DOI: 10.61782/fa.2025.0885

FORUM ACUSTICUM EURONOISE 2025

THE ROLE OF SALIENT SOUNDS IN EVERYDAY INDOOR SOUNDSCAPES

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ABSTRACT[*]

Acoustical salience is the property of certain sounds to capture attention in auditory scenes. In this study, we investigated how the most salient sound in indoor environments contributes to overall soundscapes. We reanalyzed data from a field study in which 105 participants rated the most salient sound and their overall soundscape at home several times per day during their 10-day participation. Assessed attributes of the salient sound included perceived loudness, sound source category (natural, human, technical), frequency, and liking, while overall evaluations measured soundscape pleasantness and eventfulness. Linear mixed-effects models explained 23% of the variance in eventfulness and 42% of pleasantness, underlying the importance of the most salient sound especially for the pleasantness dimension. Results further showed that higher perceived loudness was linked to increased eventfulness and reduced pleasantness, whereas liking emerged as a key predictor of pleasantness. Human and natural sounds—compared to technical sounds—increased the eventfulness, possibly due to the evolutionary higher significance in contrast to modern technical sounds but had little or even no impact on pleasantness. Our findings further support the ecological validity of bottom-up auditory processing over top-down task-driven approaches, highlighting that focusing on attention-grabbing sounds can offer critical insights for managing acoustic environments.

Keywords: *soundscapes, salience, attention, ecological validity.*

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1. INTRODUCTION

In human information processing, visual stimuli commonly dominate acoustics [1-3], leaving the acoustic environment unnoticed most of the time when carrying out daily tasks. The acoustic environment is only consciously perceived when the attentional focus is intentionally directed to the sound (top-town attention focusing) or if the salience of a sound (event) captures human attention (bottom-up). Because the soundscape standard [4] instructs participants to listen deliberately to every audible sound—reporting the intensity of various sound source categories and averaging the overall perceived acoustic quality—this method intentionally directs their attention to acoustic details that would typically remain unnoticed, potentially compromising the ecological validity of the research outcomes.

Consequently, research assessing the most salient sound seems to be more in line with the natural human information processing in contrast to the assessment of entire soundscapes, potentially providing results with increased ecologically validity. In the field of acoustic environment research, the importance of the most salient sound—often the loudest—is further underscored by theory on auditory scene analysis [5]. This theory posits that due to our limited cognitive capacity, listeners are unable to simultaneously focus on multiple auditory streams. Although research on auditory salience using natural urban soundscapes [6-7] and models of auditory salience based on technical and urban sounds [6,8-13] has been increasing—primarily in laboratory settings—studies within people's dwellings remain sparse. This gap motivates our investigation into how the most salient sound contributes to indoor soundscapes in residential environments.

Building on a lab study on sound quality in complex auditory scenes [14]—which showed that ratings of individual environmental sounds can effectively explain the overall pleasantness of a complex acoustical environment—we investigate how the most salient sound in everyday residential indoor soundscapes influences the overall judgment of these environments. Thereby, we expect a high level of agreement between the perceived salience of a singular sound and the overall soundscape judgement.

Other research [15] has demonstrated that sounds from various categories—traffic, nature, commercial—exert distinct effects on soundscape quality, both directly and indirectly (via their influence on soundscape appropriateness). Such findings underscore the importance of assessing the sound source category when studying auditory perception. Furthermore, standards such as ISO 1996-1 [16] support this approach by recommending that penalties be applied to the overall evaluation of environmental noise based on the analyzed sound source category. For example, the measured sound pressure level of aircraft noise is increased by +3 to +6 dB while that of railway noise is attenuated to better match the perceived annoyance caused by that kind of noise.
While the soundscape standard [4] proposes three (or four) major sound categories based on the characteristics and origin of the source (noise (from traffic, construction, and industry), sounds from human beings, natural sounds), others cluster the sounds hierarchically into background and foreground sounds, with the foreground sounds being defined by their function, e.g., being disruptive, calming, or stimulating [17]. However, the functions of the foreground sounds appear to be dependent on the person experiencing this sound and un-consciously constructing their individual "reality" based on the objective conditions and their personality [18]. While such approach appears promising when investigating the psychological effects of sound on individuals, we choose to adapt to the standardized sound categorization which is based on sound source characteristics only. We hypothesize that strong relationships between sound source categories and perceptual soundscape qualities and annoyance, found in recent research [19-20], could also be observed between the sound source category of the most salient sound and the overall rating of the indoor soundscapes in people's dwellings.

Nevertheless, individual's appraisal matters, leading to the same sound being liked by one person and disliked by another (e.g., your favorite music and the sound of motorcycles). Consequently, the more generally applicable factor of liking a sound seems promising for the prediction of peoples' sound evaluation [20-21] independent on the place (while the assessment of the appropriateness of a sound environment for a given place is proposed by the soundscape standard [4], if the place is of interest). Therefore, we hypothesize that the degree of liking the most salient sound will be strongly related to the pleasantness of that sound and will—following the idea of the salient sound that dominates the auditory perception—also be strongly affecting the pleasantness but not the eventfulness of the entire soundscape.

To summarize, we assessed how the most salient sound, its sound source category, and the participant's liking of that sound contribute to the overall perception of indoor soundscapes of everyday situations.

2. METHOD

2.1 Data

To answer our research questions, we re-analyzed a dataset of indoor soundscapes obtained in a study by Versümer et al. [22], in which participants recorded 6594 soundscapes at their homes on an hourly basis using a self-developed binaural low-noise recorder. Participants reported and categorized the most salient sound that occurred during the recording of 15 seconds duration. They also reported on the entire soundscape, including the most salient sound. Since each participant made multiple recordings, we faced hierarchical data, i.e., observations are nested within participants. Also, the number of observations per participant differed (mean: 63; SD: 16; n: [10, 100]), indicating imbalanced data, which, both, calls for hierarchical partial-pooling modeling.

We recruited 105 participants using in-person invitation and mailing lists. Participants aged between 18 and 68 years (mean: 36 years; SD: 14 years), had quite evenly distributed gender (female: 57%), and lived in or around Düsseldorf, Germany. While 29 participants lived alone, the median number of persons living in the dwelling was 2, with the reported maximum number of 5 persons. Their noise sensitivity ranged from 0.42 to 2.83 (scale range: [0, 3]; mean: 1.76; SD: 0.59; NoiSeQ-R [23-24]) and their well-being from 16 to 100 (scale range: [0, 100]; mean: 58.1; SD: 16.7; WHO-5 [26-27]).

Regarding the most salient sound, participants reported on the perceived *Loudness*, the *Frequency* of occurrence of that source ("how often does this sound occur?"; anchors "rarely" and "frequently" framing a continuous scale ranging [0, 100]), their *Liking* of that sound ("How much do you like the most salient sound?"; 7-point Likert scale with labels from "very disliked" to "very liked"), and classified the most salient sound into the three categories *Natural, Human* (including people, speech, music, singing), and

Technical (including household appliances, house installation, signals, traffic). It is worth noting that, while rating the most salient sound, participants had to cognitively eliminate other present sound sources which could be seen as a quite challenging task. However, presenting the most salient sound isolated from other sounds in the everyday situation was not possible.
Regarding the entire soundscape, the participants used the eight soundscape items from which the two targets soundscape *Pleasantness* and *Eventfulness* were calculated.

2.2 Analysis

Linear mixed-effects models (LMM, see Eq. (1)) were employed to account for both fixed and random effects in the data, providing robust handling of nested, i.e., hierarchical data structures.

$$y = X\beta + Zu + \varepsilon \quad (1)$$

y: observed values
β: fixed effects coefficients
u: random effects coefficients
ε: random error
X: design matrix of fixed effects
Z: design matrix of random effects

LMM were fitted using the *lme4* package (v1.1-35.5) [28] in R (v.4.1) [29], enabling the modeling of *Eventfulness* and *Pleasantness* judgments of indoor soundscapes based on the sound- and perception-related predictors of ratings of the most salient sound, the fixed-effects, while the participant's *ID* was used as the categorical random-effect (see Table 1). The final fit was based on the restricted maximum likelihood estimation (REML). QQ plots allowed the visual inspection of the residuals of the LMM, i.e., the assessment of their conformity to a normal distribution.
To estimate and compare the performance of the models, we used the marginal R^2 value based on the *performance* package (v0.12.4) [30] for R. The R^2 values allow the estimation of the explained variance of the target variable due to fixed effects only.
The three sound source categories were one-hot encoded with the most frequent category (technical sounds) being dropped, while the remaining two categories were implemented as dummy variables. Finally, all variables (including the dummies) were standardized (mean: 0; SD: 1) to enable the comparison of the estimates as a measure of effect size.
Table 1 displays the two models fitted in this study. They predict *Eventfulness* and *Pleasantness* of the soundscape, respectively, based on all predictors representing the judgments of the most salient sound and the participant *ID* for the consideration of random intercepts.

Table 1. Target variable, fixed effects (FE) and random effects (RE) for the LMM fitted in this study.

Target	Predictors
Soundscape *Eventfulness*	FE: *Loudness, Frequency, Liking, Human, Natural* RE: *ID*
Soundscape *Pleasantness*	FE: *Loudness, Frequency, Liking, Human, Natural* RE: *ID*

3. RESULTS

Regarding the *Eventfulness* model (see Table 2), we achieved a variance explanation of 23% based on all predictors. The perceived *Loudness* judgements of the most salient sound had the strongest effect (β = 0.38), followed by *Human* (β = 0.26), and *Natural* sounds (β = 0.12), whereas *Liking* (β = 0.04) and *Frequency* (β = -0.05) showed smaller contributions. Unexpectedly, a higher *Frequency* of occurrence slightly decreased *Eventfulness*.

Table 2. LMM predicting soundscape *Eventfulness* based on participant's judgments of the most salient sound.

Predictors	β	p
Loudness	0.38	**<0.001**
Frequency	-0.05	**<0.001**
Liking	0.04	**<0.001**
Human	0.26	**<0.001**
Natural	0.12	**<0.001**
Random Effects		
σ2	0.62	
τ00 ID	0.18	
ICC	0.22	
Marg. R^2 / Cond. R^2	0.225 / 0.394	
max(VIF)	1.36	

The *Pleasantness* model (see Table 3) accounted for a notably higher proportion of explained variance (42%), although the *Frequency* of occurrence and *Natural* sounds did not reach significance. Increased *Liking* of the salient sound increased *Pleasantness* the most (β = 0.57), as did quieter sounds ($\beta_{Loudness}$ = -0.15). When the most salient sound was produced by humans rather than technical devices, soundscape *Pleasantness* increased slightly (β = 0.09).

Table 3. LMM predicting soundscape *Pleasantness* based on participant's judgments of the most salient sound.

Predictors	β	p
Loudness	-0.15	**<0.001**
Frequency	0.01	0.544
Liking	0.57	**<0.001**
Human	0.09	**<0.001**
Natural	0.00	0.612
Random Effects		
σ2	0.41	
τ00 ID	0.14	
ICC	0.25	
Marg. R^2 / Cond. R^2	0.421 / 0.566	
max(VIF)	1.36	

The variance inflation factor analysis showed that multi-collinearity was not an issue for either model, with a maximum VIF of 1.36 for both.

4. DISCUSSION

This study investigated the effect of the most salient sound on judgments of the overall soundscape. Results of our analysis revealed that the statistical models based on predictors regarding the most salient sound explained 42% of the pleasantness and 23% of eventfulness of the soundscape.
These findings confirm our assumptions that the most salient sound strongly affects the entire soundscape only for the pleasantness dimension, possibly because emotion-driven judgements like pleasantness and the liking for a sound are strongly tied, while eventfulness could be analyzed more objectively and less dependently on individual emotional judgements.
While results of both models indicate a notable importance of the most salient sound for overall soundscape evaluation, there is, however, still a large proportion of unexplained variance left which might be attributed to factors not assessed in this analysis. For example, it is a widely recognized fact in soundscape research that contextual variables, such as the visibility of the sound source, the perceived control over the acoustic situation, and the activity at hand play a crucial role in sound perception [4,20,31-32]. Further, personal factors, such as age, emotional stability, noise sensitivity, and a persons' mood, were repeatedly found to affect soundscapes [32-34] although the size of those effects are usual rather small.

The analysis corroborates previous findings on the evaluation of sound quality of combined sounds in the lab, where the rating of a single environmental sound could well explain the overall pleasantness of a complex acoustical environment [14]. Here, our results underline the importance of the most salient sound in soundscape research in everyday context, which, in contrast, usually highlights the importance of a holistic approach and the consideration of any audible sound.
Our findings further support the approach of noise abatement that focuses on a specific noise source only (assuming that this noise source is salient). They emphasize the need for the successful selection and separation of the most salient sound of a soundscape recording for enabling effective salience models (e.g., as reported in [10-11,13]) for the use in soundscape research. Focusing on the evaluation of the most salient sound could lead to more ecologically valid judgments, as the task of reporting the soundscape involves the conscious direction of participant's focus also on small and less dominant details of the sonic environment that might have remained un-noticed if the participant's attention had been drawn "bottom-up" by the most salient sound.

The importance of the most salient sound in the assessment of temporally varying soundscapes could also indicate a reason for the usually small predictive performance of soundscape models based on acoustic measures only [20], because, firstly, it is unclear on which sound source(s) participant's soundscape rating is based while the recording contains all sounds, and, secondly, the typical use of statistical single-values of acoustic measures average across all sounds in the recording while the peak-end-rule [35] and research on the evaluation of combined sounds [36] oppose such use of single-value measures.

Our results showed a relation of perceived loudness of the most salient sound with eventfulness of soundscapes, indicating that louder salient sounds enable higher dynamic, i.e., higher temporal variability, in contrast to quiet sounds or silence. While the physical level of the acoustic environment predicts neither pleasantness nor eventfulness of indoor soundscapes assessed in the field [20], the perceived loudness of the most salient sound did reduce soundscape pleasantness. This finding thus underlines the ties between the single perceptual measures and the limited contribution of physical measures in predicting sound evaluations in a day-to-day context [20,32].

Despite the aforementioned findings on the effect of perceived loudness of the most salient sound on pleasantness of soundscapes, pleasantness is more defined by "subjective" perceptual measures, e.g., the liking of the most salient sound or the perceived control over the acoustic situation [20], which was corroborated in our analysis since liking showed the strongest effect on pleasantness. The results indicate again the limited potential of models based on only acoustic measures for the prediction of pleasantness of (indoor) soundscapes. By contrast, eventfulness of soundscapes repeatedly seem to be evaluated more "objectively", as it is less driven by perceptual measures, see also [20].

Regarding the role of the sound source, natural and human sounds were observed to significantly increase eventfulness. In contrast to technical sounds, from an evolutionary perspective, this finding may be explained by the fact that these sounds have played a crucial role in shaping human responses, whereas technical sounds of the modern world—despite being unavoidable—are often perceived as unnecessary noise.

In our study, however, the sound source category of the most salient sound showed no significant effect (for natural sound) or only small significant effects (for human sound) on soundscape pleasantness. This finding thus contradicts results observed in previous studies, where a strong influence of sound source categories on annoyance of quiet sounds was shown [19] and where models predicting soundscape dimensions based on the sound level of different sound categories were established [20]. Therefore, it remains unclear why the sound category of the most salient sound did not show a larger effect on soundscape pleasantness in our analysis.

Furthermore, contrary to our expectations, we observed that a more frequent occurrence of the most salient sound led to less eventful soundscapes. This finding might be explained by the fact that, when a sound occurs infrequently, it is experienced as rather novel (and potentially salient) event, whereas a sound that is heard repeatedly becomes familiar, expected, and, thus, less eventful.

In conclusion, our study suggests that basing soundscape assessments on judgments of the most salient sound—especially when evaluating its pleasantness—might provide a more ecologically valid perspective than the traditional, "top-down"-oriented soundscape assessments. This assumption is motivated by the notion that attention in everyday acoustic environments is naturally captured in a bottom-up manner by the most salient sound, and the associations we observed regarding both eventfulness and pleasantness suggest that this method better reflects genuine auditory experiences, while top-down approaches may prompt listeners to focus on specific sound events that might otherwise remain unnoticed. However, a substantial amount of variance still unexplained in the present analysis could potentially be explained in parts by situational and personal differences that have not yet been identified as relevant. We, however, argue that everyday noise management can be improved by focusing on the most attention-grabbing sounds. Following that argument, city planners and building designers might enhance everyday soundscapes by regulating these key sound sources, creating more pleasant and livable environments.

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