TOWARDS A SUBJECTIVE QUANTIFICATION OF NOISE ANNOYANCE DUE TO OUTDOOR EVENTS

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1 INTRODUCTION

Noise pollution is a growing concern in today’s society, significantly impacting human health and well-being, causing cardiovascular issues, sleep disturbance and cognitive impairments. According to the World Health Organization (WHO), environmental noise in Western European Member States alone accounts for a loss of 1.6 million healthy life years annually [1]. The American society can save $3.9 billion each year by reducing environmental noise exposure by 5 dB, simply by reducing cardiovascular disease treatment costs. Robert Koch postulated in 1910 that “One day man will have to fight noise as fiercely as cholera and pest.” The World Health Organization (WHO) has recently made notable advancements in establishing a comprehensive set of objectively derived community noise regulations [2]. These guidelines offer recommendations for understanding, monitoring, and managing noise originating from roads, railways, air travel, and wind turbines. Yet, the section on leisure noise, which encompasses outdoor entertainment events, highlights a significant gap in unbiased, objective research. This void has led to the absence of new guidelines in this domain.

To address this oversight, the study delves into the prevalent issue of noise pollution at outdoor events, emphasizing the inherent nature of noise annoyance and the associated challenges in quantifying and measuring it. Through the integration of acoustical, physiological, and psychological measurements in conjunction with subjective rating scales, the research aims to establish the groundwork for a subjectively calibrated metric. This metric is specifically tailored to assess off-site annoyance caused by the propagation of sound from live event sound reinforcement systems. Furthermore, the study sheds light on the physiological and cognitive factors that contribute to noise annoyance, providing valuable insights into potential strategies for predicting, monitoring, and mitigating noise-related issues in live event settings.

2 BACKGROUND

The development of highly amplified live rock and pop music can be traced back to the mid-to-late 1960s in the UK and the US. Two main factors contributed to this development: the need to address large, noisy audiences in adverse acoustic conditions following The Beatles' concerts, and the emergence of powerful guitar amplifiers in London's small urban clubs. This led to a race for loudness on stage, eventually resulting in the practice of "full amplification." Environmental noise and annoyance to neighbours also became prominent concerns during this period [3]. Charlie Watkins, an inventor, businessman, and operator, was arrested and brought before a judge for causing a disturbance at the 1967 Windsor Jazz and Blues Festival. Around the same time, hearing health hazards were also investigated [3].

The issue of noise and sound pollution emanating from outdoor events is a longstanding concern highlighted in various publications and studies over the past half-century. Despite this, the industry has not reached a universally agreed-upon resolution or comprehensive understanding of these problems. Research focuses on sound exposure at the event site and noise pollution affecting surrounding areas, requiring distinct strategies to mitigate immediate and long-term negative impacts [4].

In many countries, sound level regulations at music venues, with some noteworthy exclusions, are informed by environmental measures intended to minimize disturbance and inconvenience for adjacent residents and those within a specified radius, as in the case of outdoor concerts [5]. These environmental norms are typically tracked through measurement procedures conducted outside a music venue, for instance, at the nearest wall of a neighbouring residence. For larger outdoor events, it has become standard procedure to monitor sound levels on-site (commonly at the mix position, FOH), adhering to maximum L_{Aeq} and or L_{Ceq} values that were established through modelling and confirmed by stationary and/or mobile measurement setups, to ensure compliance with environmental regulations [6]. These regulations rely on objective methods and physical acoustical metrics, with limited consideration for the subjective perception of noise and human interpretation; this literature gap is addressed in this study. To work towards the subjective quantification of noise annoyance due to outdoor events, various elements involved in the subjective perception were investigated.

The psychoacoustic model of Zwicker plays a crucial role in quantifying the subjective perception of noise annoyance [7]. This model considers various psychoacoustic factors, including loudness, sharpness, fluctuation and strength. By incorporating these factors, Zwicker's model offers a comprehensive understanding of how different types of noise can be perceived as annoying. Studies have successfully applied Zwicker's annoyance model for soundscape categorization [8] and for tonal noises [9]. Despite some limitations, Zwicker's model has proven relevant in assessing annoyance caused by specific sources of noise, such as rotorcraft noise [10]. It is crucial to differentiate between short-term and long-term annoyance when using Zwicker's model, as this provides a nuanced understanding of noise's impact on individuals [11].

Physiological parameters such as skin conductance (EDA) and heart rate variability (HRV) can be valuable in the quantification of noise annoyance. These parameters provide objective measures of the body's response to noise stimuli, which can help in understanding the impact of noise on individuals' well-being. Skin conductance, also known as electrodermal activity (EDA), is a measure of the electrical conductance of the skin, which is influenced by the activity of sweat glands. EDA has been used as an indicator of sympathetic nervous system activity and emotional arousal [12]. Studies have shown that noise exposure can lead to increased physiological arousal, as evidenced by changes in skin conductance [13]. For example, experiments on wind turbine noise found that skin conductance responses were affected by both audible and inaudible characteristics of the noise [14].

Heart rate variability (HRV) is a measure of the variation in the time intervals between consecutive heartbeats. It reflects the activity of the autonomic nervous system, with high HRV indicating a healthy system. Noise exposure has been found to affect HRV, with studies showing that noise can lead to changes in heart rate and HRV parameters [15]. For instance, a study on the effects of sound loudness found significant correlations between heart rate and noise annoyance [16]. These physiological parameters can provide valuable insights into the subjective experience of noise annoyance. They offer objective measures of the body's response to noise stimuli, which can complement self-reported measures of annoyance. By examining changes in skin conductance and HRV, researchers can gain a deeper understanding of the physiological mechanisms underlying noise annoyance and its impact on individuals' well-being.

The Noise Sensitivity Questionnaire (NoiSeQ) offers a valuable tool to assess individuals' sensitivity to noise [17]. This questionnaire measures subjective noise sensitivity, a strong predictor of high noise annoyance [18]. Factors such as window orientation, duration of stay in the area, and night-time noise levels also influence noise annoyance [18]. By combining subjective parameters from psychoacoustic models, physiological recordings, and noise sensitivity questionnaires, a comprehensive understanding of noise annoyance due to outdoor events can be achieved. This multidimensional approach enhances the accuracy and depth of assessments regarding the impact of noise on individuals. These parameters can help researchers and policymakers better understand the impact of noise on individuals' well-being and develop effective strategies for noise mitigation.

3 METHODOLOGY

The primary objective of this research is to conduct a thorough examination of the impacts of noise pollution on populations living close to music-based noise sources, with a focus on assessing the effects on individuals who are directly impacted by such disturbances. Due to the nature of this study, it is crucial to establish a methodology that facilitates the recreation of these conditions in a controlled setting, thereby enabling researchers to gather precise responses from participants subjected to these simulated environments. Therefore, for the first stage of this research, as detailed in this paper, advanced computer simulation software was employed to generate all necessary scenarios and data.

3.1 Study overview

To emulate real-world conditions, simulations were conducted of four distinct scenarios, each strategically aligned and positioned at varying proximities from a simulated outdoor live event, mitigating the influence of directivity propagation patterns. This configuration was designed to replicate the circumstances experienced by residences located at different distances from sources of noise pollution, such as an outdoor concert venue. The noise pollution levels at the façade of each dwelling were calibrated to 95 dBC, 85 dBC, 75 dBC, and 65 dBC, covering a broad range of typical exposure levels and representing a diverse array of plausible real-world scenarios. For each residence, two distinct simulations were included: one with an open window (-10 dB) and another with the window closed (-27 dB) [19]. This aspect of the research aimed to assess the influence of this common variable on the infiltration and subsequent indoor levels of noise pollution, providing deeper insights into the variations in sound propagation under these two different states.

Simulations were carried out using SoundPLAN, a commercial software known for its advanced modelling capabilities in various noise environments. SoundPLAN enables a detailed analysis of noise distribution and its resulting effects. Critically, it can integrate ArrayCalc files, specialized software designed to assist with d&b audiotechnik sound system design. This integration streamlines the creation of precise noise pollution simulations, which are essential for faithfully reproducing real-world scenarios such as concerts noise propagations.

A random, unobstructed location within a set of fields around Derby, UK (52°56'06.0"N 1°33'46.6"W) was chosen to set up the stage for this study. This choice ensured ideal conditions for simulating sound propagation. A stage model from ArrayCalc was imported into SoundPlan, which included 16 GSL8 main line arrays, 8 GSL8 for outfill arrays, 24 SL-SUB subwoofers, and 8 V7P front fills. This sound system was employed to create a sound profile typical for a medium-sized outdoor live event. The sound level at FOH was calibrated to accurately replicate real concert loudness at 112 dBC [20]. Four receivers at varying distances from the stage were deployed to simulate noise levels at different residential locations. Sound levels were set at 95 dBC at 510 m, 85 dBC at 1203 m, 75 dBC at 1979 m, and 65 dBC at 3118 m, as illustrated in Figure 1.

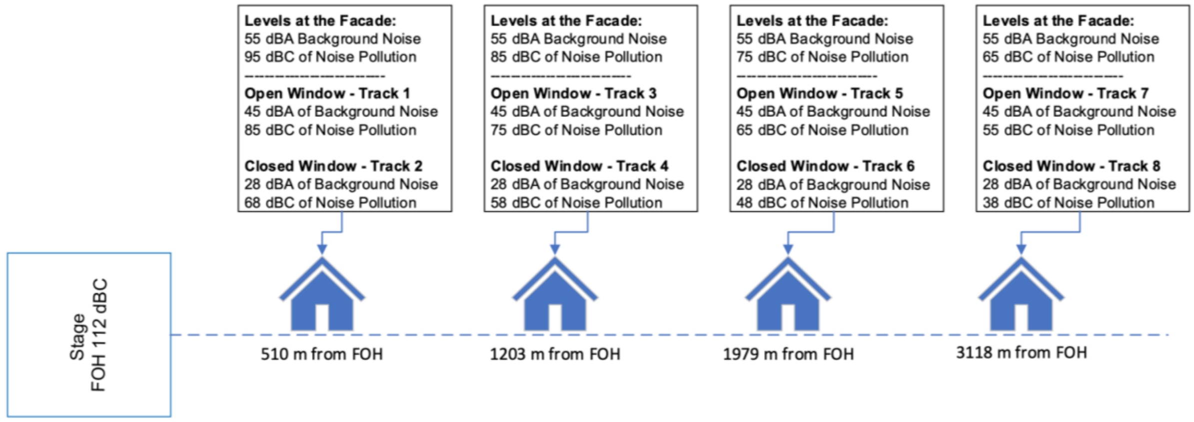

Figure 1 The different simulated household characteristics

In the literature, much of the work done included direct exposure to noise and levels. To provide a more realistic study, the simulations emphasized the importance of acoustical propagation from the outdoor to indoor environments with open and closed window configurations. This approach considered room modes; an aspect that has often been overlooked in many studies but holds significant importance. The Matlab code replicated a standard living room, with its dimensions and standard acoustical characteristics to generate an impulse response, that was later convolved with the different soundtracks and background noise. Taking these factors into account offers a comprehensive understanding and deserves more attention in noise studies. This resulted in eight distinct sound scenarios. For open windows, a -10 dB adjustment was applied with a background noise level of 45 dBA, while for closed windows a -27 dB adjustment was implemented, accompanied by a background noise level of 28 dBA.

Track Number	Window Situation	Background Noise Level	Noise Pollution Level
1	Open	45 dBA	85 dBC
2	Closed	28 dBA	68 dBC
3	Open	45 dBA	75 dBC
4	Closed	28 dBA	58 dBC
5	Open	45 dBA	65 dBC
6	Closed	28 dBA	48 dBC
7	Open	45 dBA	55 dBC
8	Closed	28 dBA	38 dBC
9	Closed	28 dBA	0 dBC
10	Closed	28 dBA	0 dBC

Table 1 The settings of the different soundtracks

Two separate sound files were required: one to simulate concert-related noise pollution, and the other to replicate ambient background noise. It was crucial to choose tracks that authentically mirrored real-world situations while respecting copyright and ethical standards. As a result, tracks were sourced from royalty-free websites, specifically FreeSound.org and Pixabay.com. One track represented a rock music, while the other was rural background noise.

3.2 Data collection

After establishing the methodology and ensuring that all parameters were appropriately configured, the focus shifted to creating a suitable data collection environment – a critical element for achieving accurate and dependable results. Given the auditory nature of the experiment, it was important to use a suitably quiet and controlled environment. To meet these requirements, the hemi-anechoic chamber at the University of Derby was chosen for its attributes that effectively minimize external noises and internal reflections. Within the chamber, a quadraphonic d&b audiotechnik system was installed to faithfully reproduce the designated soundtracks at predefined levels. This advanced audio system comprised four d&b Max2 loudspeakers, strategically placed in each corner of the room, along with one d&b B6 subwoofer to ensure spectrally balanced sound reproduction. To eliminate any potential bias that might arise from participants seeing the sound system, the equipment was concealed with a neutral black textile, ensuring that the participants' focus remained solely on the auditory stimuli.

Figure 2 View from the Hemi-anechoic chamber used for the experiment (without source screening)

3.2.1 Cognitive activity

Throughout the various scenarios, participants engaged in a Stroop test during [21] each of the six distinct stages to maintain their cognitive activity. The initial and final tests served as baselines for comparing participant performance at the beginning and end of the study, allowing for tracking potential fatigue or the development of learning habits. The intermediate four tests corresponded to four randomly selected noise scenarios. The Stroop test employed in this study was created using MATLAB, adapted from a template developed by Mr. Deba Pratim Saha [22], and customized to meet the specific requirements of the study. Each Stroop test session had a duration of 180 seconds, including a 15-second pause at the beginning and end to allow participants to recalibrate their attention and engagement. This resulted in an effective task engagement time of 150 seconds for each session.

The Stroop test, originally introduced in English by John Ridley Stroop in 1935, serves as a cognitive assessment tool designed to measure various cognitive attributes such as cognitive flexibility, selective attention, processing speed, and cognitive control capture.
The classic version of the Stroop test presents participants with a list of words representing colours (e.g., "Yellow," "Magenta," "Cyan," "Red," "Green," "Blue," "Black"), with each word displayed in ink of a colour that differs from the colour denoted by the word itself.
This incongruence between the word's meaning and the ink's colour introduces a cognitive conflict that participants must resolve. They are tasked with identifying the ink colour, not the colour mentioned by the word, and recording their response through a mouse click. Each task within the test has a time limit of 3 seconds, resulting in a total of 50 tasks.

3.2.2 Physiological recordings

While participants experienced various sound scenarios and engaged in the Stroop task, their physiological responses were monitored. Focusing on two distinct physiological parameters: Heart Rate Variability (HRV) and Skin Conductance (SC). These measurements were obtained using a BIOPAC system to gain valuable insights into the participants' physical reactions.

HRV, which assesses the variability in time intervals between successive heartbeats, was recorded using three electrodes. One electrode was affixed to each wrist, while the third was attached to the clavicle. Simultaneously, Skin Conductance (SC) was recorded using two electrodes placed on the participant's fingers. SC measures the electrical conductivity of the skin, a metric directly influenced by sweat gland activity. The level of skin conductance is widely recognized as a dependable physiological indicator of emotional arousal. Changes in SC can offer valuable insights into the participant's emotional responses to the auditory stimuli presented in each sound scenario. The data analysis of the physiological recordings was separated into two epochs. The first epoch starts 7.5 seconds before the Stroop test begins and ends 7.5 seconds after it starts, for a total of 15 seconds. The second epoch begins with the start of the Stroop test and concludes at the end of the Stroop test, lasting a total of 150 seconds. Therefore, the physiological parameters were labelled with a "1" at the end for epoch #1 and "2" for epoch #2.

3.2.3 Self-reported questionnaire

To complement the physiological measurements and cognitive Stroop test, a self-administered questionnaire was utilized to assess participants' psychological reactions to the various auditory scenarios. This three-pronged approach provides a comprehensive understanding of the participants' responses by incorporating cognitive, physiological, and psychological perspectives. The questionnaire comprised several sections. The initial portion included general demographic inquiries such as Subject ID, gender, and questions pertaining to participants' health, particularly related to their hearing, potential colour blindness, and other health-related matters.

The subsequent segment focused on how participants perceived the sound samples they encountered. Following each sample, participants were presented with the same set of four questions aligned with ISO 15666 standards [23]. They had to rate their disturbance using both a wording (DW) and numerical (DR) scale. Similarly, annoyance was rated using a wording (AW) and numerical (AR) scale, based on the four consecutive questions.

- **DW**: "Thinking about the last 3 minutes, how much did the music-based noise distract you from the task?" (Not at all, Slightly, Moderately, Very, Extremely)
- **DR**: " Thinking about the last 3 minutes, what number from 0 to 10 represents how much you were distracted by the music-based noise?"
- **AW**: Thinking about the last 3 minutes, if you were at home, how much would the music-based noise bother, disturb, or annoy you? (Not at all, Slightly, Moderately, Very, Extremely)
- **AR**: Thinking about the last 3 minutes, if you were at home, what number from 0 to 10 best shows how much you would be bothered, disturbed or annoyed by music-based noise?

This method involved querying participants about their experiences in the preceding three minutes. Firstly, participants used a word rating scale to convey the degree of distraction they experienced due to the sound. Subsequently, they provided a numerical rating between 0 and 10 for the same question. Afterward, participants were instructed to imagine themselves in their home environment, contemplating the last three minutes of the sound scenario. They again used a word rating scale and a 0 to 10 rating scale to indicate how much the music-based noise would have bothered, disturbed, or annoyed them. These questions were reiterated after each sound sample.

Additionally, the survey included a Noise Sensitivity Questionnaire (NoiSeQ). This assessed overall noise sensitivity across five different daily-life scenarios: work, communication, leisure, sleep, and habitation. Consequently, this section encompassed five subscales, each comprising seven items, where participants indicated their agreement with each statement. The questionnaire also featured a section dedicated to probing participants' musical preferences, adding an extra layer to understanding the perceived impact of different sounds. Furthermore, questions aimed at assessing the participants' place on the introvert/extrovert scale. This data offers insights into how individual personality traits might influence responses to auditory stimuli. By integrating this diverse array of data, a comprehensive understanding of participants' reactions to various sound scenarios was achieved.

4 RESULTS AND DESCUSSION

The aim of this study was to investigate the impact of different soundtracks on participants, using a wide range of metrics, from auditory characteristics to physiological and psychological responses. Data was presented in two manners (Figures 3 – 5), namely box plots and a correlation heatmap, which were employed for the preliminary data analysis and provides a comprehensive understanding of the data, revealing patterns and relationships.

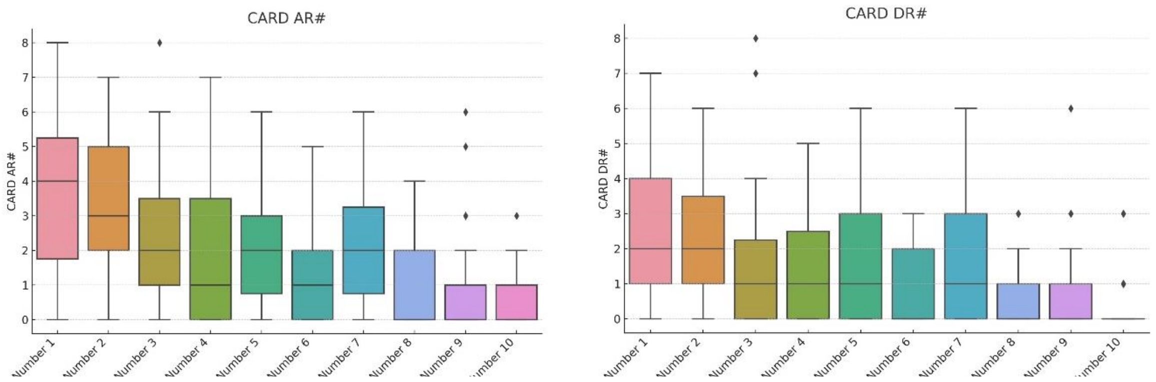

Figure 3 Distribution of Annoyance Rating (AR) (left) and Disturbance Rating (DR) (right) according to track number

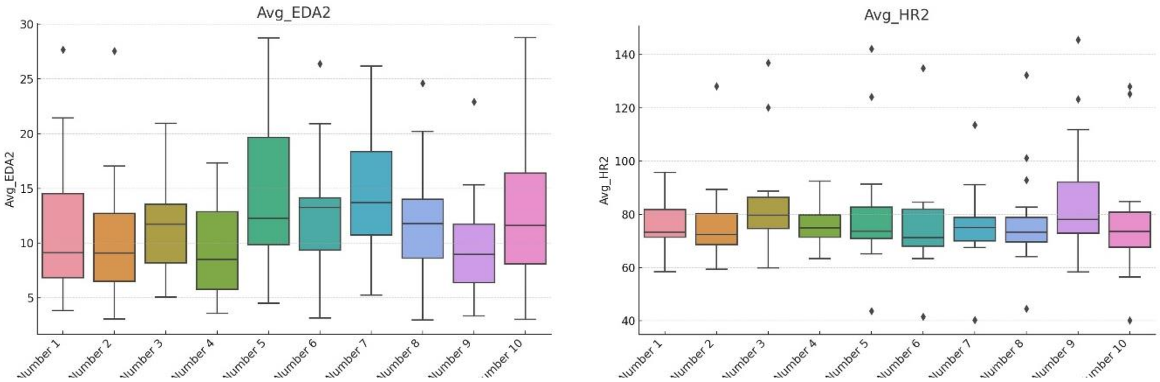

Figure 4 Distribution of the average Electrodermal Activity (EDA) (left) and Heart Rate (HR) (right) during the second epox according to the tracks number.

	Track #1	**Track #2**	**Track #3**	**Track #4**	**Track #5**	**Track #6**	**Track #7**	**Track #8**	**Track #9 & 10**
Articulation Index [%]	96,77	99,68	98,72	100	99,69	100	99,74	100	100
Fluctuation Strength [Vacil]	0,944	0,4896	0,8981	0,4986	0,6746	0,2661	0,683	0,01889	0
Loudness CPB ISO 532-2 2017 [Sone]	13,31	3,774	9,185	1,315	6,447	1,344	5,797	0,4993	0,5605
Loudness FFT ISO 532-2 2017 [Sone]	12,92	3,637	8,87	1,263	6,242	1,293	5,607	0,479	0,5412
Loudness Free [Sone]	18,02	4,752	9,892	1,63	5,247	1,185	4,297	0,3121	0,3112
Loudness Level [Phon]	81,72	62,49	73,06	47,05	63,91	42,45	61,03	26,62	26,59
Prominence Ratio [dB]	23,4	23,06	26,13	24,79	19,56	35,05	14,89	20,69	35,72
Roughness [DIN 45631 1989 Free] [Asper]	1,106	0,2512	1,282	0,0436	1,338	0,1958	1,361	0,009664	0,01038
Sharpness [Zwicker, DIN 45631 1989 Free] [Acum]	0,582	0,409	0,872	0,4178	1,129	0,8819	1,344	0,9221	1,316
Tonality	0,2789	0,2881	0,2918	0,2785	0,208	0,1655	0,1281	0,1514	0,05668
Tone Level [ANSI S1.13] [dB PA]	77,95	61,72	67,72	48,25	54,84	40,97	45,83	28,99	13,18
Tone to Noise Ratio [ANSI S1.13] [dB]	-3,564	-3,479	-2,509	-2,475	-3,075	-3,403	-3,002	-3,157	-5,741

Table 2 Acoustical parameters of the different soundtracks used in the study

The analysis reveals notable variations across the tracks. For example, loudness levels displays notable differences across tracks (Figure 5), with track 1, corresponding to the nearest household to the FOH with an open window, exhibiting a higher median loudness level than other tracks. Furthermore, data showed variability, indicating differences not only in central tendency but also in data dispersion. This variability suggests that participants' auditory experiences varied significantly depending on the track being played. Importantly, these variations could have influenced subjective metrics, such as Distraction Wording, Distraction Rating, Annoyance Wording and Annoyance Rating, indicating that tracks with higher loudness levels may lead to greater disturbance reactions in subjects. Consistent patterns across subjects would provide stronger evidence for the direct impact of auditory elements on subjective annoyance.

A correlation heatmap (Figure 5, given in this paper’s appendix) provided valuable insights. Notably, loudness level exhibited a strong positive correlation (approximately 0.8) with tonality, implying that as the loudness level of a track increased, its tonality typically increased as well. This relationship sheds light on the auditory characteristics of the tracks and how they might interact to influence the listener's experience. Moreover, certain physiological metrics, such as the maximum Heart Rate in the second epoch showed significant correlations of 0.3 with the subjective rating of disturbance. The positive correlation of approximately 0.42 between the disturbance rating and the "Loudness Level" suggests that louder tracks could lead to higher disturbance rating, thus heightened heart rates in participants, indicating a potential physiological stress response to louder sounds. Further exploration of the heatmap revealed nuanced relationships between physiological metrics and subjective responses.

Individuals with a high NoiSeQ score, around 3.77, – 0 being not at all sensitive and 5 being extremely sensitive - indicating greater sensitivity to noise, reported moderate levels of disturbance and annoyance (Disturbance rating at “Moderately” and annoyance rating at 2). They also leaned towards introversion with an extroversion score of 3.3 - 0 being introvert and 5 being extrovert -. On the other hand, those with low NoiSeQ scores (about 2.03), signifying lower noise sensitivity, expressed no disturbance or annoyance (both ratings at 0) and had a slightly higher extroversion score of 3.5.

An individual with a high introversion score (low extroversion) of 2.3, despite having a NoiSeQ score of 3.17, reported remarkably high disturbance and annoyance levels, both at 6. This suggests that highly introverted individuals may exhibit increased sensitivity to noise disturbances, resulting in elevated annoyance levels. Conversely, a more extroverted individual with an extroversion score of 3.8 and a NoiSeQ score of 2.86 reported moderate disturbance and annoyance levels, both at

These instances underline how individual characteristics can impact responses to different soundtracks. The data indicates that individuals with higher noise sensitivity tend to report greater disturbance and annoyance, regardless of their introversion or extroversion tendencies. However, introversion appears to further enhance reported disturbance and annoyance levels.

Furthermore, the highly noise-sensitive and introverted subject reported moderate disturbance and annoyance, the less noise-sensitive and slightly more extroverted individual reported no disturbance or annoyance. This underscores the potential interplay between noise sensitivity and personality traits in shaping how individuals react to various soundtracks.

5 CONCLUSIONS

These findings suggest that both individual noise sensitivity and personality traits contribute to reactions to noise. While noise sensitivity establishes a baseline for how people perceive and respond to sounds, personality traits such as introversion and extroversion can modify these reactions, potentially amplifying or lessening reported disturbance and annoyance levels.
The data provides a comprehensive understanding of the interplay between track characteristics, physiological responses, and subjective experiences. The marked variability across tracks for various

metrics underscores the critical role of track selection in noise annoyance studies. The correlations observed offer valuable guidance for future investigations, shaping hypotheses and experimental designs.

In conclusion, this analysis marks the initial stage of a comprehensive data exploration. It serves as the foundation upon which our future efforts will build, involving a more thorough investigation of all variables. The data will be examined and compared with baseline measures to identify any changes or fluctuations. Next steps involve developing advanced statistical models and conducting regression analyses. These tools will enable the authors to work towards a construction of prediction models that can integrate acoustic characteristics of sounds with individual psychological factors. Ultimately, the goal is to create a robust model capable of estimating subjective annoyance rating scores based on a holistic understanding of these intertwined elements. This effort marks the beginning of a detailed journey to better understand noise annoyance and to develop tools that enhance our insight into its complex nature.

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7 APPENDIX

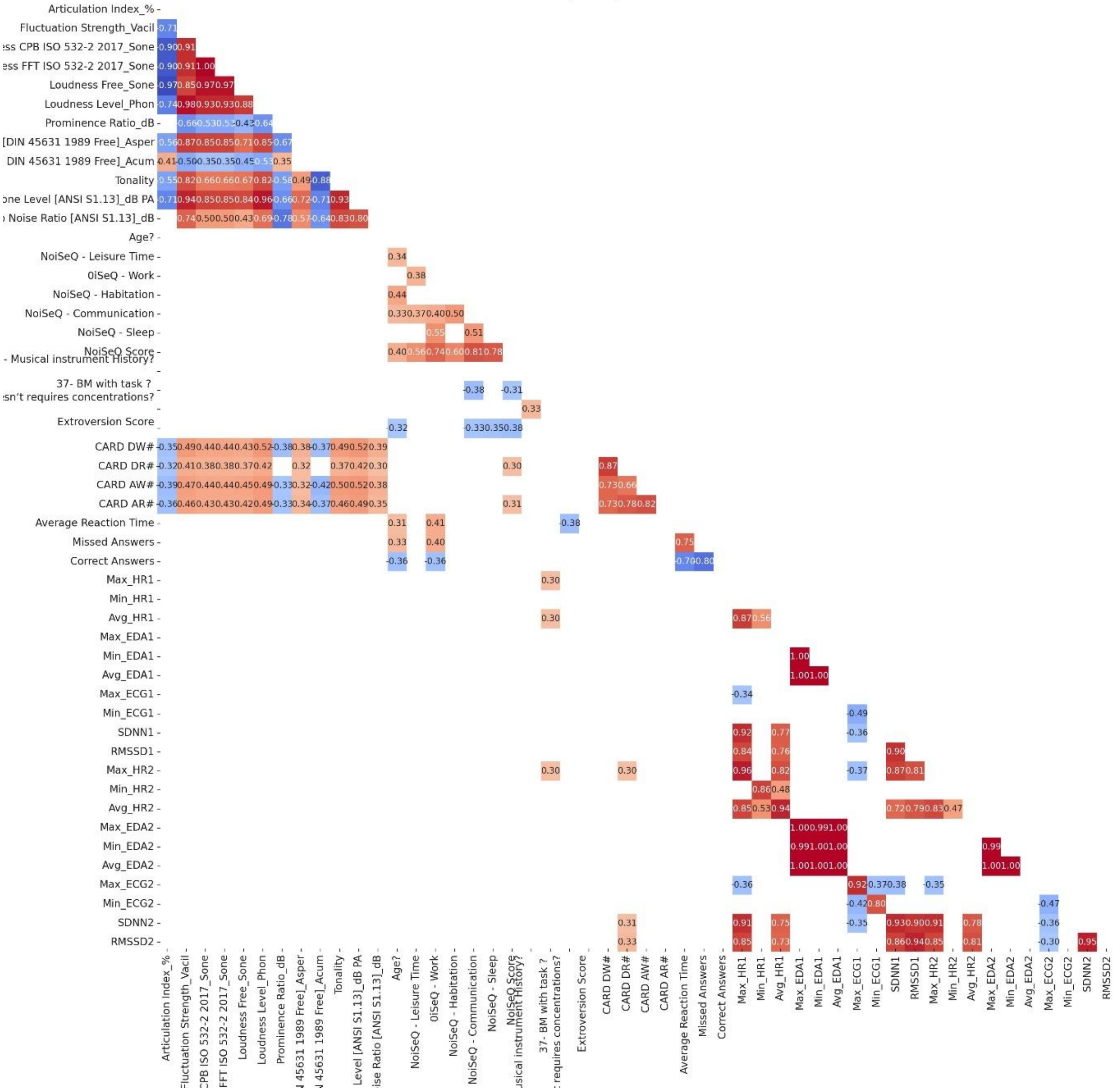

Figure 5 Heat map showing the correlation of multiple variables within a range of ±0.3