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AIRBORNE SOUND INSULATION AND NOISE ANNOYANCE: IMPLICATIONS OF LISTENING TEST METHODOLOGY

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ABSTRACT

Listening tests provide a framework for evaluating the subjective perception of sound in a controlled laboratory environment. In the literature, a number of publications can be found that use this method to study a variety of acoustic aspects, including the impact of sound insulation on indoor noise annoyance. Several publications deal with the validation/rejection of so-called single number quantities, and based on this, derive guidelines on the performance rating of construction elements. Nevertheless, there is no consensus regarding this topic in the scientific community. The outcome of these studies is greatly dependent on the sound stimuli used, which in this context are sound events filtered through the attenuation spectra of the walls. Therefore, to achieve relevant guidelines based on subjective evaluation, the stimuli must realistically reflect the range of noise exposure in buildings, and the SNQs must cover all aspects of annoyance. This work presents an overview of the methodology and sound stimuli used in the studies aimed at the impact of sound insulation on noise annoyance. Based on this overview, recommendations for future research are put forward to better incorporate all aspects of noise annoyance.

Keywords: *Listening Test, Sound Insulation, Stimuli, Subjective Assessment*

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1. THE CONCEPT OF ANNOYANCE: MEANING & RELEVANCE

The WHO Environmental Noise Guidelines for the European Region evaluated the impact of environmental noise exposure on the population in the European region [1]. In separate systematic reviews, it evaluated Exposure-Response-Relationships for cardiovascular and metabolic effects, annoyance, sleep, cognitive impairment, hearing impairment and tinnitus, adverse birth outcomes and quality of life and mental health and well-being. Furthermore, it also reviewed the evidence of the effectiveness of environmental noise interventions in reducing exposure and associated impacts on health [1]. Based on reviews of the available literature related to noise sources and exposure outcomes, annoyance was selected as the priority adverse health outcome for the recommendations regarding average exposure (L_{den}). It is recommended for road traffic, railway, aircraft and wind turbine noise that the average noise exposure does not exceed 53 dB, 54 dB, 45 dB and 45 dB L_{den}, respectively. In addition, also recommendations for leisure noise and night exposure were formulated, for these however, other health outcomes were prioritized.

In an earlier report by the WHO from 2011, the burden of some of these components was quantified in Disability Adjusted Life Years lost (DALYs), and among the studied components, sleep disturbance and annoyance related to road traffic noise made up most of the adverse outcomes of noise exposure [2]. It is estimated that 587.000 DALYs are lost yearly in the European region alone due to annoyance.

The Environmental Noise Directive (END) is the main law aimed at mapping noise pollution levels in the European Union [3]. The END only provides a framework for assessing noise exposure, but does not set limit values, nor is it aimed at assessing the outcomes of exposure, such as annoyance. However, the data collected under the END is interpreted according to the recommendations by the European Environmental Agency in the 'Environmental noise in Europe' report, and here it was estimated that 22 million people suffer from chronic annoyance [4].

As people spend most of their time indoors, sound insulation of buildings greatly affects their noise exposure. Therefore, to address the adverse impacts of environmental noise, adequate sound insulation is crucial. Currently, a variety of Single Number Quantifiers (SNQs) such as R_w, R_w+C, R_w+C_{tr}, R_w', $D_{nT,w}$, STC … are used to describe the sound insulating performance. However, the existing SNQs focus on reducing the overall indoor sound levels, rather than annoyance as the primary concern. Several researchers have tried to fill this void, this article reviews these efforts regarding the influence of sound insulation on the annoyance due to noise. First, this article discusses the framework of annoyance. Next, this article highlights the gaps in the current literature, and proposes methodological improvements so that the topic can be studied more holistically in the future.

While the WHO and END present annoyance as a significant burden on society, they focus little on the concept of annoyance itself. In the WHO report, noise annoyance is defined as 'a feeling of displeasure, nuisance, disturbance or irritation caused by a specific sound' [1]. However, a more detailed outline and knowledge of the underlying mechanisms are crucial in selecting the appropriate descriptors and subsequently systematically tackling the problem through sound insulation. For this reason, researchers have attempted to form a theoretical framework around the concept. In the broader context of environmental annoyance, thus not limited to noise, P. Lercher highlighted that annoyance is described as 'a feeling of displeasure associated with any agent or condition believed to affect adversely an individual or a group' [5]. Therefore, it follows a clear pathway: exposure → adverse effect → negative emotion = annoyance.
Regarding noise annoyance specifically, where noise is the agent, P. J. Stallen, considers it a form of psychological stress [6]. In more detail, annoyance results from the psychological perceived disturbance, moderated by perceived control over the exposure. D. Ouis considers annoyance as a feeling of displeasure following a physiological reaction to noise [7]. Furthermore, in contrast to the previous definitions, R. Rylander defines annoyance as an emotional response that occurs only after chronic disturbance [8]. All these interpretations of annoyance follow the general pathway for environmental annoyance with disturbance as the adverse effect and annoyance as a resulting negative emotion. Nevertheless, noise annoyance is interpreted in different lights according to the aim of the research and the background of the researchers. Moreover, the difference in interpretation by researchers in laboratory and field studies has been highlighted by some authors. For example, in a semantic study with experts, Guski et al. noted that among field experts, the interpretation of annoyance is closer to disturbance, while laboratory study experts tend to focus more on unpleasantness [9]. Following his definition of annoyance as a result of chronic exposure, R. Rylander also highlighted the difference in meaning in field studies with the subjective evaluation of acute exposure in laboratory studies [8]. For this reason, the short-term, self-reported annoyance under laboratory studies is referred to as annoyance potential. It is assumed, however, that these judgements are representative of real-world exposure-related annoyance [10].

2. FACTORS INFLUENCING ANNOYANCE

From the last section, it is clear that there is a broad, yet vague, consensus on what annoyance is, but that the underlying mechanisms have not yet been elucidated. Many influencing factors, however, have been identified. As the perception of the sound is the cause of annoyance, factors related to the physical characteristics of the sound, also known as acoustic factors, evidently influence the resulting noise annoyance. However, also a range of non-acoustic factors, which are not related to the sound itself but to the perceiver, the source or the situation have been shown to influence the annoyance responses in field studies; different overviews are presented in [11-13].
The non-acoustic factors can be categorized under personal, social, demographical, and situational factors [11-13]. Personal factors are linked to individuals and are stable over time, they include sensitivity to noise, attitude towards the source and perceived control. When such personal factors are shared by a group of people, they can be considered as social factors, for example, general evaluation of the source or mistrust in authorities. Demographical factors such as age, gender and income appear to have no or little effect on annoyance. Lastly, regarding field studies, situational factors are also reported to influence annoyance. Some situational factors such as time spent at home, soundproofing of the dwelling, dwelling orientation and distance from the source are related to the actual exposure to noise in field studies, and can therefore not be considered as purely non-acoustic factors. Other factors, such as activity during noise exposure, mood and overall

multisensory perception of the environment directly influence annoyance.

The acoustic factors can be related to the properties of individual noise events or multiple events combined. Relevant properties of individual noise events entail the evolution of the SPL such as rise time, duration, and maximum level [11]. Furthermore, psychoacoustic descriptors such as loudness, sharpness, tonality, fluctuation strength, roughness, … quantify the spectral and temporal behavior along the human perceptual dimensions [11]. Considering multiple noise events, their macro-temporal pattern also affects annoyance; the number of events, duration of quiet periods in between, and regularity of events all have an impact [14].

Moreover, in the real world, exposure is generally due to a combination of different sources. In this context, overall annoyance refers to the total annoyance due to the combined exposure, partial annoyance refers to the annoyance attributed to a single source under the combined exposure, and lastly, specific annoyance is due to a single source in an isolated environment [15]. In the combination of multiple noise sources, several interactions between the noise sources potentially occur. For example, the strongest component may dominate, and as a result, the contribution of other sources becomes negligible [16]. Moreover, attentional focus on different components may result in varying overall perceptions among individuals [17]. Alternatively, when the contribution of the sources is more equal, synergetic or inhibition effects can occur, where the total annoyance is greater or lower than the sum of the partial annoyance, respectively [10, 16]. This may be the result of masking effects, or due to contrasts in the sound which draw attention to specific components of the noise with a lesser or greater annoying character.

Several models have been derived to describe how the individual sources, including background noise, contribute to the overall annoyance, yet no single model is effective in all situations of combined exposure [16, 18]. These models can be categorized as physical or perceptual. In physical models, it is assumed that the overall annoyance can be derived from the sound pressure levels (SPL) of the individual sources [16, 18]. For example, based on the summation of the sound energy of the individual sources, or a linear combination of the equivalent SPL of the sources, whether including a correction factor for the differences between sources or not, among others. Alternatively, perceptual models form the overall annoyance based on partial annoyance due to the individual sources [16, 18]. Different perceptual models are based on a dominating source, weighted sum of partial annoyance of several sources, or differences in the partial annoyance of individual sources.

In field studies, however, exposure-response relations for noise and annoyance are still generally derived based on equivalent SPL (L_{eq}, L_{den}, …). Given the influencing factors presented above (both acoustic and non-acoustic), it is evident that these parameters are insufficient to describe the annoyance responses. In the WHO report, the exposure-response-relationships for L_{den} and the percentage of Highly Annoyed people (%HA) were derived for road traffic noise, aircraft noise, railway noise, and industrial noise (in the respective order of importance) based on a meta-analysis of existing studies [1]. For each of the noise sources, L_{den} could only describe less than 20% of the variance in annoyance. This was also confirmed by Brink who showed that the average explained variance in annoyance among 41 studies by such predictors was only 15% [19].

In view of evaluating the impact of noise-reducing measures, such as dwelling soundproofing, on annoyance, only the acoustic factors are of interest. The research in field studies and low explained variance by equivalent SPL indicates that the non-acoustic factors are important and should not be neglected, however, the remaining unexplained variance indicates the acoustic descriptors may still be improved. To achieve better acoustic descriptors for optimizing annoyance-reducing measures, it is necessary to study the underlying mechanisms of annoyance.

3. ANNOYANCE IN LABORATORY STUDIES REGARDING SOUND INSULATION

While field studies are best suited for evaluating the practical significance of noise exposure on annoyance, the noise exposure is generally estimated through noise maps, where the description of the noise exposure is typically limited to equivalent outdoor exposure levels. Meanwhile, the actual exposure is influenced by factors such as time spent at home, the orientation of the dwelling, sound insulation of the dwelling, and more [11]. As a result, field studies do not lend themselves to studying the intricacies of the aspect of the noise on annoyance. Instead, laboratory studies provide a controlled environment for studying the underlying mechanisms of the annoyance concept and deriving the relevant (acoustic) factors. In addition, the influence of several non-acoustic factors is ruled out by keeping them consistent: activity, general perception of the environment, …

Moreover, given that people spend most of their time indoors, it is relevant to study the impact of the dwellings' sound insulation on annoyance. A review of the literature

Table 1. Overview of literature on annoyance potential due to indoor noise exposure.

Reference	Aim	Annoyance Question	No. of partici-pants	Stimuli	Stimuli duration	Stimuli level
Vian et al. [21]	Evaluate adequacy of SNQ	10 point scale	24	6 music genres played through 2 playback systems and filtered through 12 simulated walls	2 min	Avg. L_A: 19-42 dB
Park & Bradley [22]	Compare SNQs in predicting annoyance and loudness	7 point scale	10	Speech: 3 Harvard sentences, or music: 3 samples (rap, house and pop music) + ambient sound (34.7dB), filtered through 20 walls	unknown	Average L_A: 72-75dBa
Pedersen et al. [23]	Evaluate online listening test as a experimental method	10 point scale (ISO TS 15 666)	22	4 neighbor noises: music, conversation, party sounds & toilet flush, filtered through 6 walls	20 s	L_{Aeq}: 64-99 dB (uncalibrated)
Hongisto et al. [24]	Propose alternative reference curve for SNQ	10 point scale (ISO TS 15 666)	59	6 neighbor noises: guitar, music modified to RTN spectrum, music, modified to 'living sounds' spectrum, baby cry, loud speech & dog bark, filtered through 9 wall spectra	18 s	L_{Aeq}: 8-40 dB
Hongisto et al. [25]	Compare SNQs in predicting annoyance and loudness	10 point scale (ISO TS 15 666) + inaudible option	43	5 traffic sounds: different compositions of light & heavy vehicles, at different speeds, filtered through 12 wall spectra	20 s	L_{Aeq}: 12-46 dB
De la Prida et al. [26]	Compare SNQs in predicting annoyance and loudness + Propose alternative reference curve for SNQ	2-Alternative Choice	119	5 urban sounds: 2 traffic noise recordings, an aircraft flyover, a commercial pedestrian street with a siren & pink noise	15 s	unknown
Ryu & Song [27]	Comparison of outdoor noise to indoor noise & Effect of sound insulation on annoyance	Comparison to a ref. on a 7 point scale	45	Outdoor sounds: traffic noise, railway noise & aircraft noise, Indoor sounds: outdoor sounds filtered through 2 SRI's in 1/3rd octave bands	10 s	L_{Aeq}: 65 dB

on the impact of sound insulation on the subjective evaluation of indoor sound exposure in laboratory experiments from 1980 to 2018 has already been presented in [20]. This review, however, covered subjective evaluation in general and combined the works on annoyance and for example, loudness. To shed light on the current state of the art regarding the impact of sound insulation on annoyance potential specifically, relevant articles were extracted from this review [21-24]. Furthermore, a literature search was done to expand the collection [25-27]. The literature is summarized in Table 1 and discussed in the following sections.

The majority of the studies aimed at evaluating the existing single number ratings for sound insulation through their correlation with annoyance responses [21, 22, 24-26], and based on their findings, some of the authors also proposed an alternative reference curve [26, 28, 29]. Two articles had a different focus; one was focused on evaluating an online listening test as a procedure, but still incorporated the impact of attenuation by different constructions [23], and the last focused on comparing the annoyance due to outdoor and indoor noise exposure [27].

Regarding their methodology, all but two articles used a scaling method for self-reported annoyance. The scale proposed in ISO 15 666 was the most popular and was used in three studies [23-25], while two other studies used an alternative 7-point or 10-point scale [21, 22]. In contrast, two articles used a comparative method: [26] used the 2-Alternative Choice method, while in the other the participants were asked to scale the stimulus in comparison to a (changing) reference on a 7-point scale [27].

In almost all articles, the participants were actively listening; in four studies the participants were told to imagine a situation at home [22-25], however, in two other articles, such instructions for the participants were not further specified [26, 27]. The studies that used the scale proposed by ISO 15 666 did not follow the recommendation regarding the question presented to the participants. This is because the ISO 15 666 question is aimed at annoyance in retrospective judgement over a longer time period in field studies, and is therefore not applicable in laboratory studies [30]. The majority of the studies also used relatively short stimuli of 10 – 20 s, the stimulus length was not specified in one article. In contrast to the active listening activity in these articles, in the study by Vian et al. [21] the participants read magazines while the stimuli were presented for 2 minutes, the participants reported their annoyance after the exposure. In this situation, the participants were not actively listening, which may be more representative of real-world noise exposure.

The studies employed a range of sounds. Four studies concerned neighbor noises and were mostly focused on speech [22-24] (both intelligible [23, 24] and unintelligible [22]) and music [21-24], however, also other inter-dwelling sounds such as dog barking [24], toilet flushing [23] and party sounds [23] were incorporated in some studies . Three other studies focused on outdoor sounds [25-27], with one study purely on road traffic noise [25], and the other studies also incorporating aircraft noise [26, 27], noise from a commercial street [26], and railway noise [26, 27]. In half of the studies, the sounds were presented at heightened playback levels, these levels ranged from 64 – 99 dBA [22, 23, 27]. Meanwhile, three studies presented the stimuli at natural levels [21, 24, 25]. To know if the participants were able to hear the sounds, a separate answer option was dedicated to inaudible sounds in [25]. In addition to the specific noises under study, two articles added ambient noise to the stimuli [21, 22], both articles focused on neighbor noises, and remarkably, the spectrum of the ambient noise was similar to traffic noise.
Regarding the findings of the studies, most of the articles focus on the correlation between the SNQs and the annoyance responses. Several works pointed out that the correlations were depended on the sound stimuli used [21, 22, 24, 26]. Furthermore, the review also noted the divergence of findings among studies and attributed this to variation in sound stimuli used [20]. However, only one article quantified their influence on the variance in annoyance responses [21]. In the study, the different sounds accounted for only 20% of the explained variance in annoyance responses. This study, however, considered only music pieces, when comparing sounds of different natures, the influence is expected to be larger. Little attention, however, is given to explaining the annoyance responses by acoustic aspects of the sound stimuli used in the studies, nor how they are influenced by the sound insulation. While most works present the averaged frequency content of the original sounds, this appears to be insufficient: For example, both studies by Park & Bradley [21] and Vian et al. [22] contained music stimuli, they found however, that more low and high-frequency content was more annoying, respectively, this contradiction indicates that alternative factors are necessary to explain the responses. In addition, the study in [24] considered dog barking, of which the annoyance is likely to be related to its impulsive character, while the road traffic noise samples in study [25] were modified so that the temporal evolution of SPL was limited. It may be assumed that for the stimuli in these articles, the annoyance is due to different annoyance mechanisms, related to the temporal properties of the sounds or the attitudinal aspects regarding the noise source.
Lastly, several studies also evaluated the subjective loudness of the stimuli and found a high correlation with the annoyance responses. Park & Bradley [22] and Hongisto et al. [25] reported R^2 values above 0.94 for the correlation within a specific sound type. The correlation over sounds of different natures was only reported in [23], where the R^2 was higher than 0.95. However, due to the online nature of this study, the frequency response of the stimuli presentation could not be calibrated. Nevertheless, these findings indicate that subjective loudness appears to be an interesting alternative to annoyance potential, even more so when considering the lower variance in loudness responses by the participants reported by [25]. Before using it as a substitute for annoyance, its suitability should first be further evaluated as differences in loudness and annoyance have been pointed out in other works regarding spectrum [31] and temporal weighting of events [32].

4. HOW TO STUDY ANNOYANCE

The previous section painted a picture of the currently available literature covering the influence of sound insulation on indoor noise annoyance evaluated under laboratory conditions, also known as annoyance potential. In short, there is a good similarity in the methodologies used in the studies regarding stimuli presentation and methods for obtaining self-reported annoyance, however, there is still a great divergence in the findings. This was attributed to differences in the sound stimuli used. Such diversity in stimuli is desired as it encompasses the full spectrum of exposure in the real world. However, rather than exploring the reasons behind these differences, the literature focuses on the correlation of annoyance ratings with the Single Number Quantity ratings (SNQ). As a result, it is not considered whether the SNQs are appropriate descriptors for the underlying mechanisms of annoyance. Achieving an appropriate SNQ for subjective loudness already proved difficult, meanwhile achieving one for annoyance is even more complex due to its psychological and emotional aspect. To shed light on the impact of sound insulation on annoyance, a deeper evaluation of these mechanisms influencing annoyance is necessary. The limited information available about the sound stimuli used did not allow to clarify the influence of these differences in this brief review.

Regarding the methodology, while it was relatively consistent across the literature, it may be improved further to evaluate the annoyance under more realistic conditions: In most literature, the participants were listening actively and focused on the stimuli. D. Ouis for example, already pointed out that under real exposure, people employ adaptive measures and ignore sounds, while in laboratory studies with active listening, the elements that would be ignored are under attention [7]. An alternative to the active listening is already present in this article; in the study by Vian et al. [21] the participants rated their annoyance after being exposed to the stimuli while reading magazines. Alternatively, a Stroop test also demands the participants to focus on a task and in addition it allows to evaluate the impact of the noise exposure on the cognitive performance. Comparing cognitive performance as a measure of distraction may help to elucidate the annoyance mechanism, as done in [14]. Aside from the activity of the listeners and regarding the stimuli presentation, natural playback levels should be preferred over heightened levels. Due to the non-linearity of the hearing system, the perception of the sound at heightened levels is no longer representative for that of natural levels [24]. To achieve natural levels, simply applying the attenuation of single individual sound insulation elements as a filter to the original sounds may not be realistic: For example, for a façade the effective sound insulation is due to both the wall structure and windows, and in the case of neighbor noise, also flanking noises can have a significant impact. A field study in Switzerland evaluated the outdoor and indoor level difference for road traffic noise and found a median level difference of 28 dB(A) for a façade with closed windows [33]. Moreover, according to the German DIN 4109-1 [34] and Austrian OIB Richtlinie 5 [35], the recommended overall sound insulation of the façade is so that the indoor exposure is approximately 20-30 dB L_{AEq}. These levels can be used as a guideline for realistic indoor exposure. Lastly, additional ambient background noise is rarely employed in the evaluated studies. Ambient background noise may result in masking of components related to annoyance under real conditions, and is thereby also relevant to add to the stimuli when studying annoyance.
The active listening, heightened levels and no background noise in this review presented the sounds in a worst-case scenario, meaning more extreme responses. Although easier to study, the annoyance responses may no longer be realistic, by considering the suggestions above, more relevant annoyance responses can be achieved.

Regarding the sound samples in the listening test, as already pointed out, it is not clear which factors that modify annoyance are affected by the sound insulation. The averaged frequency spectra of the stimuli are insufficient to describe the annoyance ratings. Moreover, some stimuli were of impulsive nature while others were rather steady, nevertheless, this received no attention. Also, in the current literature, the stimuli used are mostly of short duration and without quietness for context. In short, the temporal aspects of the sounds, either related to single events or their macro-temporal structure, have not been not considered with regard to the impact of sound insulation on annoyance. Other literature has explored temporal aspects regarding indoor noise exposure but did not evaluate the effect of sound insulation [36, 37]. These studies employed longer sound stimuli of 10 min to account for the macro-temporal structure. It is suggested to incorporate stimuli of longer duration in studies regarding façade sound insulation.
A final aspect not covered in the current literature is the informational content carried by the stimuli. With regard to speech, it is known that its intelligibility has a major impact on annoyance ratings [38]. Moreover, for other noises, the annoyance may be linked to the attitude towards the source. Dealing with this, however, is complicated, as the noises from different sources inherently have different spectral and temporal compositions. Consequently, so far only few have put forward a method that can isolate the attitudinal aspect of annoyance. For example, Fastl and Zwicker proposed a method that results in transformed stimuli with the same loudness evolution and the same spectral envelope, however, the information about the source is obscured [39]. Comparing the normal to the obscured sounds may allow to derive the attitudinal aspect of annoyance. Alternatively, in [40] a method was presented in which the averaged spectral content in 1/3rd octave bands of a sound sample is matched to that of a second sound from a different source for every window of 125 ms. This way, the spectral contribution and loudness evolution are similar, while it is reported that recognition of the source type remains possible, although more difficult. The difference in annoyance between the two spectral and temporally matched sounds may therefore be assumed to be due to the attitude towards the source.

To consider all aspects of noise annoyance and the influence of sound insulation, future studies should consider not only the spectral content, but also the temporal structure, and the attitude of apartment/building users towards the noise source. Methods to evaluate these aspects in laboratory experiments have been proposed. Combining them in a single experiment, however, is likely unfeasible as the great number of stimuli and their longer duration would undoubtedly result in fatigue among the participants. For this reason, it seems best suited to study these aspects in three sub-tests regarding the spectral, temporal, and attitudinal aspects where the stimuli duration and spectra can be manipulated for the respective aim of the part.

5. ACKNOWLEDGMENTS

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