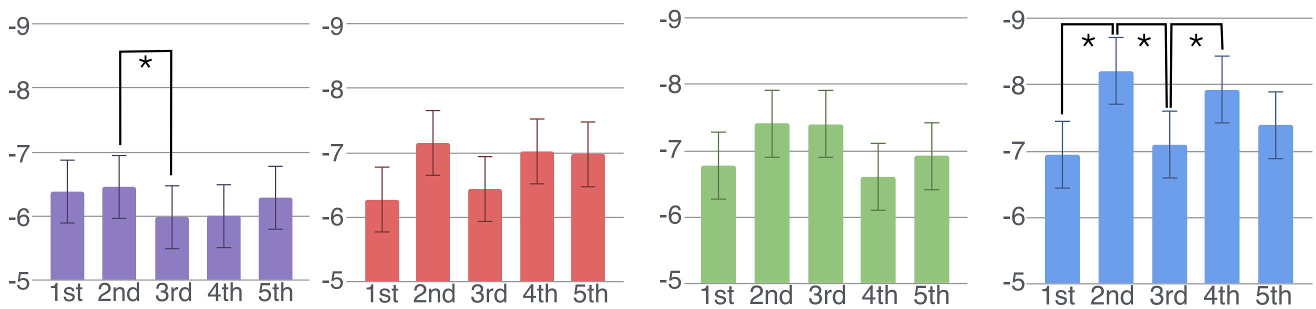
In the case of Dev3 (AIAIA), the comparison of MMN1, MMN3, and MMN5 amplitudes exhibited no significant differences (Figure 3d), which indicated that there was no RS effect happened in Dev3. However, Dev3's MMN2 and MMN4 amplitudes were, respectively, significantly larger than its MMN1 and MMN3 amplitudes. This was because MMN2 and MMN4 were elicited by intensity-modulated alarm I (MMN2 > MMN1 ($F(1,896) = 8.5041$, $p = 0.0036$), MMN2 > MMN3 ($F(1,896) = 6.9481$, $p = 0.0084$), MMN4 > MMN3 ($F(1,896) = 3.9394$, $p = 0.0472$); see Figure 3d); and the amplitudes of MMN2 and MMN4 (all alarm I) had no significant differences between them. Interestingly, in Dev3, MMN2 is significantly larger than both MMN1 and MMN3, yet MMN4 is significantly larger than only MMN3. This result might indicate that the modulation effect varies with the alarm order, which is worth further investigations in the future.

Having thus confirmed that there was no RS effect within either Dev2 or Dev3, we further investigated whether these modulated alarms induced higher levels of auditory perception in the participants than Dev1 did, taken in isolation. As shown in Figure 4, at the first alarm, there were no significant differences between the three deviants' MMN1s, which was unsurprising given that the first alarm in Dev2, Dev3 and Dev1 (isolated) were all the same sound, A. At the third alarm, however, the MMN3 amplitude of Dev2 was significantly larger than that of Dev1 (isolated) ($F(1,1025) = 14.0984$, $p = 0.0002$); and the MMN5 amplitude of Dev3 was significantly larger than that of both Dev2 ($F(1,904) =$



(a) Dev1, isolated (N=568) **(b) Dev1, mixed (N=471)** **(c) Dev2 (N=461)** **(d) Dev3 (N=456)**

Figure 2: MMN and P3a curves of all deviants. The y axes represent the voltages (μV) of the MMN and P3a amplitudes, and the vertical lines, the onset times of each alarm.



(a) Dev1, isolated (AAAAA) **(b) Dev1, mixed (AAAAA)** **(c) Dev2 (APAPA)** **(d) Dev3 (AIAIA)**

Figure 3: Averaged MMN amplitudes of each alarm of each deviant. The y axes represent the voltages (μV) of the MMN amplitudes, and the error bar, the standard error.

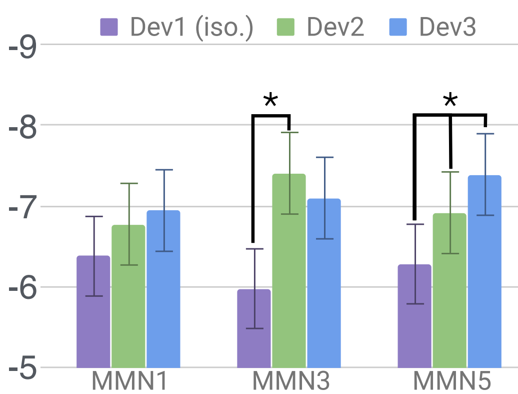
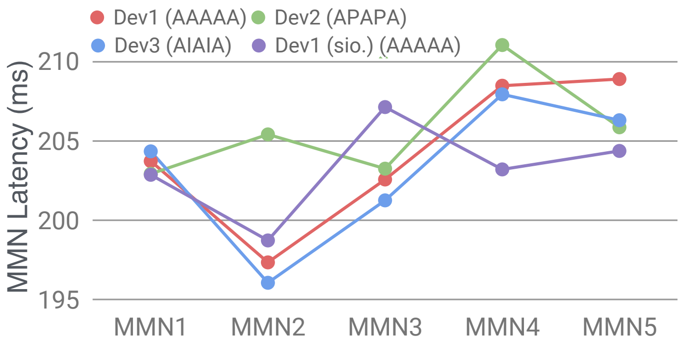


Figure 4: Comparison of MMN amplitudes of alarm A across Dev2, Dev3, and Dev1 (isolated sessions). The y axis shows the voltages (μV) of the MMN amplitudes of MMN; the figure indicates that Dev2 reduced RS effect at earlier repetitions, whereas Dev3 reduced RS effect at later repetitions.

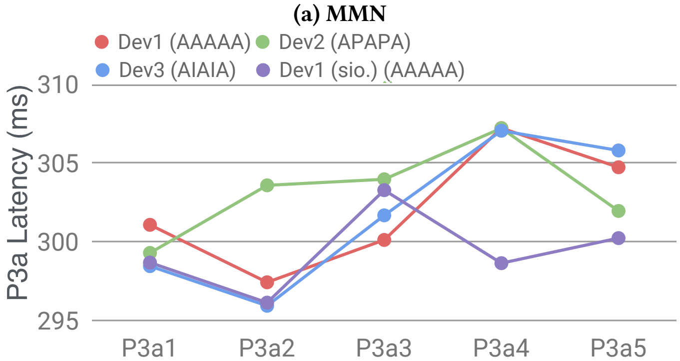
1.3253, p=0.02497) and Dev1 (isolated) (F(1,1020) = 7.8282, p = 0.0052). These findings indicate that modulation of alarms can reduce RS. Notably, the pitch- and intensity-modulated alarms reduced it in different ways: P being more effective in the case of MMN3, and I with MMN5.

Priming Effect

Although this study yielded no definite findings regarding how MMN latency related to the confirmation of the RS effect, or how/why modulated alarms reduced that effect, some interesting results in MMN and P3a latencies were observed. Firstly, when MMN latencies were compared within deviants (Figure 5a), it was found that the latency elicited by the second alarm of Dev1 was shorter than those elicited by the first, fourth or fifth alarms (MMN2 < MMN1, MMN4 and MMN5, $p < 0.05$). Figure 5b reveals a similar trend in P3a latencies among the different alarms of Dev1: with the latency of P3a2 being significantly shorter than that of P3a4 ($F(1,930) = 6.8118$, $p = 0.0091$). The shorter latencies of the second responses in series of identical repeating alarms suggest that there might be a priming effect, i.e., an acceleration of response due to the preceding stimulus [47]. However, no priming effect was identified in Dev1 (isolated), despite it also consisting of identical repeating alarms. As such, the hypothesized priming effect will require further empirical confirmation.



(a) MMN



(b) P3a

Figure 5: MMN and P3a latencies of each deviant.

5 DISCUSSION

Repetition-suppression Effect of Repeating Auditory Alarms

With regard to this paper's first research question, which asked whether repeating identical auditory alarms would lead to RS in a realistic auditory scenario, it was found that when the participants only listened to identical repeating alarms (i.e., Dev1 in the isolated sessions), their MMN3 was significantly smaller than their MMN2. This means that RS effect could happen on users' pre-attentive auditory detection while listening to identical repeating alarms.

Prior studies that investigated the RS effect based on just two successive identical single-tone alarms, using the traditional oddball paradigm [34, 46], have shown that second alarms are associated with significant reductions in MMN amplitude. In the present results, in contrast, MMN amplitudes (in the Dev1 isolated condition) only differed significantly between the second and the third responses (Figure 3a). The other key difference between the present results and those of prior studies is that, in the Dev1 (isolated) condition, no RS effect on P3a amplitude could be identified. There are two potential explanations for these two discrepancies.

First, both might have been caused by the similarities in intensity between Dev1 (isolated) and the background sound, i.e., 70 dB. Five of the 14 participants reported that they did not notice there were five repetitions of an identical alarm in some trials where this had in fact occurred; and if they simply failed to notice some repeating alarms, the participants could hardly be expected to become habituated to them. This lack of habituation, in turn, could have led to both the late appearance of RS effects on MMN amplitude and the non-observation of such effects on P3a amplitude. As our participants' brains might be not activated enough to cause habituation until the second repetition, RS effect happened at the third repetition due to the fatigue after their brain cells were fully activated.

Second, the present study's experimental paradigm differed from those of the prior studies in question. Specifically, the earlier studies [34, 46] adopted the traditional oddball paradigm, in which alarms are played without any background sound, which meant that their participants received entirely identical successive auditory stimuli besides standard single tones appearing regularly; whereas in the present experiment, reliance on ambient sound recorded in a coffee shop meant that the successive auditory stimuli - considered as alarm plus background - all differed somewhat, even when their foreground alarms were identical. Because the background recorded in a real environment was full of unexpected bursts of different sounds (e.g., human speech and footsteps), its overlapping with the successive auditory stimuli also probably inhibited habituation to the repetitive identical alarms. Moreover, as shown by the results of Dev1 in the mixed sessions, participants' expectations regarding the next alarm were continuously changed by the prior deviant and background. Therefore, the RS effect on MMN and P3a in the present study is not as evident or clear-cut as in previous research. A future study, which adopts the traditional oddball paradigm with the standard and deviants overlapping with a real-world background sound, could arrive more conclusive evidences on how the background sound inhibits the habituation to repetitive identical alarms.

For why there was no significant RS effect on MMN amplitude after the third repetition of Dev1 (isolated) in the present study, one possible explanation is the influence of attention. RS effect was found to comprise both attention-independent and attention-dependent processes [23, 27], which indicates that whether the participants attend to the stimuli would influence the RS effect. In the present study, because most of the participants' attention had already been directed to the audio alarms by the third repetition, it is expectable that the RS effect on MMN amplitude in the fourth and fifth repetitions would not be the same as it is in the earlier repetitions. Moreover, prior studies only investigated RS effect on MMN and P3a in two successive single-tone sounds without exploring human's brain reaction to the subsequent repetitions after RS effect occurred [34, 46]. Hence, the conclusion that

RS effect happens in the third repetition of Dev1 (isolated) can be at least ensured. However, more future studies are needed to understand and confirm the occurrence of RS effect in the successive repetitions.

On the other hand, since the current study's experiment integrated more features pertinent to the real world than its predecessors did, its results may be a more realistic reflection of users' cognitive states under the influence of RS. For example, the formation of habituation to a stimulus in a noisy place could require more time than such formation would take in an otherwise quiet controlled environment. Additionally, real-world users' attention might be relatively insensitive to RS due to the distractions of continually changing events. Nevertheless, the RS effect in the isolated session suggested audio alarm design in monotonous-sound or safety-critical scenarios [41, 51], e.g., aircraft cockpits, automobiles, or operating rooms, should take the RS effect into account and adopt the proposed modulation for repeating alarms.

Modulated Auditory Alarms Reduce the Repetition-suppression Effect

When humans hear a series of incoming auditory stimuli, their brains receive the new sounds and update the "standard" repertoire of sounds in their memory traces [46]. This could explain why, in the present research's isolated sessions, identical auditory alarms elicited smaller MMN amplitudes than the modulated auditory alarms [34]. In the mixed session, on the other hand, the modulated auditory alarms (P or I) inserted into Dev2 and Dev3 had higher novelty values than the un-modulated alarms in the same deviants. This led to larger MMN amplitudes and thus benefits alarm design because this finding indicates that the participants can detect the modulated alarms more easily. As such, it appears that modulated alarms can reduce RS and cause individuals to perceive repeating alarms more strongly.

When Dev1 (isolated), Dev2 and Dev3 were directly compared (Figure 4), it was found that the proposed modulation method can reduce the RS effect by interrupting the adaptations of the participants' brains. However, pitch- and intensity-modulated alarms behaved differently as the number of repetitions increased (i.e., the pitch-modulated alarm reduced the RS effect at the third repetition, while the intensity-modulated alarm reduced it at the fifth repetition). This might indicate that the former could perform better over a short sequence of alarms, and the latter, better over a somewhat longer series. Future studies with shorter and longer alarm series are needed to confirm this assumption.

Design Implications

The current study results provide the following design implications.

- [Figure 3a; Dev1 (isolated): MMN2>MMN3] Based on the results of MMN amplitude elicited by Dev1 (isolated), it is suggested that the designers should avoid using repeating identical sounds as auditory alarms because the RS effect has been confirmed to reduce users' pre-attention auditory detection even in naturalistic auditory settings.
- [Figure 4; MMN3: Dev2>Dev1 (isolated)] When designing alarms for time-sensitive real-world situations in which, ideally, RS should be prevented from occurring at all, the use of pitch-modulated alarms is recommended, since their reductions to the RS effect occur earlier than those of intensity-modulated alarms do.
- [Figure 4; MMN5: Dev3>Dev2 & Dev1 (isolated)] Although intensity-modulated alarms regained the participants' auditory perception (as measured by MMN amplitude) later, i.e., at the fifth repetition, the success with which they recovered it was higher than either their pitch-modulated or un-modulated counterparts. Thus, especially in an environment with fluctuating intensities of random ambient sound (as replicated in the experiment), using intensity modulation will render alarms more prominent, provided only that there are at least five of them per series. Therefore, designers should consider using intensity modulation if they expect their alarms to be heard in noisy places, and if immediate responses from users are not crucial to the application.

To give a specific example: for alarm-clock alarms, the simplest design would be to repeat the same alarm again and again (AAAAA). To avoid the RS effect, based on the design implications provided above, the designer could insert some modulated alarms between the A tones. If his/her priority is to definitely regain users' auditory awareness at some point, rather than to attract and retain it as rapidly as possible, he/she should use intensity-modulated alarms (AIAIA). Otherwise, the designer could choose pitch-modulated alarms (APAPA), but with the caveat that their RS benefits will be diminished if the number of repetitions is too large.

6 LIMITATIONS AND DIRECTIONS FOR FUTURE RESEARCH

Several limitations of the present research should be noted. First, it was found that the playing of multiple deviants in a session affected the RS effect of Dev1, raising the possibility that the Dev2 and Dev3 results might also be affected to some extent if they, too, were isolated; however, the experimental design did not include Dev2 (isolated) or Dev3 (isolated) conditions. To control for any interactive effects of multiple deviants, future work should include such additional sessions.

Second, to control for other possible confounding factors, the experiment only used sine waves as auditory alarms, which contrasted with the wide array of auditory alarms people experience in their daily lives. Future studies on this topic should therefore include real-world auditory alarms, to increase the ecological validity of their results and proposed methods.

Third, the present work only used one pattern to examine the effect of modulated alarms, i.e., APAPA and AIAIA. In further studies, we plan to examine the effects of modulated alarms that occur in a wider range of patterns (AAPAA, APIA, and so forth). Moreover, pitch and intensity are not the only categories of modulation that could be applied to alarms: with other potentially useful acoustic parameters being duration, harmonic richness and timbre. We believe that exploring additional methods of modulation will broaden and enrich the design space of how to moderate the RS effect.

7 CONCLUSION

Repeating identical tones can induce RS and reduce users' awareness of the alarms in question. By inserting pitch- and intensity-modulated alarms between identical repeating alarms, this study succeeded in reducing the RS effect without resorting to multiple, wholly different tones, which could require unacceptably high levels of user effort to memorize. EEG was also found to be a useful technique for examining the effects of modulated alarms on RS in a more realistic scenario than has hitherto been used in RS research. Despite this greater realism, it was confirmed that repeating identical auditory alarms do induce an RS effect; and the experiment further demonstrated that the use of modulated alarms could reduce it. Lastly, it was shown that pitch- and intensity-modulated alarms had different influences on RS: with the former acting more quickly, but the latter, more strongly. It is hoped that, based on these findings and the design implications highlighted by the researchers, designers will be able to create more effective repeating auditory alarms.

ACKNOWLEDGMENTS

We thank the reviewers, the participants, and the former director of Brain Research Center, Prof. Chin-Ting Lin. This work was supported in part by the Ministry of Science and Technology of Taiwan under grants 104-2628-E-009-001-MY3, 105-2221-E-009-095-MY3 and 107-2218-E-009-053-.

REFERENCES

[1] Rafa Absar and Catherine Guastavino. 2008. Usability of non-speech sounds in user interfaces. In *International Conference on Auditory Display.*

[2] Bonnie Brinton Anderson, C Brock Kirwan, Jeffrey L Jenkins, David Eargle, Seth Howard, and Anthony Vance. 2015. How polymorphic warnings reduce habituation in the brain: Insights from an fMRI study. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems.* 2883–2892.

[3] Torsten Baldeweg. 2006. Repetition effects to sounds: evidence for predictive coding in the auditory system. *Trends in Cognitive Sciences* 10, 3 (2006), 93–94.

[4] Dorothy VM Bishop, Mervyn J Hardiman, and Johanna G Barry. 2011. Is auditory discrimination mature by middle childhood? A study using time-frequency analysis of mismatch responses from 7 years to adulthood. *Developmental Science* 14, 2 (2011), 402–416.

[5] Meera M Blattner, Denise A Sumikawa, and Robert M Greenberg. 1989. Earcons and icons: Their structure and common design principles. *Human–Computer Interaction* 4, 1 (1989), 11–44.

[6] Claire Braboszcz and Arnaud Delorme. 2011. Lost in thoughts: neural markers of low alertness during mind wandering. *Neuroimage* 54, 4 (2011), 3040–3047.

[7] Cristian Bravo-Lillo, Lorrie Cranor, Saranga Komanduri, Stuart Schechter, and Manya Sleeper. 2014. Harder to ignore? Revisiting pop-up fatigue and approaches to prevent it. *Symposium on Usable Privacy and Security* (2014), 105–111.

[8] Cristian Bravo-Lillo, Saranga Komanduri, Lorrie Faith Cranor, Robert W Reeder, Manya Sleeper, Julie Downs, and Stuart Schechter. 2013. Your attention please: designing security-decision UIs to make genuine risks harder to ignore. In *Symposium on Usable Privacy and Security.* 6:1–6:12.

[9] Stephen A. Brewster, Peter C. Wright, and Alistair D. N. Edwards. 1995. Experimentally derived guidelines for the creation of earcons. In *Adjunct Proceedings of the British Computer Society Conference on Human Computer Interaction.* 155–159.

[10] Jennifer L Burt, Debbie S Bartolome, Daniel W Burdette, and J Raymond Comstock Jr. 1995. A psychophysiological evaluation of the perceived urgency of auditory warning signals. *Ergonomics* 38, 11 (1995), 2327–2340.

[11] Andrew CN Chen, Weijia Feng, Huixuan Zhao, Yanling Yin, and Peipei Wang. 2008. EEG default mode network in the human brain: spectral regional field powers. *Neuroimage* 41, 2 (2008), 561–574.

[12] Fu-Yin Cherng, Wen-Chieh Lin, Jung-Tai King, and Yi-Chen Lee. 2016. An EEG-based approach for evaluating graphic icons from the perspective of semantic distance. In *Proceedings of the 2016 CHI conference on human factors in computing systems.* 4378–4389.

[13] Fu-Yin Cherng, Wen-Chieh Lin, Jung-Tai King, and Yi-Chen Lee. 2018. Understanding the Influence of Musical Parameters on Cognitive Responses of Audio Notifications. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems.*

[14] Diana Deacon, Hilary Gomes, Jo Manette Nousak, Walter Ritter, and Daniel Javitt. 2000. Effect of frequency separation and stimulus rate on the mismatch negativity: an examination of the issue of refractoriness in humans. *Neuroscience Letters* 287, 3 (2000), 167–170.

[15] Arnaud Delorme and Scott Makeig. 2004. EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods* 134, 1 (2004), 9–21.

[16] Judy Edworthy and Elizabeth Hellier. 2006. Alarms and human behaviour: implications for medical alarms. *British Journal of Anaesthesia* 97, 1 (2006), 12–17.

[17] Judy Edworthy, Sarah Loxley, and Ian Dennis. 1991. Improving auditory warning design: Relationship between warning sound parameters and perceived urgency. *Human Factors* 33, 2 (1991), 205–231.

[18] Carles Escera, Kimmo Alho, Erich Schröger, and István Winkler Winkler. 2000. Involuntary attention and distractibility as evaluated with event-related brain potentials. *Audiology and Neurotology* 5, 3-4 (2000), 151–166.

[19] Stavros Garzonis, Chris Bevan, and Eamonn O'Neill. 2008. Mobile service audio notifications: intuitive semantics and noises. In *Proceedings of the 20th Australasian Conference on Computer-Human Interaction: Designing for Habitus and Habitat*. 156–163.

[20] Stavros Garzonis, Simon Jones, Tim Jay, and Eamonn O'Neill. 2009. Auditory icon and earcon mobile service notifications: intuitiveness, learnability, memorability and preference. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 1513–1522.

[21] William W Gaver. 1986. Auditory icons: Using sound in computer interfaces. *Human-computer Interaction* 2, 2 (1986), 167–177.

[22] Kalanit Grill-Spector, Richard Henson, and Alex Martin. 2006. Repetition and the brain: neural models of stimulus-specific effects. *Trends in Cognitive Sciences* 10, 1 (2006), 14–23.

[23] Mareike Grotheer and Gyula Kovács. 2016. Can predictive coding explain repetition suppression? *Cortex* 80 (2016), 113–124.

[24] Ellen C Haas and Judy Edworthy. 1996. Designing urgency into auditory warnings using pitch, speed and loudness. *Computing & Control Engineering Journal* 7, 4 (1996), 193–198.

[25] Kurt Hecox, Nancy Squires, and Robert Galambos. 1976. Brainstem auditory evoked responses in man. I. Effect of stimulus rise–fall time and duration. *The Journal of the Acoustical Society of America* 60, 5 (1976), 1187–1192.

[26] János Horváth and István Winkler. 2004. How the human auditory system treats repetition amongst change. *Neuroscience Letters* 368, 2 (2004), 157–161.

[27] Yi-Fang Hsu, Jarmo A Hämäläinen, and Florian Waszak. 2014. Repetition suppression comprises both attention-independent and attention-dependent processes. *Neuroimage* 98 (2014), 168–175.

[28] Yi-Chieh Lee, Wen-Chieh Lin, Jung-Tai King, Li-Wei Ko, Yu-Ting Huang, and Fu-Yin Cherng. 2014. An EEG-based approach for evaluating audio notifications under ambient sounds. In *Proceedings of the 32nd annual ACM conference on Human factors in computing systems*. 3817–3826.

[29] Howard Levene. 1961. Robust tests for equality of variances. *Contributions to probability and statistics. Essays in honor of Harold Hotelling* (1961), 279–292.

[30] Mats Liljedahl and Johan Fagerlönn. 2010. Methods for sound design: a review and implications for research and practice. In *Proceedings of the 5th Audio Mostly Conference: A Conference on Interaction with Sound*. 2.

[31] Steven J Luck. 2014. *An introduction to the event-related potential technique*. MIT press.

[32] Clemens Maidhof, Martina Rieger, Wolfgang Prinz, and Stefan Koelsch. 2009. Nobody is perfect: ERP effects prior to performance errors in musicians indicate fast monitoring processes. *PLoS One* 4, 4 (2009), e5032.

[33] Scott Makeig, Tzyy-Ping Jung, Dara Ghahremani, and Terrence J Sejnowski. 1996. Independent component analysis of simulated ERP data. *Institute for Neural Computation, University of California: technical report INC-9606* (1996).

[34] Dagmar Müller, Andreas Widmann, and Erich Schröger. 2005. Deviance-repetition effects as a function of stimulus feature, feature value variation, and timing: a mismatch negativity study. *Biological Psychology* 68, 1 (2005), 1–14.

[35] Risto Näätänen, Petri Paavilainen, Teemu Rinne, and Kimmo Alho. 2007. The mismatch negativity (MMN) in basic research of central auditory processing: a review. *Clinical Neurophysiology* 118, 12 (2007), 2544–2590.

[36] Risto Näätänen, Mari Tervaniemi, Elyse Sussman, Petri Paavilainen, and István Winkler. 2001. "Primitive intelligence" in the auditory cortex. *Trends in Neurosciences* 24, 5 (2001), 283–288.

[37] Jo Manette K Nousak, Diana Deacon, Walter Ritter, and Herbert G Vaughan Jr. 1996. Storage of information in transient auditory memory. *Cognitive Brain Research* 4, 4 (1996), 305–317.

[38] Nikolai Novitski, Mari Tervaniemi, Minna Huotilainen, and Risto Näätänen. 2004. Frequency discrimination at different frequency levels as indexed by electrophysiological and behavioral measures. *Cognitive Brain Research* 20, 1 (2004), 26–36.

[39] Petri Paavilainen, Crista Kaukinen, Oskari Koskinen, Julia Kylmälä, and Leila Rehn. 2018. Mismatch negativity (MMN) elicited by abstract regularity violations in two concurrent auditory streams. *Heliyon* 4, 4 (2018), e00608.

[40] Satu Pakarinen, Rika Takegata, Teemu Rinne, Minna Huotilainen, and Risto Näätänen. 2007. Measurement of extensive auditory discrimination profiles using the mismatch negativity (MMN) of the auditory event-related potential (ERP). *Clinical Neurophysiology* 118, 1 (2007), 177–185.

[41] Roy D Patterson. 1990. Auditory warning sounds in the work environment. *Phil. Trans. R. Soc. Lond. B* 327, 1241 (1990), 485–492.

[42] Evan M M Peck, Beste F Yuksel, Alvitta Ottley, Robert JK Jacob, and Remco Chang. 2013. Using fNIRS brain sensing to evaluate information visualization interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 473–482.

[43] John Polich. 1989. Habituation of P300 from auditory stimuli. *Psychobiology* 17, 1 (1989), 19–28.

[44] John Polich. 2007. Updating P300: an integrative theory of P3a and P3b. *Clinical Neurophysiology* 118, 10 (2007), 2128–2148.

[45] Timm Rosburg, Michael Weigl, Ronja Thiel, and Ralph Mager. 2018. The event-related potential component P3a is diminished by identical deviance repetition, but not by non-identical repetitions. *Experimental Brain Research* (2018), 1–12.

[46] Mikko Sams, Kimmo Alho, and Risto Näätänen. 1984. Short-Term Habituation and Dishabituation of the Mismatch Negativity of the ERP. *Psychophysiology* 21, 4 (1984), 434–441.

[47] Stefan R Schweinberger, Eva-Maria Pfütze, and Werner Sommer. 1995. Repetition priming and associative priming of face recognition: Evidence from event-related potentials. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 21, 3 (1995), 722.

[48] Elyse Sussman, István Winkler, Walter Ritter, Kimmo Alho, and Risto Näätänen. 1999. Temporal integration of auditory stimulus deviance as reflected by the mismatch negativity. *Neuroscience Letters* 264, 1-3 (1999), 161–164.

[49] Mari Tervaniemi, Titta Ilvonen, Janne Sinkkonen, Anu Kujala, Kimmo Alho, Minna Huotilainen, and Risto Näätänen. 2000. Harmonic partials facilitate pitch discrimination in humans: electrophysiological and behavioral evidence. *Neuroscience Letters* 279, 1 (2000), 29–32.

[50] Chi Thanh Vi, Izdihar Jamil, David Coyle, and Sriram Subramanian. 2014. Error related negativity in observing interactive tasks. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 3787–3796.

[51] Michael J Waltrip and Carryl L Baldwin. 2018. Scalable Auditory Alarms. In *Congress of the International Ergonomics Association*. Springer, 54–58.

[52] Christopher D Wickens, Justin G Hollands, Simon Banbury, and Raja Parasuraman. 2015. *Engineering psychology & human performance*. Psychology Press.