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Harmony Matters in Alarm Design: Investigating the Impact of Consonance on Alarm System

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Abstract

Alarm system performance is a critical aspect of safety. While existing research has extensively examined the influence of acoustic attributes on alarm performance, consonance's impact remains largely uncharted territory. This study bridges this research gap by investigating the effect of consonance on alarm systems. We extend our investigation to encompass not only the sound characteristics of the alarm but also the acoustic qualities of the surrounding environment, recognizing their potential impact on alarm efficacy. Prior studies consistently link consonance to annoyance levels, resulting in a negative user experience. Thus, we explore the relationship between consonance and alarm system performance, with a particular focus on modulating annoyance as an explanatory factor. Utilizing an oddball paradigm, we categorized standard and oddball sounds into consonant and dissonant types, creating four sound combinations. Participants were asked to respond to the irregularly presented oddball sounds while ignoring the constantly presented standard sounds. Our results reveal significant differences between groups, with the Standard Consonant/Oddball Dissonant (SC/OD) group displaying notably slower response times than the Standard Dissonant/Oddball Consonant (SD/OC) group. This reaction time variation aligns with differences in annoyance levels, as the SC/OD group reports higher annoyance, suggesting that reaction time discrepancies may be linked to increased arousal due to heightened annoyance.

Keywords: *Human-Computer Interaction, Auditory Perception, Consonance, Dissonance*

1. INTRODUCTION

An alarm plays a vital role in ensuring safety in both industrial and commercial contexts. While it serves as a crucial tool for providing timely alerts to prevent accidents, reduce risks, and enhance overall performance, it's important to acknowledge that alarms themselves can introduce potential hazards. The Emergency Care Research Institute (ECRI) identified alarm-related issues as the primary *Health Technology Hazard* in 2012, and it continues to be a top concern in 2020 [1, 2]. One prominent concern associated with auditory alarms is *Alarm Fatigue,* which refers to the desensitization to alarm sounds due to sensory overload. In the case of Johns Hopkins Hospital, for example, the alarm rings approximately 350 times a day on average, which raises

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the risk of task failure due to an excessive number of alarms [3]. Given that alarm systems often incorporate multiple auditory alerts, it is crucial to consider the characteristics of these sounds when designing effective alarm systems.

Numerous studies have explored the various attributes of auditory alerts and how they influence perceived urgency. Hellier et al. demonstrated the impact of speed, fundamental frequency, repetition units, and inharmonicity on auditory alerts [4]. Marshall et al. expanded on this by investigating the manipulation of sound characteristics such as formants and pulse durations to enhance perceived urgency and annoyance [5]. Notably, recent research in auditory interface design emphasizes not only urgency but also the aesthetics and ergonomic functionality of alert sounds [6]. For instance, Sreetharan et al. showed that manipulating amplitude envelopes can reduce annoyance while maintaining learning and memory [7]. Building on this existing body of work, our research team proposes that consonance and dissonance in auditory alerts should also be considered when combining multiple auditory alerts.

Consonance is an impression of stability and relaxation, while dissonance is an impression of tension and clash when one listens to a certain combination of tones or notes [8]. In the field of music, a body of study was made about the basis of consonance and dissonance. Plomp and Levelt suggested that dissonance arises from *beating* when two sounds within the critical bandwidth of one auditory channel are played simultaneously [9]. McDermott et al. argued that dissonance can be perceived without *beating* and that the frequency ratio of two notes plays a role in determining dissonance [10].

While there are conflicting theories about the origins of dissonance, studies have demonstrated a universal and biologically innate capacity to distinguish between consonant and dissonant sounds. Infants as young as two to four months and native African populations without exposure to Western music can differentiate between consonant and dissonant chords, displaying a preference for consonant sounds [11, 12]. Neuroscientific investigations by Bidelman and Krishnan and Fishman et al. have shown distinct neural responses in favor of consonant sounds, reinforcing the idea that consonance is inherent rather than acquired [13, 14].

This evidence suggests that the degree of consonance is a critical factor that draws one’s attention to the sound itself instinctively. There is mixed empirical evidence regarding the effect of dissonant intervals on human cognition. Several empirical evidence found that exposure to dissonant chords deteriorates the performance for modified Stroop task, and decreases accurate movement when participants were asked to synchronize their finger movements to the auditory stimulus [15, 16]. Sanada et al. have found that the amplitude of the P3a event-related potential (ERP) component was larger when participants listened to a consonant interval compared to a dissonant one, suggesting that people pay more attention when they hear a consonant sound [17]. On the contrary, Bodner et al. found that the performance of cognitive tasks improved when listening to a dissonant sound compared to a consonant sound [18]. The debate over which sound type is superior in terms of performance is ongoing, with contextual factors likely influencing the outcomes.

Despite the significance of consonance and dissonance in sound perception, there has been limited research on applying these factors to auditory alarm design. Given the potential impact of consonance and dissonance on alarm sounds, this study aims to investigate how the degree of consonance in alert sounds, when combined with background sounds, influences overall performance. Understanding how sound consonance and dissonance impact alarm perception can aid in the design of effective alarm systems that minimize annoyance and optimize attention-capturing properties. Our goal is to offer insights into the design of efficient alarm systems by considering the degree of consonance in alert sounds.

Additionally, our research explores the level of annoyance when two sounds with different levels of consonance coexist. It is known that dissonant sounds can elicit negative experiences, which may, in turn, affect overall performance negatively. For example, Jafari et al. found that tonal noise not only decreased performance but also increased the level of annoyance [19]. Examining participants’ perceived annoyance when presented with alerts will shed light on a dimension that extends beyond performance measurements.

Previous literature has handled the problem of consonance with performance, but none has investigated the effect of background noise and the consonance of sound. The background sound and the alert sound have a different role in the cognitive process and therefore consonance has a chance to affect the performance in a different direction. Our object is to investigate performance change in different consonance combinations.

2. METHOD

2.1 Experiment Design

The experiment was designed following a between-subject factorial design, employing an oddball paradigm to investigate the impact of the alarm system [20]. The oddball paradigm, a well-established experimental procedure frequently utilized in electroencephalogram (EEG) studies, was chosen to explore participants' responses. In this paradigm, participants were required to disregard frequently presented *Standard* stimuli and respond to less frequent, irregularly introduced *Oddball* stimuli. The independent variable in this study was the combination of consonance in the background sound and the oddball sound.

The independent variable in this study was the combination of standard and oddball sounds differing in their degree of consonance. Four combinations of standard and oddball sounds were used in this study: a consonant standard with a consonant oddball (SC/OC), a consonant standard with a dissonant oddball (SC/OD), a dissonant standard with a consonant oddball (SD/OC), and a dissonant standard with a dissonant oddball (SD/OD). Participants were randomly assigned to one of the four combinations. Reaction times to the oddball sound were used as a major dependent variable, along with participants' ratings of annoyance for each sound type.

We chose the oddball paradigm because it was a simple yet ecologically valid representation of the working environment. In work settings, critical auditory alerts are infrequent and irregular, often standing out among other more common sounds. We aimed to investigate how reaction times to auditory alerts are influenced by the characteristics of the task-relevant sound and the alert sound itself. In this context, the standard sound represents environmental sounds, while the oddball sound simulates critical auditory alerts.

To assess perceived annoyance levels, a survey was conducted after the main trials. Each participant listened to a series of sound combinations, consisting of three standard sounds and one oddball sound. Subsequently, participants rated the level of annoyance induced by the oddball sound. Participants provided annoyance ratings for all four combinations, and the order of presentation was randomized for each participant.

The following are our detailed hypotheses:

H1: RT of SD/OC will be faster than that of SC/OC.
H2: RT of SD/OC will be faster than that of SC/OD.
H3: RT of SD/OC will be faster than that of SD/OD.
H4: The level of annoyance to SD/OC will be lower than that of SC/OC.
H5: The level of annoyance to SD/OC will be lower than that of SC/OD.
H6: The level of annoyance to SD/OC will be lower than that of SD/OD.

2.2 Participants

A total of 127 participants were recruited for this experiment through Amazon Mechanical Turk (Amazon MTurk). All participants were required to have English as their first language, self-report normal vision, and possess the capability to operate a keyboard and mouse without any restrictions. We established specific screening criteria, which included achieving an accuracy rate of 90% for all responses and a minimum of 50% accuracy for oddball responses. Following the screening process, data from 27 participants were excluded, resulting in a dataset comprising responses from 100 participants, which was utilized for subsequent analysis.

Participants who successfully completed all tasks and surveys were compensated with a reward of $0.5 via the MTurk platform. It's important to note that our research adhered to the principles outlined in the Declaration of Helsinki, and all participants provided written consent to participate in the study. This ensured that all participants were well-informed about the study and willingly contributed to the research while maintaining their right to withdraw from the survey at any time. The consent form included the following statements that participants had to agree to:

(a) I comprehend the purpose of this study and willingly consent to participate.
(b) I am aware that I have the option to discontinue the survey at any point.

2.3 Materials

The experiment was designed with PsychoPy 2022.2 [21]. The auditory stimuli used in this experiment were designed with *FL Studio 11 and audiocheck.net* [22]. The standard sounds were either a consonant perfect 5th interval (C-G) or a dissonant tritone interval (C-F#) composed of two sine tones. The oddball sounds were either a consonant major 3rd interval (C-E) or a dissonant major 2nd interval (C-D) created with the *FL Piano (13)* timbre. The oddball sounds were designed to be 13 dBFS louder than the standard sounds.

Participants used a personal computer with a keyboard and mouse for this experiment via Amazon MTurk, Pavlovia, and Qualtrics. Participants had to use headphones or earphones during the experiment. They were randomly assigned to different sound type groups (i.e., SC/OC, SC/OD, SD/OC, and SD/OD) for the experiment.

In the main trials, two types (Standard/Oddball) of sound were presented. As shown in Figure 1, Participants had to react to the oddball sound with the spacebar key in 2000ms. Response to oddball sound and non-response to standard sound was recorded as a correct answer. The oddball sound was presented three times in every 10 sound presentations. The total number of trials was set as 300, so 30 oddball responses and 270 standard responses were collected. After the main experiment, participants listened to each sound type combination and answered the level of annoyance using the sliders. The sliders collected the level of annoyance on a 21-point scale from -10 to 10. All reactions to four combinations were collected.

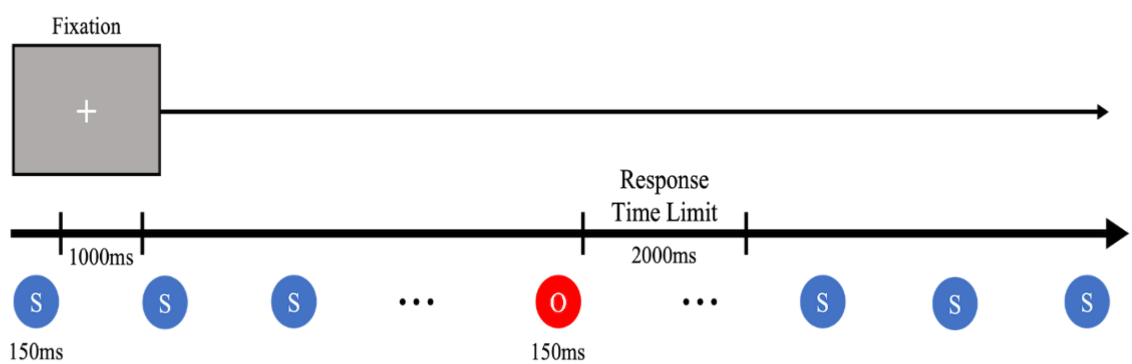

Figure 1. Overview of the oddball paradigm in the experiment

2.4 Experimental Procedure

The following are the procedures of the experiment session:

1. Participants who accessed the experiment via Amazon MTurk were first provided with a detailed explanation of the experiment's purpose and objectives.
2. After expressing their willingness to participate, participants were directed to a Qualtrics survey link. Their MTurk worker ID was recorded for reference, and they were then provided with the Pavlovia experiment link.
3. Subsequently, a comprehensive explanation of the experiment was presented to the participants, who were then guided through practice trials to familiarize themselves with the task. To progress to the primary session, participants were required to achieve a minimum accuracy rate of 75% during the practice phase.
4. Each participant was randomly assigned to one of the sound type combinations (i.e., SC/OC, SC/OD, SD/OC, or SD/OD) and proceeded to complete a set of 300 main trials.
5. Following the main experiment, participants were asked to assess the level of annoyance associated with each sound type using a slider-based rating system. This step involved participants listening to all four combinations of sound types and providing their annoyance ratings.
6. To conclude the experiment, demographic information from each participant was collected after all trials and surveys were completed.

2.5 Data Analysis

To minimize the influence of statistical outliers in measuring reaction time (RT), the median was used in the analysis of RTs. A repeated-measure analysis of variance (ANOVA) was conducted in reaction time. In the analysis of the level of annoyance, a one-sample t-test was done with a test value of 0 to analyze the effect of the sound type on annoyance. All statistical analyses were conducted via JASP software.

3. RESULTS

A one-way ANOVA was conducted on the reaction time data to investigate the effect of the combination of consonance on the participant's performance in terms of reaction time. The result shows that reaction times between groups were significantly different, $F(3, 96) = 3.25$, $p = .025$, $\eta_p^2 = .09$.

We conducted a Bonferroni post-hoc test to examine the difference between each consonance condition. As shown in Figure 2, the SC/OC group's RT ($M = 0.93$, $SD = 0.41$) didn't have significant differences with the SC/OD group ($M = 1.18$, $SD = 0.36$), $t(96) = -2.13$, $p = .216$. SC/OC group's RT ($M = 0.93$, $SD = 0.41$) didn't show significant differences with the SD/OC group ($M = 0.84$, $SD = 0.40$), $t(96) = 0.78$, $p = 1.000$. SC/OC group's RT ($M = 0.93$, $SD = 0.41$) didn't have significant differences with the SC/OD group ($M = 0.93$, $SD = 0.40$), $t(96) = -0.06$, $p = 1.000$. SC/OD group's RT ($M = 1.18$, $SD = 0.36$) didn't have significant differences with SD/OD group ($M = 0.93$, $SD = 0.40$), $t(96) = 2.21$, $p = .178$. SD/OC group's RT ($M = 0.84$, $SD = 0.40$) didn't have significant differences with the SD/OD group ($M = 0.93$, $SD = 0.40$), $t(96) = -0.90$, $p = 1.000$. Unlike others, the SC/OD group's RT ($M = 1.18$, $SD = 0.36$) was significantly slower than the SD/OC group's RT ($M = 0.84$, $SD = 0.40$), $t(96) = 3.01$, $p = .020$. Hence, H1 and H3 were not supported while H2 was supported.

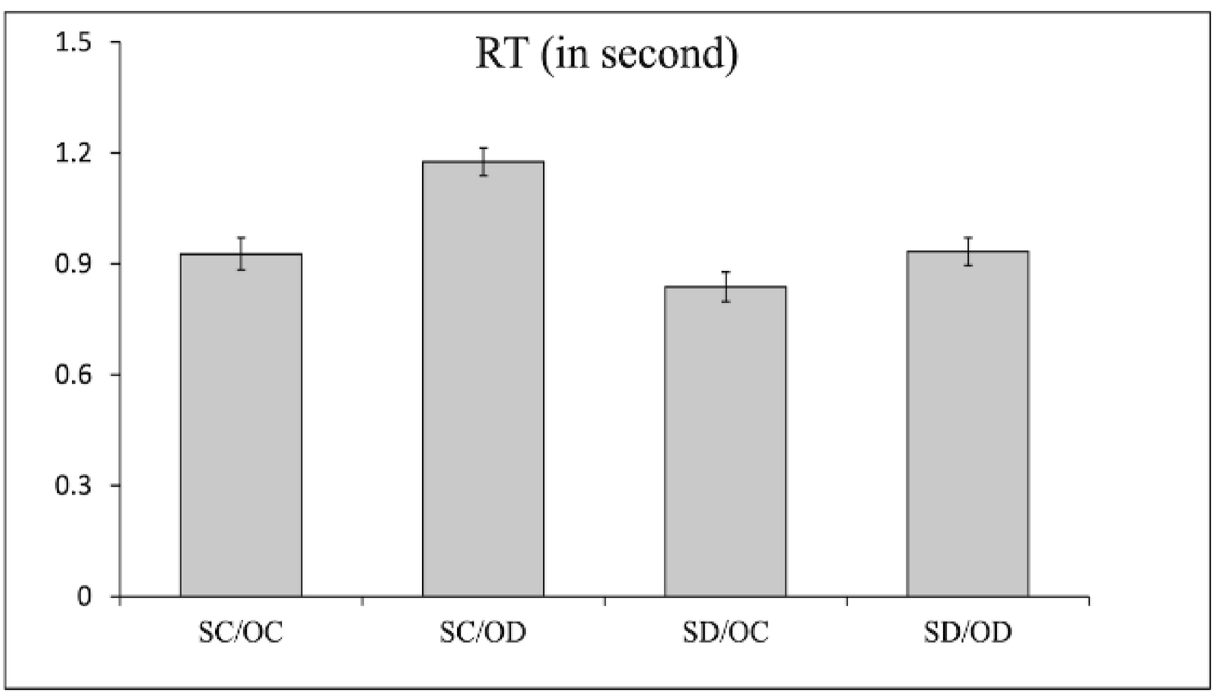

Figure 2. Reaction times to the oddball sound of each group

A one-sample t-test was conducted on the level of annoyance to investigate the difference between them with the test value of 0. Figure 3 shows that the level of annoyance while listening to SC/OC ($M = -1.79$, $SD = 6.08$) was significantly lower compared to the test value, $t(99) = -2.94$, $p = .004$. Similarly, the level of annoyance while listening to SD/OC ($M = -2.59$, $SD = 5.83$) was significantly lower compared to the test value, $t(99) = -4.44$, $p < .001$. However, the level of annoyance while listening to SC/OD ($M = -0.71$, $SD = 6.08$) did not show a significant difference compared to the test value, $t(99) = -1.17$, $p = .246$. The level of annoyance while listening to SD/OD ($M = -0.65$, $SD = 5.97$) did not show a significant difference compared to the test value, $t(99) = -1.09$, $p = .279$. In summary, the combinations with consonant oddball caused less annoyance compared to dissonant oddball sounds.

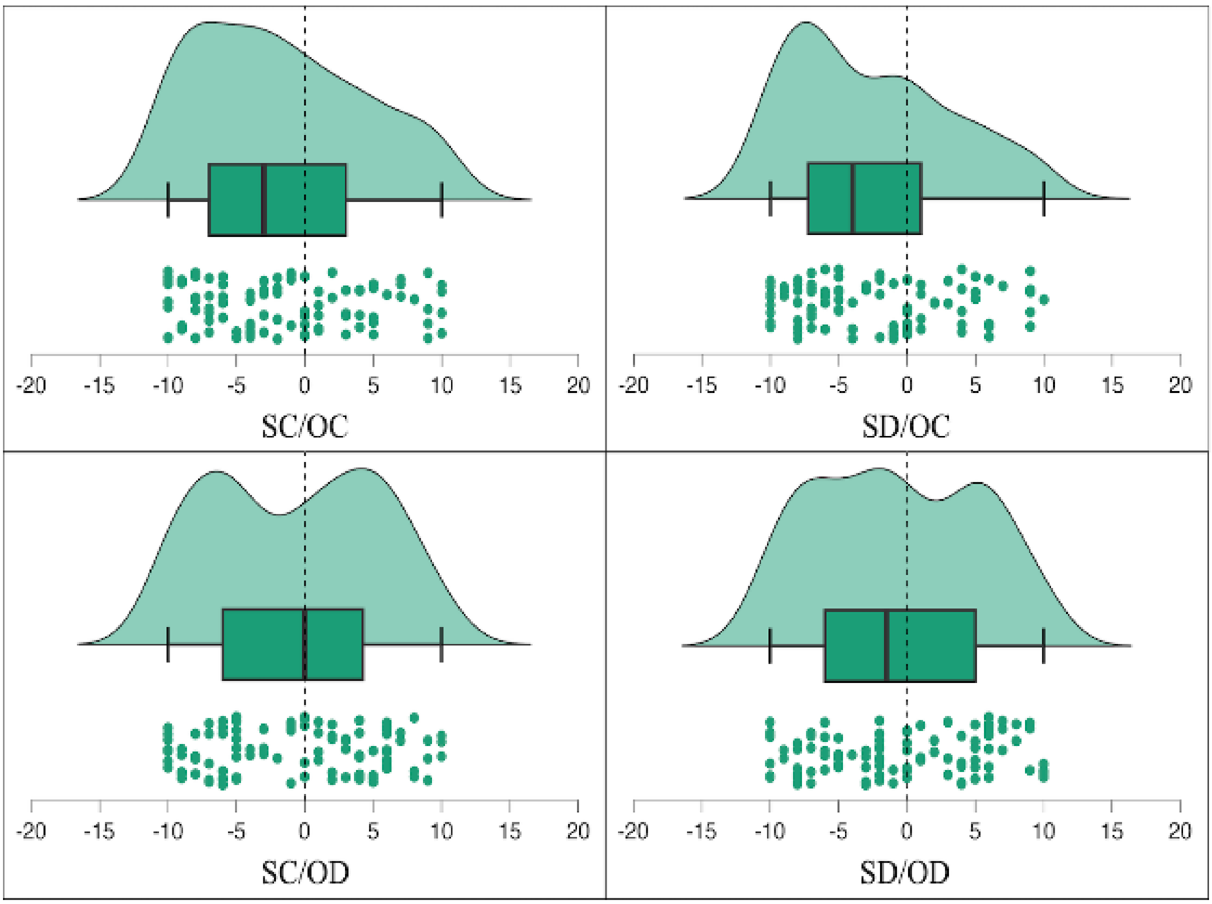

Figure 3. The distribution of level of annoyance of each group

Additionally, to explore the difference in annoyance between each condition we conducted a mixed ANOVA. Figure 4 shows that annoyance between each sound type condition showed a significant difference, $F(3, 96) = 3.88$, $p = .010$, $\eta_p^2 = .04$. To further investigate the difference between each condition, we conducted a Bonferroni post-hoc test. The result reveals that combination SC/OD ($M = -0.71$, $SD = 6.08$) showed a higher level of annoyance than SD/OC ($M = -2.59$, $SD = 5.83$), $t(96) = 2.82$, $p = .031$. Similarly, combination SD/OD ($M = -0.65$, $SD = 5.97$) showed a higher level of annoyance than SD/OC ($M = -2.59$, $SD = 5.83$), $t(96) = -2.87$, $p = .027$. Table 1 and 2 shows that there are no significant differences between each group. Therefore, H5 and H6 were supported while H4 was not.

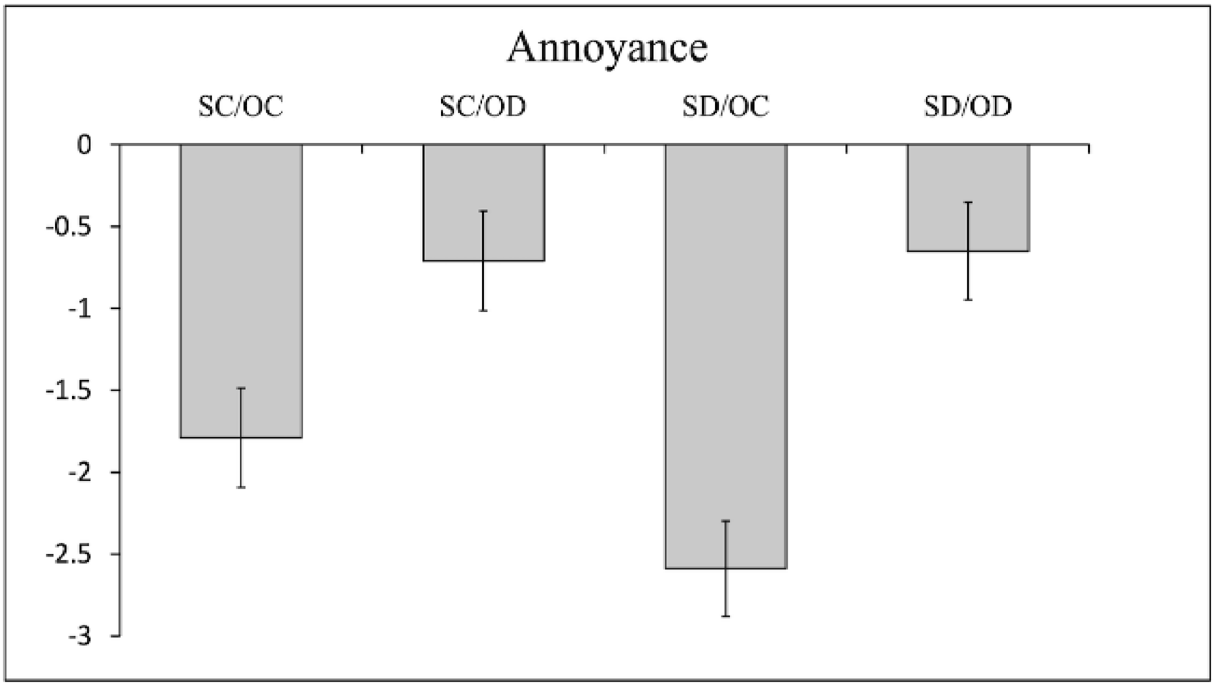

Figure 4. Level of annoyance of each group

Table 1. Descriptive statistics for the level of annoyance

Case	N	*M*	*SD*
SC/OC	29	-1.79	6.08
SC/OD	28	-0.71	6.08
SD/OC	28	-2.59	5.83
SD/OD	31	-0.65	5.97

Table 2. The result of t-test for the level of annoyance

Case		df	*t*	*p*
SC/OC	SC/OD	96	-1.68	.560
	SD/OC	96	1.14	1.000
	SD/OD	96	-1.73	.504
SC/OD	SD/OC	96	2.82	.031
	SD/OD	96	-0.05	1.000
SD/OC	SD/OD	96	-2.87	.027

4. DISCUSSION

The present study aimed to investigate the impact of the degree of consonance in background and alarm sounds on alarm system performance and the level of annoyance associated with auditory alerts. The findings provide valuable insights into the relationship between sound characteristics and cognitive performance, with implications for auditory interface design.

An optimal level of arousal is essential for performance. Hebb's concept of an inverted U-shaped relationship between arousal and learning suggests that performance reaches its peak at a specific optimal level of arousal. This implies that both insufficient and excessive arousal can hinder performance [23]. Easterbrook further illustrated that heightened emotional drive narrows the range of available cues [24]. An ideal level of emotional drive or arousal helps individuals utilize the optimal number of cues needed for the task, ultimately leading to improved performance.

Numerous studies have demonstrated that dissonant sounds evoke higher arousal levels. For instance, Costa et al. found that participants associated dissonant sounds with more potent and arousal-related adjectives, such as *strong* or *vigorous* [25]. Sammler et al. discovered that dissonant sounds caused a deceleration in heart rate, indicating an increase in arousal in response to unpleasant stimuli [26]. Zentner and Kagan found that 4-month-old infants exhibited higher motor activity when exposed to dissonant sounds, suggesting increased arousal [27].

The amount of arousal elicited by an auditory stimulus may vary depending on the context. In music, dissonant harmonies are used to create tension, making the resolution to consonant harmony sound more pleasant. This suggests that presenting dissonant sounds in a consonant musical context may amplify their negatively arousing characteristics. Koelsch et al. demonstrated that even non-musicians displayed an early right-anterior negativity (ERAN) ERP component when exposed to an unexpected chord [28]. The participants showed ERAN in response to Neapolitan 6th chords, which contained notes (A♭, D♭) that did not conform to the expected diatonic scale of C major. This indicates that sounds that violate musical expectations are processed differently on a neural level.

In the current study, participants in the SD/OC condition outperformed those in the SC/OD condition. Two potential explanations for this result can be considered. First, in the SD/OC condition, the dissonant standard sound may have helped participants maintain their arousal at an optimal level. Second, in the SC/OD condition, the dissonant oddball sound may have excessively aroused participants, hindering their performance. The consonant standard sound creates expectations about upcoming sounds, while the dissonant oddball sound violates these expectations, leading to an overload of arousal.

Our explanation is further supported by the ratings of annoyance that the participants filled out. Participants rated oddballs of the SC/OD and the SD/OD combination more annoying than SD/OC. Also, consonant oddballs were rated significantly more pleasant compared to the test value of 0, while the dissonant oddballs did not. These results suggest that people were more annoyed while listening to dissonant oddballs, and therefore more negatively aroused. These differences in annoyance ratings provide a potential explanation that the dissonant oddball alerts may have caused excessive arousal in participants, hindering performance.

While this study provides critical insights into the influence of consonance combinations on alarm system performance, the specific mechanisms underlying the performance differences remain unclear. Future research is necessary to delve deeper into the underlying processes.

However, this study has several limitations. First, the sample size for each group may be considered relatively small, with fewer than 30 participants in each group. This could be a limitation for conducting ANOVA. Nonetheless, as all conditions in our experiment passed the equal-variance test, we have confidence that our findings are applicable to real-world working environments.

Secondly, there was much variance in each condition when measuring annoyance. However, we have found a significant difference between sound combination conditions on annoyance, and the consonant oddballs were rated significantly more pleasant compared to the baseline, while the dissonant ones were not. Therefore, we conclude that even though the variance was not small enough to compare between groups, the participants did find the consonant oddballs less annoying.

Thirdly, not all consonant or dissonant harmonies were used in this research. Our experiment only used the perfect 5th and the major 3rd as the consonant interval, and tritone and the major 2^{nd} as the dissonant interval. While these intervals are representative examples, it is possible that other consonant and dissonant harmonies may influence performance differently. Furthermore, we have only used two-tone intervals for this experiment. Since there is a possibility that harmonies with 3 or more notes may impact performance differently, further studies are needed.

Lastly, the online environment used in this study allowed participants to use their own computers and headphones, which resulted in some uncontrollable variables, such as differences in monitor size, screen brightness, and sound volume. Future studies should consider conducting experiments in controlled laboratory settings to mitigate these limitations.

5. CONCLUSION

This study provided behavioral evidence that the consonance of alarm sounds affects performance directly. However, in a situation where more than multiple sounds are present, the effect of consonance differs based on the relationship of the sound itself. It turned out that dissonant sounds as an oddball in a consonant background situation have a disadvantage over consonant sounds as an oddball in a dissonant background situation. Discrimination of those two sounds is the same, however, the relationship of the sound as background sound or the alarm sound influenced the performance. Further study needs to be done to clarify why certain combination is superior to other, but this study shows that sound traits of the background sound need to be considered to make a high-performance alarm system. While in terms of usability, this study suggests that using a consonant alarm will have an advantage in controlling annoyance.

To the best of our knowledge, this study is the first study that reveals how the degree of consonance of an auditory stimulus impacts performance. Whether the auditory stimuli are consonant or not does not affect task performance unidirectionally and it is mitigated by the degree of consonance of other task-irrelevant sounds. Therefore, sound designers need to assign sounds with appropriate harmonic characteristics to appropriate situations.

This study holds two important practical implications. Firstly, critical auditory alerts should be designed with consonant harmonies. Our result shows that performance was best when the oddball was consonant. There are various ways to explain this result. Consonant intervals drive more attention, additionally, they prevent from causing excessive arousal. Hence, it is crucial to use consonant notes to signal events of maximum importance.

Secondly, music in the workplace should be used cautiously. Our findings indirectly show the downside of playing music in the workplace. Some studies claim that listening to music in the workplace improves mood states, and therefore leads to better performance [29]. However, this may not be the case if the task involves detecting and reacting to an auditory alert. Based on our results, it is plausible to say that the consonant task-irrelevant sounds may hinder performance. Since consonant harmonies are majorly used in music, listening to music in the workplace may slow down the operator's reaction in urgent situations. Therefore, managers need to consider the pros and cons of playing music while working.

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