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INVESTIGATION INTO THE EFFECT OF HORIZONTAL SOURCE DIRECTION ON PSYCHOACOUSTIC ANNOYANCE

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ABSTRACT

A limited number of studies have explored the impact of spatial acoustic features on perceived annoyance. Existing auditory annoyance models do not consider spatial features and are restricted to mono audio signals. A listening experiment has been carried out to investigate the effect of horizontal source direction on the subjective annoyance caused by a series of commonly occurring domestic sounds. 7 source recordings were presented binaurally, positioned at 45° intervals surrounding the listener. The perceived annoyance caused by each stimulus was graded by 54 participants. The results indicated that for most sources, the lowest annoyance level was reported when the source was situated at 180°, and highest when positioned at ±90°. This confirms the hypothesis that source direction affects perceived annoyance level. However, this appears to be dependent on source type, with several sources demonstrating no significant differences in perceived annoyance across the tested source positions. Differences in perceived annoyance were also observed depending on whether the sources were presented in a simulated reverberant or anechoic space. The findings of this study will serve as the basis for the development of a spatially-weighted psychoacoustic annoyance model.

Keywords: *Annoyance, Subjective evaluation, Indoor domestic noise*

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1. INTRODUCTION

Noise annoyance is a critical factor influencing both indoor and outdoor soundscape quality, with documented negative effects on mental health, communication, and sleep. Previous studies have extensively investigated the attributes of psychoacoustic annoyance (PA), leading to the development of several widely used theoretical annoyance prediction models. While these models and many previous annoyance studies focus on the effects of noise level and spectral content, spatial characteristics such as sound source azimuth and reverberation, which are important aspects of soundscape perception, remain unexplored. Furthermore, the validity of existing models has not been comprehensively tested across a diverse range of sound sources. Zwicker and Fastl's PA model [1] was the first to become commonly used. They suggested that annoyance level can be predicted based on the hearing sensations loudness, sharpness, fluctuation strength, and roughness. More recent studies have identified potential limitations in this model. Stojanow and Liebetrau [2] expressed that the original PA model [1] was inaccurate for complex signals and could be improved with a more appropriate combination of psychoacoustic parameters. Di et al. [3] found that for tonal sounds, annoyance level was underestimated. They and More [4] improved upon Zwicker and Fastl's model [1], both incorporating Aures' tonality model [5]. Di et al. [3] found this addition to significantly increase annoyance estimation accuracy. Additional models have been developed, including those presented in [6–11], aiming to more accurately predict annoyance caused by a range of sound types.

In soundscape quality research, annoyance is typically assessed subjectively, with participants rating their perceived annoyance level in response to a given soundscape. ISO 15666 [12], based on the ICBEN [13] recommendation, outlines a standardized method for annoyance evaluation. This approach, which is widely used in annoyance assessment studies, recommends that participants answer two questions and provide ratings using both a five-point scale with verbal anchors and an 11-point (0-10) numerical scale. Other soundscape quality assessment methods include in-situ assessments such as soundwalks. For example, the soundscape quality protocol developed by Axelsson et al. [14] is commonly employed in soundscape quality assessment, which uses the fundamental components pleasantness and eventfulness to describe subjective perception of soundscapes.

Existing research on the spatial attributes of annoyance perception is not extensive, with the focus of most studies on the effect of interaural cross-correlation coefficient (IACC). Frescura et al. [15] and Jeon et al. [16] found that IACC significantly affected annoyance responses and should be considered in annoyance evaluation. Kitamura et al. [17] and Sato et al. [18] identified that fluctuations in spatial factors, such as IACC, affected annoyance ratings, potentially due to increased cognitive load. A study by Zhao and Chen [19] recently assessed the effect of source azimuth on annoyance, however some limitations have been identified in their methods. For example, the study was conducted with a limited sample size, and their implementation of the ISO 15666 [12] 11-point scale appears to deviate from the standard approach, raising concerns about the validity of their results. Although, this remains the only known investigation into the effect of source direction on annoyance responses.

This study aims to extend existing knowledge on the spatial characteristics of psychoacoustic annoyance, by investigating the effects of source azimuth and reverberation on perceived annoyance for a selection of common domestic sounds. A series of listening tests have been conducted and the results were analysed. The findings of this investigation will contribute to the development of an improved PA model, with implications for architectural acoustics, noise policy, and indoor soundscape design.

2. METHODS

2.1 Stimuli Creation

Seven sound sources were chosen for the subjective listening experiment. Five of the sounds were recorded using a Schoeps CCM41 hypercardioid microphone (positioned at a distance of approximately 15cm), a Merging HAPI AD/DA interface, and Reaper DAW. The sources were surrounded by sound-absorbing materials to reduce nearby surface reflections, ensuring exclusive capture of the direct sounds. The recorded sound sources were: a coffee grinder, coffee machine, vacuum cleaner, handwashing dishes, and a washing machine. Two additional sources were generated using MATLAB: pink noise bursts and 3500Hz sawtooth signal bursts. The latter was used to simulate the sound of an emergency alarm, as it is hereafter referred to.

A Neumann KU100 dummy head binaural microphone was used to capture binaural room impulse responses (BRIRs), in a kitchen environment. HAART [20] was employed in the BRIR capture, using the exponential sine sweep method. 5s sine sweeps were played back through a Genelec 8331A loudspeaker, set to a height of 110cm, which is the approximate height of a kitchen worktop. The KU100 was placed 2m away from the source at approximate ear height for a seated listener (125cm). The BRIRs were captured with the KU100 positioned at 45° azimuth intervals. Anechoic KU100 head-related impulse responses (HRIRs), retrieved from the TH Köln Spherical Near-Field HRIR database [21], for the positions corresponding to the those of the measured BRIRs, were also utilised, and extracted using MATLAB functions.

A 10s long excerpt of each sound source recording was convolved with each BRIR and anechoic HRIR, creating 112 individual binaural stimuli. Headphone EQ correction was also applied for playback over Sennheiser HD650 headphones. The sound pressure level (SPL) of the sources was measured at the BRIR capture distance in the kitchen environment, and a MiniDSP EARS binaural microphone with Room EQ Wizard (REW) software were used to calibrate the playback levels for the stimuli.

2.2 Listening Test Procedure

A subjective listening experiment was conducted, in which 54 participants (39 male, 13 female, and 2 non-binary), aged 18-59, were asked to grade their perceived level of annoyance caused by each stimulus. A combination of both experienced and naive listeners were tested. All participants were asked to complete a consent form and two questionnaires prior to the experi-

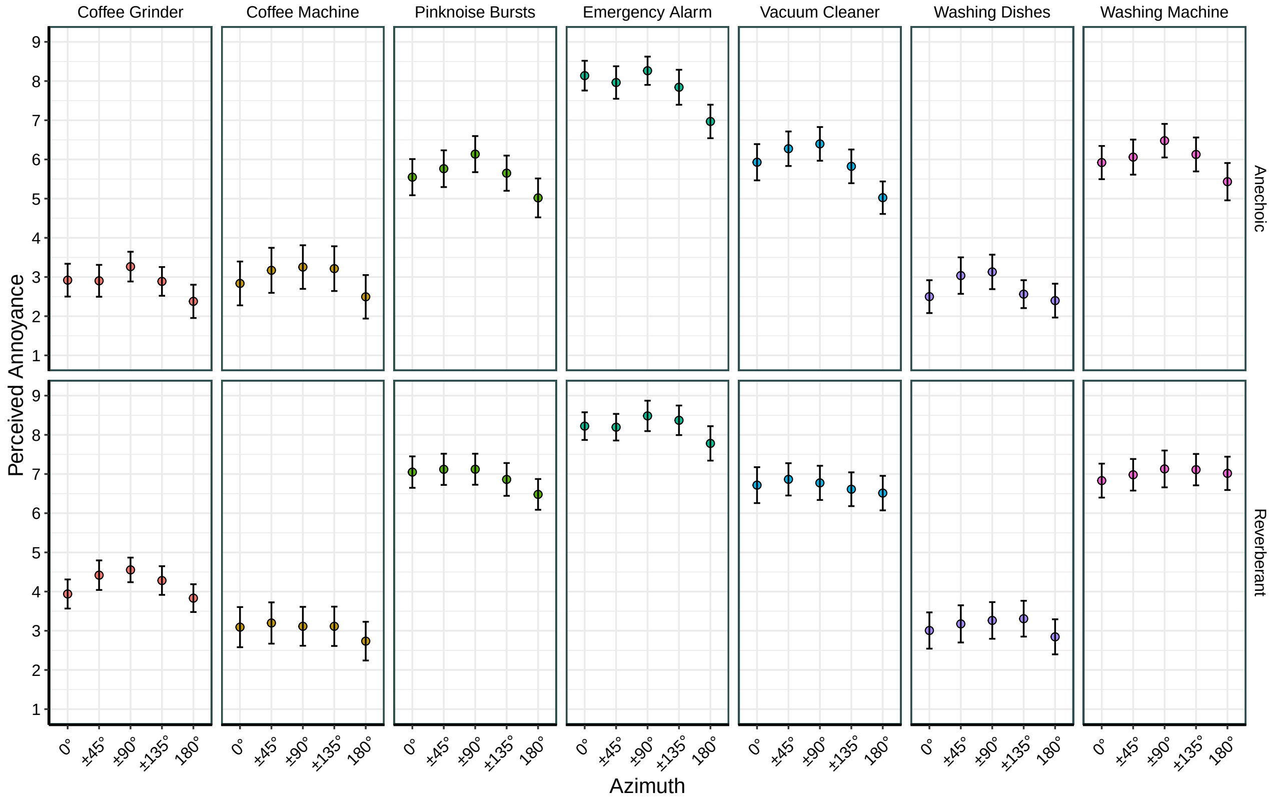

Figure 1. Normalised 11-point scale responses.

ment. Normal hearing was reported by all participants. The listening experiment was carried out in an ITU-R BS.1116-3 compliant listening room at the University of Huddersfield. Any loudspeakers that were visible at the listening position were covered with curtains, in order to remove any visual bias. Participants were asked to sit facing a computer screen and the listening test procedure was explained. They were encouraged to ask the interviewer to clarify anything they didn't understand, and completed a familiarisation process to ensure full understanding of the test procedure and interface.

During the experiment, 140 sounds were presented: all 112 stimuli, with each 0° and 180° source azimuth stimulus presented twice. This provided an even number of stimuli for the left and right ears, meaning that symmetry could be assumed during analysis. Each participant was asked to listen to each stimulus once and answer the question: "How much does the sound bother, disturb or annoy you?". Their response was then graded using two scales, as suggested in [12]: a continuous 11-point numerical scale (0-10), with the endpoints "Not at all annoying" and "Extremely annoying", and a 5-point scale with verbal anchors. The 11 point scale and audio playback were presented through HULTI-GEN V2 [22], and the 5-point scale responses were collected using Google Forms. The listening test was divided into three sections, providing participants two short breaks to prevent fatigue. The experiment lasted approximately 60 minutes overall.

3. RESULTS

3.1 Subjective Results

Fig. 1 presents the means and 95% confidence intervals for the normalised 11-point scale results. Normalisation was applied using the method recommended in ITU-R BS.1116-3 [23]. The results shown in Fig. 1 demonstrated that the majority of sound sources caused the lowest level of annoyance when situated directly behind the listener (at 180°). For most sources, an increase in mean annoyance could be seen as the source position moved towards ±90°. This is demonstrated clearly for all anechoic stimuli. Repeated measures ANOVA and t-test results confirmed this finding, with the identification of significant differences ($p<0.05$) between the 180° and ±90° responses for all anechoic sources, and a moderate effect size (Cohen's d>0.5) for three of the sources. The responses for several sources showed significant differences between the ±45° and 180° positions, and differences in responses for the anechoic stimuli with source azimuths ±135° and 180° were also mostly significant ($p<0.05$), however the effect sizes for the latter comparisons were small. No significance was found when comparing the difference between responses for the 0° and 180° source positions for the anechoic sources, excluding the emergency alarm and vacuum cleaner. These two sources were also found to cause the highest level of annoyance for all source positions.

The three anechoic sources that caused the lowest level of perceived annoyance overall, where mean responses were lower than 5, demonstrated a smaller range of mean responses across the five source azimuth stimuli. The reverse was found for sources with higher average annoyance, suggesting that the directional effect becomes more pronounced as the overall annoyance level increases. The reverberant stimuli, however, did not follow this trend. An increase in mean annoyance towards the ±90° azimuth stimuli was also present for the reverberant stimuli, however the difference in mean responses within each source was much reduced compared to that of the anechoic responses. Repeated measures ANOVA results showed no significance ($p>0.05$) for four of the reverberant sources. Source azimuth was found to have a significant effect ($p<0.05$) on annoyance level for the remaining three sources (coffee grinder, pink noise bursts, and emergency alarm), however the effect size was small (Cohen's d $\approx$ 0.3).

3.2 Effect of Reverberation

The 11-point scale responses for all sources were pooled independently for the reverberant and anechoic conditions and the mean responses and 95% confidence intervals are presented in Fig. 2. On average, the reverberant stimuli were found to cause a higher level of annoyance than

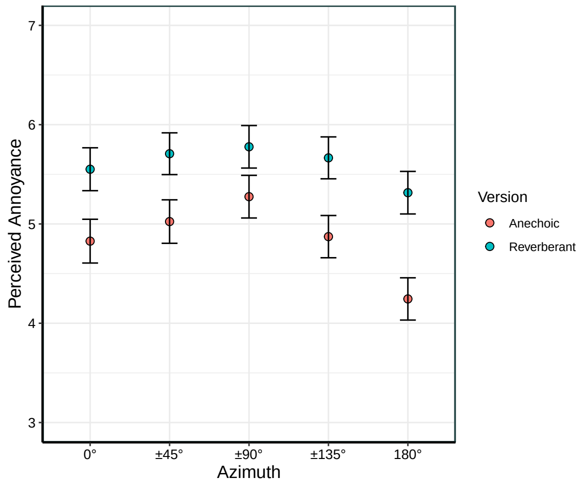

Figure 2. Mean and 95% CI azimuth responses, grouped by room condition.

the anechoic stimuli, for any source azimuth. This is supported by t-test results, which found a significant difference ($p<0.05$) in all five pairs of responses. A variation in mean responses is present for both conditions, however a larger range was identified for the anechoic stimuli, as stated in section 3.1. Significance was found between several pairs of responses for the reverberant environment, although effect sizes were generally very small. For the anechoic conditions, the greatest variation in mean responses was found between the ±90° and 180° stimuli, with a difference of approximately 1 unit of perceived annoyance. This was found to be statistically significant according to t-test results ($p<0.05$), similarly to most other pairs of responses for the anechoic stimuli. Only the comparisons between the 0°, ±45°, and ±135° source azimuths were found to be non-significant.

Fig. 3 presents the pooled 11-point scale responses for all sources for the anechoic and reverberant conditions, demonstrating the effect of reverberation on perceived annoyance for each source. These results again demonstrate an increase in mean annoyance for the reverberant stimuli, for all sources. This annoyance rise was significant ($p<0.05$) for all but one of the sources: the coffee machine. The responses for both the anechoic and reverberant conditions demonstrate a similar trend, with the greatest annoyance level caused by the emergency alarm, and the coffee grinder, coffee machine, and

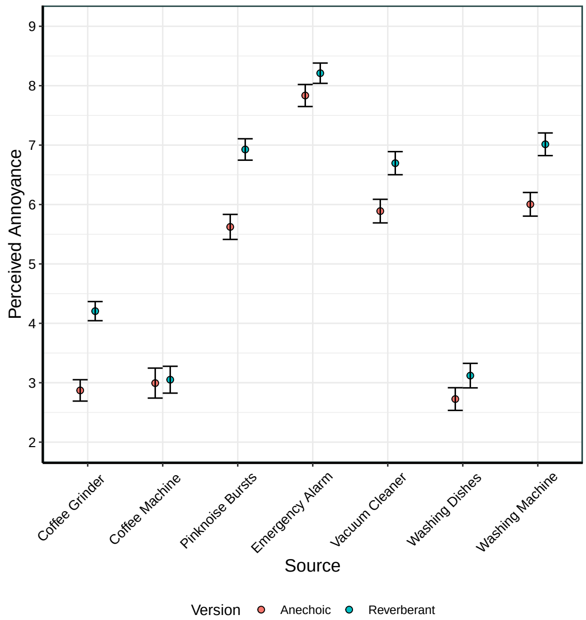

Figure 3. Mean and 95% CI responses by source, grouped by room condition.

washing dishes sources provoking the lowest annoyance response. The difference between responses for the latter three sources was found to be insignificant (*p>0.05*). However, responses for the reverberant coffee grinder source were significantly greater (*p<0.05*) than the remaining two sources.

4. DISCUSSION AND CONCLUSION

The results presented in section 3 suggest that sound source azimuth strongly affects the level of perceived annoyance for a range of commonly experienced indoor domestic sounds. The perceived level of annoyance was found to be greatest for sources positioned at an azimuth of ±90°, and lowest at 180°. A higher level of annoyance for lateral sources may be attributed to a larger disparity in SPL between the listener's ears. For some sources at an azimuth of 0°, a higher level of annoyance was reported than for those at 180°. This may be due to an increase in sharpness at this level. It could also be explained by listeners exhibiting higher sensitivity at the 4000Hz range for frontal sources compared to sources at 90° and 135°, as found by Dickinson and Lee [24]. It is important to consider the contextual characteristics of annoyance. For example, the addition of a visual cue may affect the variation in annoyance between frontal and rear sources. Annoyance caused by frontal sources may be reduced when the source is visible, as the listener will be aware of the cause of their annoyance, however introducing head rotation may counteract this effect. The responses for the anechoic stimuli demonstrated that the directional effect was diminished for sources that incited lower average annoyance responses. This correlates with source SPL. A smaller interaural level difference of the lateral stimuli, for the quieter, less annoying sources, may also contribute to this finding.

In comparison to the anechoic stimuli, the variation in mean responses for the reverberant stimuli was significantly reduced, and mean annoyance responses were greater. The kitchen environment's more diffuse sound field may provide some explanation for both findings, as it causes the sound to be more evenly distributed between the ears and increases envelopment rather than the source originating from a single, distinct direction.

The effect of reverberation could also be seen for individual sources, as presented in Fig. 3. Broadband noise-based sources demonstrated a greater increase in mean annoyance level for the reverberant stimuli, when compared to anechoic. The coffee machine, washing dishes and emergency alarm sources, which displayed more impulsive, transient, and tonal characteristics, were the least affected by reverberation, exhibiting negligible difference in annoyance responses. Noise-based sources in the reverberant environment may cause higher levels of annoyance due to greater room excitation, as a wider frequency range is reflected. Additionally, the continuous nature of three of these four sources provided no respite for the listener, unlike the remaining more intermittent impulsive sources. Some sources, like the coffee machine, may have caused low annoyance responses due to the listeners' familiarity with the source, making them more comfortable with the sound. For example, the sound of a coffee machine is a common household sound and is typically associated with the preparation of a hot beverage. A similar but opposite effect may be present for the emergency alarm source, as the purpose of alarms is to be aurally unpleasant, in order to alert individuals to potential dangers.

The results of the listening test have highlighted the significant effect of source azimuth on the level of annoyance caused by a range of domestic sound sources. The effect of reverberation has also been explored, revealing a significant increase in annoyance responses for sounds presented in a reverberant environment, compared to anechoic versions of same sounds. Lower variability of mean annoyance responses was also exhibited by the reverberant stimuli, for all tested sound sources. These findings present novel insights into the spatial characteristics of noise annoyance and offer a range of potential applications. The observed effects, in addition to planned further investigation, could be employed in indoor urban environmental design, particularly in room acoustics optimisation for annoyance reduction. Additionally, these findings will be instrumental in developing an improved PA model that integrates spatial characteristics. Some limitations should be acknowledged, however. For instance, as the listening test was conducted in controlled laboratory conditions, the results may not fully translate to real-world environments. Although, the fundamental influence of source azimuth has been established, and real-world applicability will be further explored through future experimentation. Future research could expand on these findings by investigating the effect of reverberation across a range of indoor environments. Also, the influence of visual cues and task completion on the spatial characteristics of annoyance perception will be examined to provide a more comprehensive and ecologically valid understanding of the effect.

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