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Study on human response to the cumulative impact of air source heat pump noise

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Abstract

Within the International Energy Agency (IEA) Technology Collaboration Programme Heat Pumping Technologies (HPT) Annex 63 on “Placement Impact on Heat Pump Acoustics”, a task group is addressing the psychoacoustics of Air Source Heat Pumps (ASHPs). A joint listening experiment was conducted across seven European countries and ten organisations to evaluate the cumulative impact of multiple ASHPs in residential back gardens. This study investigates noise annoyance responses to a sample of sounds of ASHPs in scenarios with varying numbers of operating units, and under varying operating conditions, considering three different noise barrier types and two background noise sound pressure levels. The experiment comprised three parts: (1) assessment of a single ASHP in various operating states, combined with two background noise levels and all three noise barrier types; (2) analysis of paired ASHPs with varying distances, operating state combinations, and inter-unit noise barrier types; and (3) evaluation of configurations with three to six ASHP units, simulating realistic residential layouts. In each part, participants provided annoyance ratings using a standardised scale. The study aims to identify how factors such as the number of operating units, their spatial arrangement, operating conditions, and the presence of noise barriers influence noise annoyance. The results provide valuable insights for the development of psychoacoustic models for estimating ASHP noise annoyance, and for the acoustic planning and design of heat pump installations in high-density urban areas.

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Keywords: heat pump noise; psychoacoustics; noise annoyance; listening experiment; acoustics; multiple heat pumps;

1. Introduction

The International Energy Agency (IEA) Technology Collaboration Programme on Heat Pumping Technologies (HPT) Annex 63 addresses the “Placement Impact on Heat Pump Acoustics” [1]. One of its task groups focuses explicitly on the psychoacoustics of Air Source Heat Pumps (ASHPs). The previous project,

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IEA HPT Annex 51 on “Acoustic Signatures of Heat Pumps” [2], examined how reducing acoustic emissions is a crucial factor to increase the acceptance of heat pumps and to minimise noise annoyance.

Prior to IEA HPT Annex 51, Kasess et al. [3] conducted a laboratory study to investigate perceptual ratings of air-to-water heat pump emissions under different mitigation measures and emission directions. Recordings were done in a climate chamber. Their results showed that annoyance was strongly direction dependent and could be better explained by additional psychoacoustic descriptors rather than by using the A-weighted sound pressure level alone. These findings provided important groundwork that was later extended within Annex 51 Part 12 [4], where additional listening experiments were carried out in Austria and Sweden to evaluate the annoyance caused by ASHP sounds under different operating conditions. To investigate the importance of psychoacoustic parameters such as loudness, sharpness, roughness, and tonality, the A-weighted sound pressure level of the sound samples was equalised to 40 dB(A). The analysis revealed significant effects of position and operating condition, showing that the low-compressor speed condition was judged the most annoying. Further results indicated that no single variable explained the annoyance ratings, but a combination of descriptors, including loudness level, sharpness, roughness, and tonality, offered a much better explanation. This led to the proposal of an annoyance index to relate psychoacoustic parameters to the assessed annoyance response.

In a recent long-term case study in Germany [5], the acoustic impact of ASHPs was evaluated under real residential conditions. The results showed that the perceived noise strongly depends on the surroundings and the background noise, and that the probability of exceeding permissible nighttime immissions increased particularly when units were installed in back gardens at very short distances to neighbouring windows. Comparisons of laboratory and field measurements have shown qualitatively similar radiation characteristics of ASHPs, although quantitative differences arise from device size and installation conditions [6]. Recent advances in diagnostic measurements, such as scanning intensity methods, allow the localisation of dominant sources, like fans and compressors, and provide detailed directivity data. This offers higher-fidelity insights beyond overall sound power and supports improved propagation modelling [7]. Simulations of sound propagation in residential environments were validated with measurement data and proved to be a useful tool for predicting neighbourhood noise [6].

Beyond physical measurements, psychoacoustic evaluations have provided further understanding of how ASHP sounds are perceived, complementing the findings of [3] and [4]. A listening experiment has shown that loudness and preference judgments of ASHP sounds can diverge, with preference penalties not being explained by loudness alone [8]. Psychoacoustic parameters as descriptors were found to be critical for explaining subjective perception, pointing towards the need for multi-parameter models of perception. In line with this, recent experiments have focused on human responses under more complex listening contexts. In a study by Acun et al. [9], participants listened to steady-state and transient ASHP noise under different background noise levels and source distances. It revealed that annoyance is not determined solely by the heat pump itself but also by its interaction with the acoustic environment. This emphasises the importance of situating psychoacoustic evaluation within realistic usage scenarios. Building on this, machine learning approaches have been applied to predict annoyance caused by ASHP noise [10]. Gradient Boosting models outperformed linear methods, revealing that emotional responses such as arousal and valence are dominant predictors, while psychoacoustic parameters showed only indirect influence. This underlines the necessity of considering also non-acoustic factors when evaluating ASHP noise impacts.

The aforementioned studies highlight that heat pump noise perception arises not only from technical characteristics but also from environmental context and psychoacoustic factors. In contrast to these previous investigations, which primarily examined the perception and evaluation of a single heat pump, the present work addresses the cumulative acoustic impact of multiple units operating simultaneously.

Complex listening contexts are investigated in which a background noise is also introduced to reflect realistic residential conditions. To extend this realism, the surrounding structures of a neighbourhood are simulated through auralisation, including different types of noise barriers embedded. This approach allows listeners to assess annoyance within a controlled yet authentic simulation of real-life acoustic situations. In addition, questionnaires were included in the experiment to gather information on participants’ living situations and individual noise sensitivity, to relate these factors to the annoyance ratings.

The experiment was conducted across seven European countries at ten sites, with a total of 273 participants. It was carried out in the respective national languages: English, French, Swedish, Dutch, Italian, and German. The ten participating organisations were (alphabetical order):

- Acoustics Research Institute, Austrian Academy of Sciences, *AUT*
- CETIM, Multi-Physics Engineering, *FRA*

- Department of Architecture and Industrial Design, Università degli Studi della Campania "Luigi Vanvitelli", *ITA*
- Fraunhofer Institute for Building Physics IBP, *DEU*
- HEAD acoustics GmbH, *DEU*
- Institute for Hearing Technology and Acoustics, RWTH Aachen University, *DEU*
- Peutz bv, Department of Installation Acoustics, *NLD*
- Politecnico di Milano, Department of Energy, *ITA*
- RISE Research Institutes of Sweden, *SWE*
- Salford Acoustics Innovation Institute, University of Salford, *GBR*

2. Methods

2.1. Acoustic Environment

For a more realistic sound environment in the listening experiment, the ASHP stimuli were rendered into an acoustic scene using auralisation. Auralisation refers to the process of simulating how sounds are perceived within a given environment, including effects such as reflections and transmissions by surrounding structures. Before the auralisation process began, an acoustic environment was created for the simulation. The simulated acoustic environment was inspired by the layout of English terraced houses, where adjacent homes share walls, and the gardens of two rows face each other. Each building had a height of 7.4 m. Two rows of three terraced houses were included in the simulation. Each garden measured 5.0 m × 4.4 m, including a 2.0 m × 4.4 m patio. A top view of the simulated acoustic environment is shown in Figure 1. The receiver position (red dot) was located 1.7 m above ground. During the listening experiment, both the number of operating ASHPs and their positions varied, with potential positions indicated as A to K in the figure (marked in yellow). The grey lines denote the placement of noise barriers. Three types of noise barriers were considered between the gardens: a wire fence (acoustically transparent, treated as no noise barrier), a wooden fence (similar to a thin visual protection), and a brick wall. Additional materials used in the acoustic simulation include grass for the lawn areas, bricks for the house walls, and concrete for the patios and roofs.

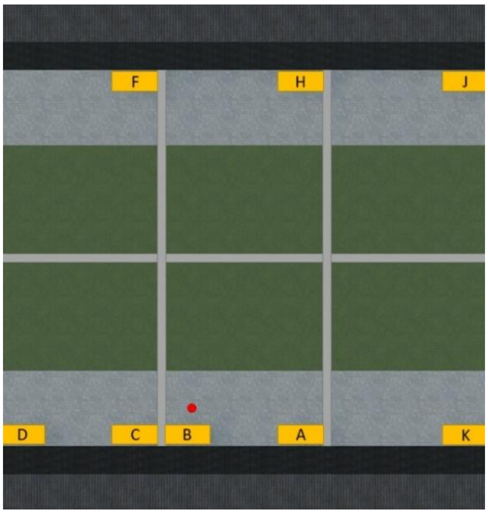

Figure 1. Top view of the simulated acoustic environment. The receiver position is marked in red. Heat pumps positions marked in yellow and labelled A through K.

2.2. Stimuli processing and playback

The stimuli for the listening experiment are recordings of the outdoor unit of a Mitsubishi Electric PUZ-WM112YAA heat pump. This heat pump was selected as a typical heating unit for an existing single-family house available on the open market in the year 2022. It was installed in the hemi-anechoic chamber at the Institute for Hearing Technology and Acoustics, RWTH Aachen University, Aachen, Germany. A low-noise measurement microphone was positioned 3 m from the centre of the heat pump, 30° off-axis relative to the front and recorded the heat pump at various operating states. The directivity of the heat pump was also recorded and used for the auralisation. Details about the measurement procedures and the directivity measurement can be found in the technical report and database by Stürenburg et al. [11]. Twelve recordings were selected from this database for the listening experiment. Additional variants were generated by shifting the stimuli, as six stimuli were required for each operating condition in part three of the listening experiment. All recordings had a duration of 10 s, with a 5 ms fade-in and fade-out applied using a Hann window.

For the auralisation, the impulse responses of each source-receiver combination and each noise barrier type need to be convolved with the recordings. Therefore, the generation of the impulse responses involved the following steps: (1) determining the geometric acoustic propagation paths based on the image edge model [12] using the PIGEON software [13], (2) calculating the impulse responses based on these propagation paths, and (3) incorporating the transmission loss into the impulse responses to consider the transmission caused by the noise barriers.

The background noise used in the listening experiment was recorded during a field measurement campaign in a suburban area in the city of Zoetermeer, The Netherlands. The measurements were taken in a residential area. The microphone was positioned on a street between two rows of terraced houses. The distance to major public main roads was about 200 m. The level of the background noise was adjusted to 39 and 45 dB(A) before it was added to the auralised, binaural heat pump sounds to create the final stimuli for the experiment.

For the binaural synthesis of the signals, Head-Related Transfer Functions (HRTFs) of the HEAD acoustics HMS II.3 artificial head measurement system were used. This approach ensures aurally correct playback when using a compatible HEAD acoustics playback setup. For this purpose, all participating institutions were equipped with the mobile HEAD acoustics BPU Bundle playback system, including Sennheiser HD 650 headphones. The BPU (binaural USB Playback Unit) automatically applies corresponding headphone equalisation to ensure accurate binaural reproduction.

The stimuli were equalised using ID equalisation (Independent of Direction) [14]. This equalisation was applied for analysis purposes to compensate for the influence of the artificial head. It enables correct interpretation of the recorded data, as many evaluation procedures, including psychoacoustic standards, require measurements unaffected by the artificial head. Free-Field (FF) equalisation was not suitable because the stimuli included sound incidence from several directions and were not measured under true free-field conditions. Diffuse-Field (DF) equalisation was also inappropriate, as the simulated scenario did not represent a diffuse sound field. Under these conditions, ID equalisation has proven to be the most reasonable choice, since it compensates only for the direction-independent resonances of the artificial head, ensuring that the stimuli remain unbiased with respect to sound incidence. Although the equalisation was included in the signal-processing chain, it did not affect the auditory characteristics of the playback.

2.3. Listening Experiment Parts

In the listening experiment, participants rated the annoyance of the ASHP sounds using a 0-to-10 opinion scale, based on [15]. The question in English was "How much does the noise from the heat pump bother, disturb or annoy you?". Participants first listened to the recording before responding and could listen to it again one more time. Once they had responded, they moved on to the next recording. The listening experiment comprised three parts.

In the first part, one ASHP was operating at position A, cf. Figure 1. The recordings varied in the operating state of the ASHP and in the level of background noise presented simultaneously with the ASHP sound. Additionally, the influence of the noise barrier type was tested, using either a wire fence or a wooden fence. While the fences do not serve as conventional noise barriers in this scene, since they are not located between the source and the receiver, they are nevertheless referred to as noise barriers throughout this work. In total, this part included 24 recordings that were rated by the participants.

The second part of the experiment involved two ASHPs operating simultaneously. But their positions varied during the recordings and could be either A and D, A and C, or B and C, resulting in different distances between the ASHPs. Additionally, various operating states and all three noise barrier types were tested. This led to 26 recordings, all of which included background noise at a fixed level.

In the third part, the acoustic scenes were more complex with multiple ASHPs operating simultaneously. In six varied settings, the ASHPs at positions A, C, F, H, J, and K were operating. In one setting, all six units were running, while in the others, both the number and the combinations of positions differed. Furthermore, different operating states of the ASHPs were tested, while the background noise level and the type of noise barrier remained constant throughout the 18 recordings in this part.

In Figure 2, the user interface of the listening experiment is shown. Playback was conducted using the HEAD acoustics jury-testing software SQala. The use of HEAD acoustics equipment for binaural rendering, playback software, and playback hardware ensured a calibrated and aurally correct reproduction of the stimuli, minimising potential inter-institutional differences in playback conditions (e.g., due to individual calibration procedures).

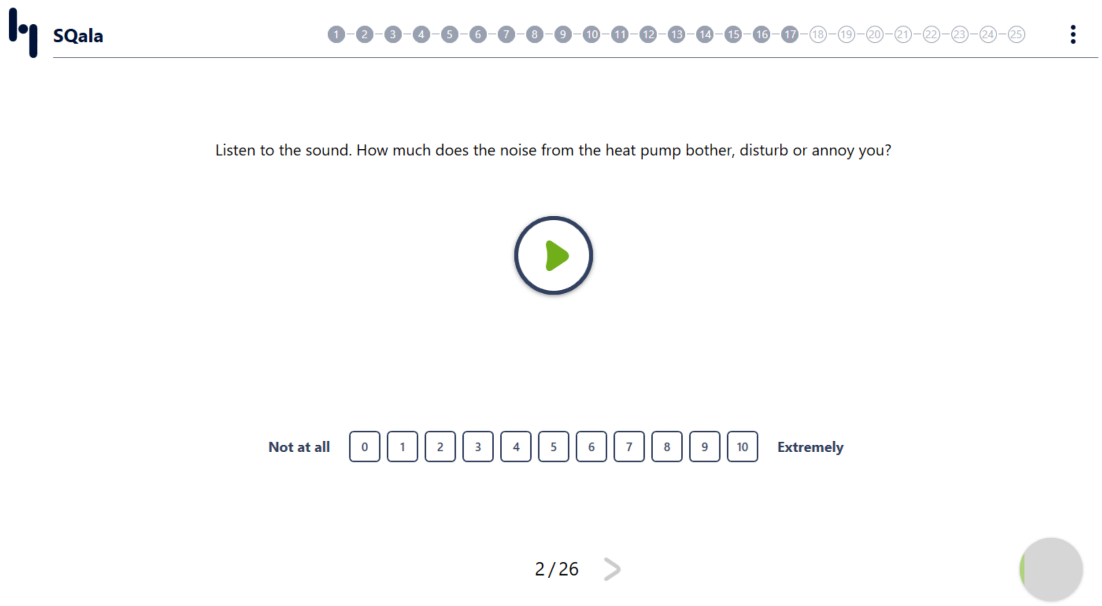

Figure 2. User interface of the experiment using the HEAD acoustics jury-testing software SQala. Participants are asked to rate the ASHP sound on a scale of 0 to 10.

2.4. Questionnaires

In addition to the listening experiment consisting of three parts, the experiment comprised several questionnaires. Aside from questions about participants' personal information, such as nationality, gender, and age, they were asked about their living situation and whether they owned a heat pump. Further questions covered their hearing abilities, musical or audio expertise, as well as their environmental noise or urban planning expertise. Participants were also asked to complete a noise concerns questionnaire, adapted from [16], and the NoiSeQ (Noise Sensitivity Questionnaire) [17].

As an addition to the experiment, at the end of each listening experiment part, the participants were asked to select up to five adjectives from a list to describe their overall impression of the sound environments they had experienced.

3. Preliminary Results

While the experiment has been completed and all required data have been collected, the analysis is still ongoing, and detailed results will be reported once the evaluation process is concluded. This work presents preliminary results for Part 1 of the listening experiment.

In the first part of the experiment, an ASHP was operated at position A, cf. Figure 1. The heat pump in operation was therefore located near the receiver (red dot in Figure 1) and in the same enclosed garden. The recordings varied in the ASHP's operating status and in background noise level, which occurred simultaneously with the ASHP noise. Additionally, the influence of the type of noise barrier was tested, either a wire fence or a wooden fence was used. For the analysis, only data from participants who did not meet the exclusion criteria were included, resulting in a total of $N = 242$ participants.

Table 1 summarises the A-weighted sound pressure levels of the stimuli used, separated by two background noise levels (39 and 45 dB(A)) and two noise barriers (wire fence and wooden fence). Importantly, the overall levels at the ears vary only slightly even though the background noise level differs between the two blocks: for each stimulus, the ear-level SPL remains essentially stable (e.g., around 56-57 dB(A) for Medium Capacity, 66-67 dB(A) for Maximum Capacity, and 45-46 dB(A) for Minimum Capacity). In addition, reporting left- and right-ear values reveals only small interaural differences of up to 2 dB, which can be expected due to the positioning of the ASHP and the receiver in the simulated acoustic environment.

Table 1: A-weighted sound pressure level of the stimuli used in Part 1 of the listening experiment. Two stimuli had the same capacity. Two different background noise levels (39 and 45 dB(A)) and two different noise barriers (wire fence and wooden fence) were used. The overall levels are shown for the left and right ears.

Stimulus no.	**Capacity**	**Background noise level**	**Wire fence**		**Wooden fence**	
			Left Ear	Right Ear	Left Ear	Right Ear
		dB(A)	dB(A)	dB(A)	dB(A)	dB(A)
1	Medium	39	56	57	57	56
6	Medium	39	57	57	57	56
24	Maximum	39	66	67	67	65
25	Maximum	39	66	66	67	66
27	Minimum	39	46	45	46	46
28	Minimum	39	46	45	45	45
1	Medium	45	56	57	57	56
6	Medium	45	57	57	57	56
24	Maximum	45	66	67	67	65
25	Maximum	45	66	66	67	66
27	Minimum	45	46	45	46	46
28	Minimum	45	46	45	45	45

Figure 3 shows baseline-corrected annoyance ratings for two noise barrier conditions (wire fence and wooden fence). Annoyance ratings are expressed relative to a background noise-only control condition, thereby isolating the effect of adding ASHP noise to the ambient background.

Each point represents an individual annoyance rating, illustrating the spread of responses across all stimuli and participants. The boxplots summarise the central tendency and variability, with the horizontal line indicating the median and the box representing the interquartile range, while whiskers show the broader spread of the data. The side-oriented histograms show the frequency distribution of baseline-corrected annoyance values. The red dashed horizontal line at zero indicates no change relative to the control condition; values above this line reflect increased annoyance compared to background-only sound, while the values below this indicate reduced annoyance.

As expected, for both barrier types, the distributions are shifted upward relative to the baseline, clearly indicating that the presence of the ASHP increased the annoyance response in both conditions. The wooden fence condition shows a slightly higher central tendency than the wire fence condition, visible from the upward shift in the distribution and median. This could be due to sound reflections off the wooden fence, although the change in the overall sound pressure levels between the two fences is small.

A participant-level Wilcoxon signed-rank test conducted on median baseline corrected annoyance values for each participant demonstrated that the difference between the two barrier conditions is statistically significant ($p < 0.001$, shown at the top bracket). Despite substantial overlap between the distributions, there is a small but systematic effect of noise barrier type on perceived annoyance, where the wooden fence elicits higher annoyance. Since these stimuli consisted of an ASHP operating at a fixed position in the owner's back garden, this difference is likely caused by the reflections from the wooden surface. This suggests that, in addition to the sound levels, reflections may alter the perceived acoustic character of the ASHP noise, even if the overall level change is minor. More sophisticated statistical analyses will be conducted to expand on this finding.

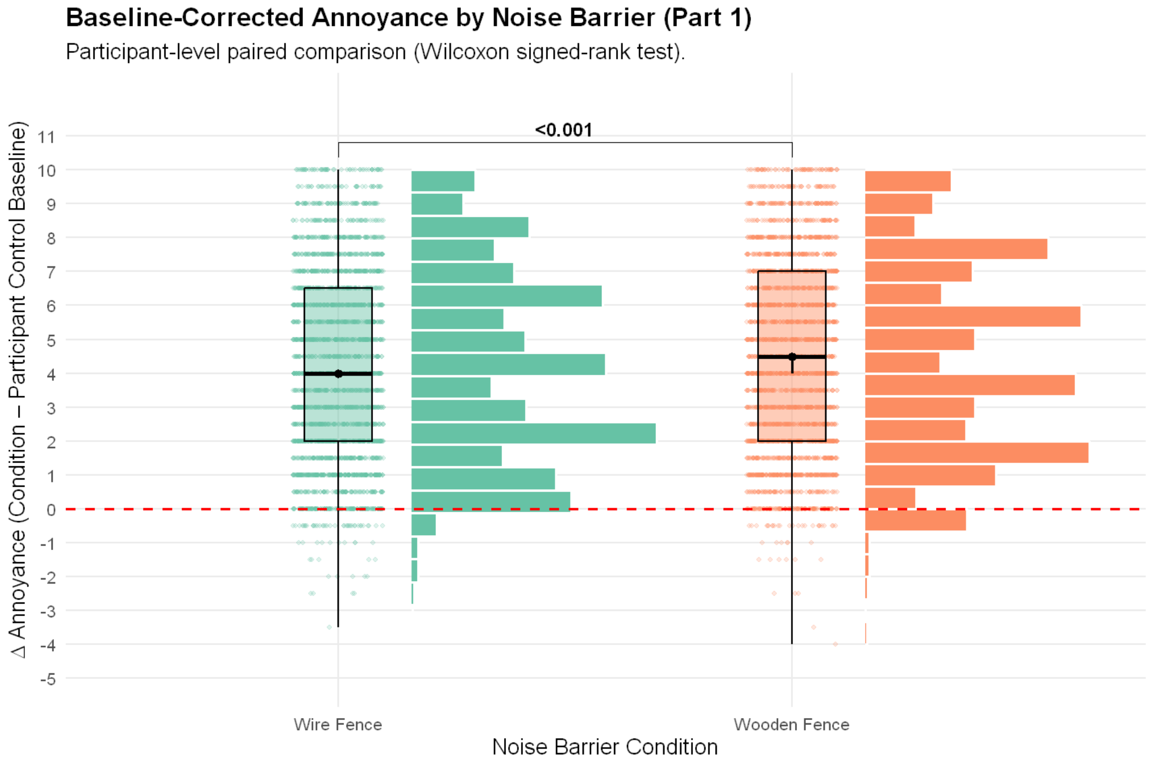

Figure 3. Baseline-corrected annoyance ratings for the wire fence and wooden fence conditions. The red dashed line at zero represents the ambient-only baseline; values above zero indicate increased annoyance due to the ASHP. The bracket indicates a statistically significant difference between conditions ($p < 0.001$, Wilcoxon signed-rank test).

Figure 4 presents the annoyance ratings across three operating conditions and two ambient noise levels (39 dB(A) and 45 dB(A)). As expected, there is a positive trend between operating capacity and annoyance, with higher capacities eliciting significantly higher ratings. At Minimum Capacity, no difference is observed between the two background conditions. For Medium Capacity, while the 45 dB(A) condition exhibits a larger interquartile range, the overlapping notches indicate that the medians are not significantly different. However, at Maximum Capacity, the median annoyance for the 45 dB(A) condition is visibly lower than the 39 dB(A) condition. This suggests a masking effect, where the higher ambient noise level mitigates the perceived annoyance of the ASHP by reducing its prominence relative to the background.

4. Outlook

The analysis examines how factors such as the number of operating units, their spatial arrangement, operating conditions, and the presence of noise barriers affect noise annoyance. Understanding these influences will contribute to the development of psychoacoustic models for estimating ASHP noise annoyance. Overall, these findings will support acoustic planning and design of heat pump installations in high-density urban areas.

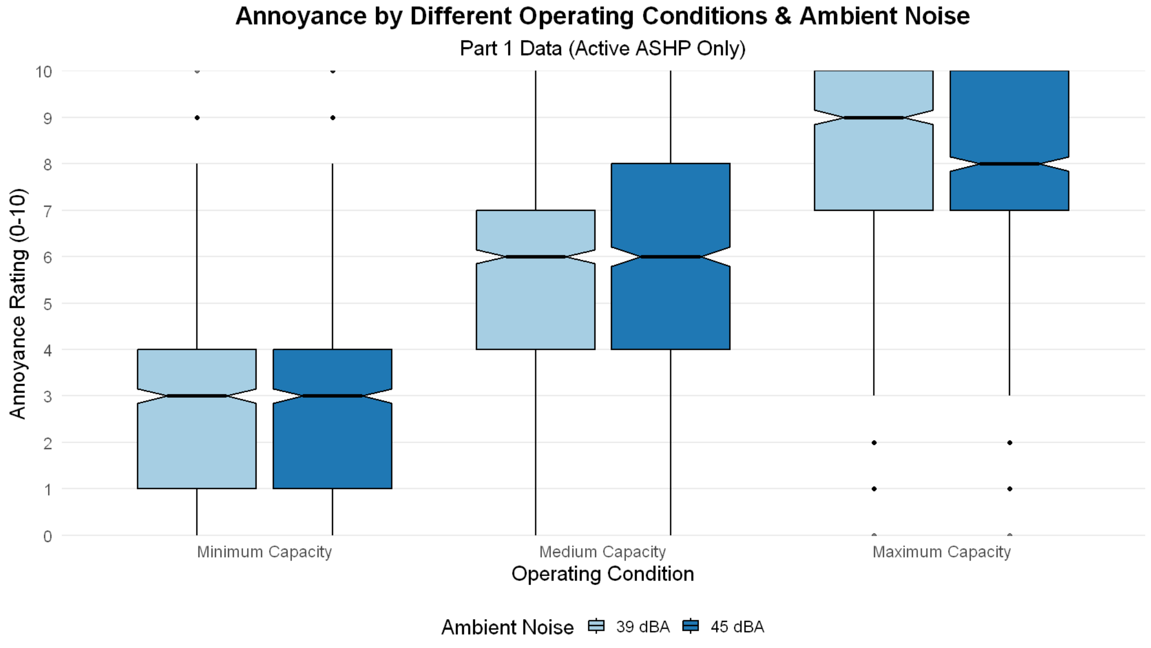

Figure 4. Distribution of annoyance ratings as boxplots for the varying capacity of the operating heat pump and varying background noise level for Part 1 of the listening experiment.

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