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ACOUSTIC COMFORT OF LIGHTWEIGHT TIMBER WALLS: CORRELATION BETWEEN SUBJECTIVE EVALUATIONS AND OBJECTIVE MEASUREMENTS

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ABSTRACT

Sound insulation of timber frame walls has been the object of several studies over the past 30 years. Most concerns about acoustic comfort of lightweight partitions is their poor sound insulation at low frequencies, in contrast with a high sound insulation performance at higher frequencies usually exceeding the one of traditional heavy weight structures. These characteristics are usually considered of great concern because it has been established that perceived sound insulation is strongly affected by the perception of low frequencies. This study investigates comfort levels experienced by subjects that are asked to listen to audio tracks that reproduce noises through several lightweight timber frame walls with different sound insulation properties, previously tested in laboratory conditions, and to rate the perceived annoyance. This information is then correlated to the single number ratings associated to the measurement and to the spectral adaptation constants that can be added. The results show that (i) users express different annoyance ratings for walls having the same single number rating but different spectra; (ii) the use of the spectral adaptation constants C and C_{tr} improves the correlation between single number rating and annoyance; (iii) subjects can consistently evaluate annoyance upon multiple administration of the same tracks.

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1. INTRODUCTION

The development of multi storey timber construction brought the attention to the sound insulation properties of lightweight assemblies. It is well established that timber structures, due to the low density of wood in relation to its stiffness, provide good sound insulation properties at high frequencies, while poor performance in the low frequency ranges, as typical of double walls [1]. Achieving good sound insulation levels at low frequencies is of great importance in attaining good acoustic comfort performance even if it may be difficult to correlate that to the actual evaluation from the occupants, particularly in this specific frequency range. Recent literature started to investigate which metrics (including low-frequency correction terms) are most closely related to the subjective evaluation of acoustic comfort [2-3]. In this study, subjective evaluations on comfort are compared to the objective sound insulation measurements of lightweight timber construction, with the aim to gain a deeper understanding on (i) the correlation between subjective evaluation and airborne sound insulation indices (ii) the identification of spectral adaptation constants that improve such correlation and (iii) the evaluation of the reliability of the responses upon multiple administrations.

2. METHODOLOGY

2.1 Characterization of the sound reduction index of timber frame walls

A measurement campaign on timber frame walls has been conducted at the Building Envelope Lab of the Free University of Bozen-Bolzano, Italy. The measurement campaign encompassed different configurations, including three kinds of linings: (i) gypsum board plates directly fixed to the timber frame wall, (ii) gypsum board plates fixed to wood studs screwed to the structure, and (iii) completely decoupled drywall with stainless steel C profiles. Membranes and damping profiles were also tested as improvement measures that positively affect the performance whilst minimally increasing the wall thickness. Measurements were conducted both using the EN ISO 10140-4 standard [4] and by additional testing according to the EN 16283-1 standard [5].
The base timber frame wall analyzed for this study consists of timber studs (60x140 mm, 600 mm spacing), mineral wool (140 mm, 70 kg/m^3), OSB (15 mm, 550 kg/m^3). Among the wall elements tested, 6 construction solutions were selected, exhibiting different sound insulation properties:

- **Wall #1**: Timber frame wall.
- **Wall #2**: Timber frame wall. On the emitting and receiving sides: timber studs (40x60 mm, 600 mm spacing), mineral wool (40 mm, 38 kg/m^3), 1x gypsum board (12.5 mm, 720 kg/m^3).
- **Wall #3**: Timber frame wall. On the emitting side: closed cell polyethylene strip (3 mm, 25 kg/m^3), timber studs (40x60 mm, 600 mm spacing), mineral wool (40 mm, 38 kg/m^3), 1x gypsum board (12.5 mm, 720 kg/m^3).
- **Wall #4**: Timber frame wall. On the emitting and receiving side: timber studs (40x60 mm, 600 mm spacing), closed cell polyethylene strip (3 mm, 25 kg/m^3), mineral wool (40 mm, 38 kg/m^3), 1x gypsum board (12.5 mm, 720 kg/m^3).
- **Wall #5**: Timber frame wall. On the emitting and receiving side: closed cell polyethylene strip (3 mm, 25 kg/m^3), timber studs (40x60 mm, 600 mm spacing), mineral wool (40 mm, 38 kg/m^3), soundproofing bitumen sheet (5 kg/m^2), 1x gypsum board (12.5 mm, 720 kg/m^3).
- **Wall #6**: Timber frame wall. On the emitting and receiving side: 10 mm airgap, C-profiles (50 mm), mineral wool (40 mm, 38 kg/m^3), 1x gypsum board (12.5 mm, 720 kg/m^3).

The single number rating for airborne sound insulation was calculated together with the relevant spectral adaptation constants: C, $C_{50\text{-}3150}$, $C_{50\text{-}5000}$, $C_{100\text{-}5000}$, C_{tr}, $C_{tr,50\text{-}3150}$, $C_{tr,50\text{-}5000}$, $C_{tr,100\text{-}5000}$. An overview of the results of the sound reduction index measurements is presented in Figure 1, while the relevant features and single number ratings are listed in Table 1.

Table 1. Characteristics of the walls selected for the listening tests.

#	m' (kg/m^2)	R_w (dB)	C (dB)	C_{tr} (dB)
1	24.3	41	-3	-8
2	49.5	49	-4	-10
3	37.0	49	-4	-10
4	49.7	53	-5	-11
5	59.7	57	-4	-12
6	49.1	62	-7	-15

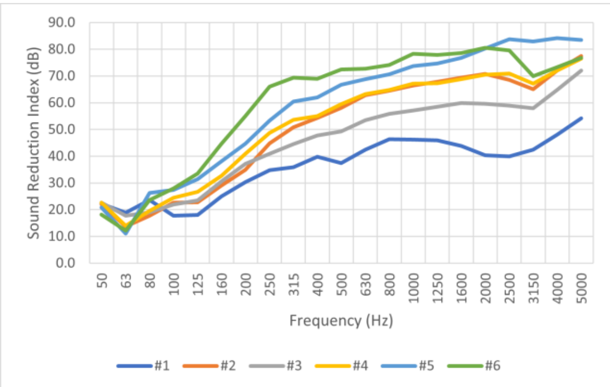


Figure 1. Sound reduction index of the 6 walls used as reference for the listening tests.

The R_w of the chosen walls ranges from 41 dB (wall #1) to 62 dB (wall #6), covering a wide range of conditions. Walls identified as #2 and #3 have the same R_w but a different spectral response, as seen in Figure 1. Other walls are characterized by different R_w and different spectral responses.
To understand how much the different frequency-dependent sound insulation performance affects comfort, and to understand which metric and spectral adaptation

term most closely matches the comfort votes expressed, listening tests were performed.

2.2 Listening tests design

A full factorial design was used in which subjects listened to 16 audio tracks and rated the perceived annoyance. The audio tracks were generated from two baseline signals, a traffic noise and a speech noise, both lasting 40 seconds. Traffic noise was chosen to mimic the response to façade sound insulation, while speech was used to evaluate the annoyance of airborne sound from adjacent environments.
The baseline signals were equalized (in terms of dBA) and filtered based on the spectra recorded when measuring sound insulation properties of the walls. Repeated tests were performed on tracks 3 and 5, to verify if the responses were consistent upon multiple administration, thus testing the repeatability of the results. As such, 8 tracks were created for both speech and traffic audio files. These audio files underwent a low pass filtering (30 Hz, slope 6 dB/oct) and a high pass filtering (16 kHz, slope 6 dB/oct), and 2 seconds of fade in and fade out effects were added.

The listening test was structured in 5 steps:

- **Part I: Introduction.** Subjects were informed about the scope of the test and signed privacy disclosure. Personal data (age, gender, living context, first language, and self-reported hearing impairment) were collected to check whether they influenced the responses.
- **Part II: Pretest A**. To allow subjects to get familiar with the audio tracks, they were fed a short portion (20 s) of three audio tracks, among those that would be tested afterwards, in the following order: the louder, the fainter, and in intermediate one. They were not asked to report any evaluation.
- **Part III: Test A** (traffic noise, 8 tracks). Listeners had to listed to 8 audio tracks, whose order was randomized. They could listen again to the tracks, if thew wanted. After each listening, they were asked to evaluate the annoyance on a digital questionnaire.
- **Part IV: Pretest B**. Same as Part II, with speech noise.
- **Part V: Test B** (speech noise, 8 tracks). Same as Part III, with speech noise.

Before starting the listening tests, subjects were given the following context: “When the sound is playing, imagine you are alone at home in an apartment building in complete peace. You are reading a magazine or a book or browsing the internet and you start hearing noises from outside/the apartment upstairs.”
The annoyance rating was introduced by the following question: “How much does the sound disturb, annoy, or bother you?” The evaluation scale was a modified version of the ISO/TS 15666 [6] annoyance scale: instead of having 11 points, the neutral point was removed resulting in 10 points, ranging from 1 (“Not at all”) to 10 (“Extremely”). If they could not hear the sound, they were asked to leave the questionnaire blank (“zero” votes in the analysis of the results).

2.3 Test environment and measurement equipment

Tests were carried out in a room located in an unoccupied area of an office building, with dimensions 3.30 x 4.50 x 3.18 m. Tests were administered during 5 working days, between 18.03.24 and 22.03.34, from 8 am to 1 pm.
The overall duration of the test was approximately 30 min for each participant. Circumaural closed-back headphones ATH-M70x and a Zoom F8 sound card were used for the reproduction of audio tracks. During the tests, environmental conditions were monitored as illustrated in Figure 2.

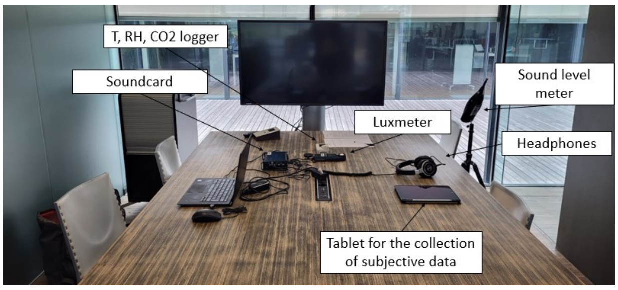


Figure 2. Test environment and equipment.

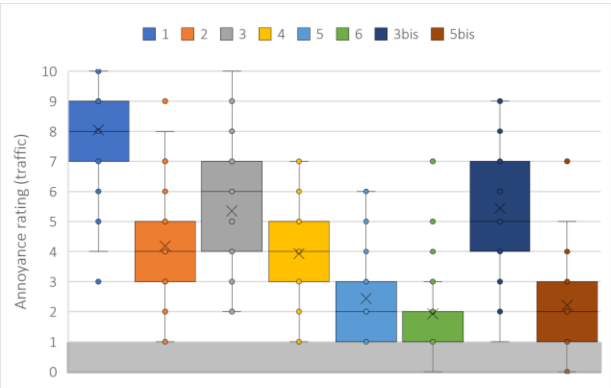
Sound pressure level was monitored close to the subject (h = 1.20 m) using a B&K 2270 sound level meter; illuminance on the desk was measured with a Konika Minolta T-10A illuminance meter, while temperature, relative humidity and CO_2 concentration were monitored using a HOBO MX1102 logger located on the desk. Subjective responses were collected using a tablet.

3. RESULTS

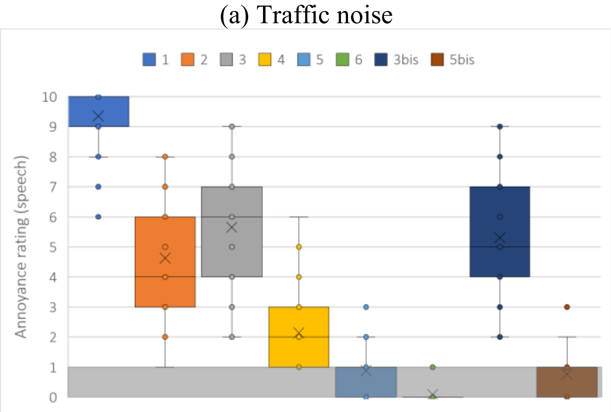
3.1 Overview of participants profiles

The test was completed by 43 participants, whose profiles are summarized below:

- **Age:** 40% between 21 and 30 years, 44% between 31 and 40 years, 16% between 41 and 50 years
- **Gender**: 49% females, 51% males
- **Living context**: 12% countryside, 67% small village, 21% city
- **First language**: 81% Italian, 9% Spanish, 7% German, 2% French
- **Hearing impairment**: none



(a) Traffic noise



(b) Speech noise

Figure 3. Annoyance rating for the 8 audio tracks related to traffic (a) and speech noise (b).

The environmental conditions monitored during the tests, expressed in terms of average and standard deviation, displayed a sound pressure level of (37.2 ± 1.1) dBA, an illuminance of (1460 ± 860) lx, a temperature of (23.9 ± 1.2) °C, a relative humidity of (35 ± 4) % and a CO_2 concentration of (550 ± 110) ppm.

3.2 Annoyance ratings

The distribution of annoyance responses is represented in Figure 3a for traffic noise and Figure 3b for speech noise.

In Figure 3, the “zero” vote in the annoyance scale, shaded in grey, was associated with subjects who could not hear the track. For speech noise, many subjects could not detect tracks #5 and #6, filtered by spectra characterized by high sound insulation values at mid-high frequencies.

Significant differences in the annoyance rating is evident between walls #2 and #3, characterized by the same R_w, a sound transmission curve dominated by low frequency and a different energy content over the whole frequency range. Wilcoxon rank sum tests were conducted to check whether the distribution of votes related to tracks 2 and 3 were had significantly different medians. The test results confirmed that the distributions have different medians at the 5% significance level, both for speech and traffic noise.

The repeated response to tracks 3 and 5, aimed at evaluating the consistency of the answers of the subjects, confirmed the ability of subjects to evaluate consistently their annoyance, both for traffic noise and for speech noise.

3.3 Spectral adaptation constants

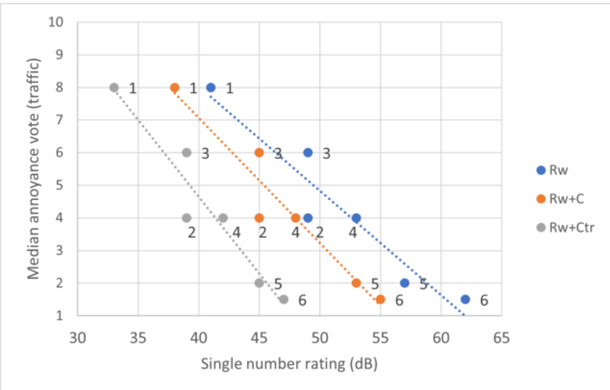
To evaluate which spectral adaptation constant is better suited to describe the relation between single number rating and annoyance level, regression analysis was performed between the median annoyance vote expressed by the subjects and the single number rating with different spectral adaptation constants. The R^2 of each correlation is reported in Table 2.

Table 2. R^2 of the correlations between single number rating and annoyance level.

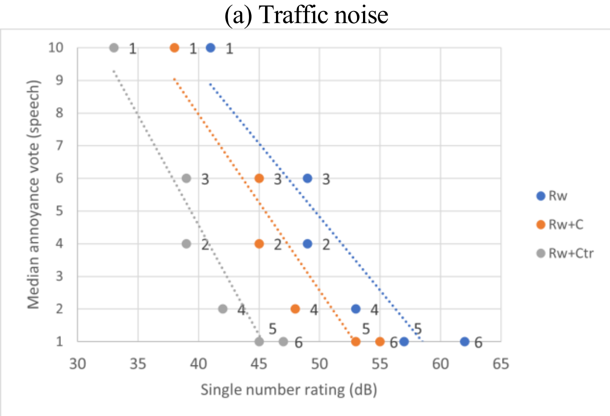
	Traffic noise	Speech noise
R_w	0.91	0.86
$R_w + C$	0.93	0.89
$R_w + C_{tr}$	0.93	0.91
$R_w + C_{50\text{-}3150}$	0.78	0.89

$R_w + C_{50\text{-}5000}$	0.78	0.89
$R_w + C_{100\text{-}5000}$	0.93	0.89
$R_w + C_{tr,\ 50\text{-}3150}$	0.06	0.14
$R_w + C_{tr,\ 50\text{-}5000}$	0.06	0.14
$R_w + C_{tr,\ 100\text{-}5000}$	0.93	0.91

The results show that the spectral adaptation constants C and C_{tr} help improve the explained variance of the correlation, while spectral adaptation constants evaluated in different frequency ranges do not necessarily do so. Correlations with C_{tr} evaluated over the ranges 50-3150 Hz and 50-5000 Hz display extremely low R^2 values, as these spectral adaptation constants tend to flatten the differences among the single number ratings. In Figure 4, the correlations between single number rating and annoyance are reported for R_w, R_w + C and R_w + C_{tr}.



(a) Traffic noise



(b) Speech noise

Figure 4. Correlations between single number rating and annoyance for traffic (a) and speech noise (b).

It should be noted that the median value of 1.5 (Figure 4a) is estimated as the average between two numbers occupying the central position in the distribution as, for that specific case, there is an even number of occurrences.

3.4 Personal factors affecting the response

Finally, the categorical variables collected related to personal information (age range, gender, living context and first language) were used to run an ANOVA and check whether there was a significant impact of any of those features on the expression of votes. In detail, the living context might have been relevant in the evaluation of the traffic-related annoyance, while the first language might have had an impact on the evaluation of the speech noise. Statistical analysis showed that, at a significance level of 5%, none of the categorical variables listed above was significant, neither for the traffic noise nor for the speech noise.

4. DISCUSSION

The main outcomes of the presented research can be summarized as follows:

- Subjects were able to coherently rate annoyance in a proportional manner with respect to the airborne sound insulation provided by the walls and the interquartile range spans 2 or 3 votes.
- Speech noise is generally attributed higher annoyance levels compared to traffic noise.
- Both for speech and traffic noise, subjects rated wall #3 as more annoying compared to wall #2. The two walls have the same R_w but different spectra; this suggests that additional considerations should be performed when evaluating the perceptual relevance of sound insulation indices.
- Repeated exposure to the same audio track returned consistent results for both speech and traffic noise.
- The spectral adaptation constants C and C_{tr} improve the correlation between R_w and median annoyance vote, confirming the relevance that they have in relation to the expression of subjective ratings.
- The slope of the regressions for speech is steeper compared to traffic noise, indicating a much more limited range for acceptability of such conditions.
- Age, gender, living context and first language were not significantly impacting the distribution of votes, neither for speech nor for traffic noise.

Some limitations might have affected the results presented above, namely:

- Spectral filtering might be considered a suboptimal solution to perform listening tests, compared to recordings.
- Specific features of the original audio signals might have led to a visual and/or acoustic mismatch between the sound scene and the room where the tests took place.
- Tests were performed in a quiet environment; nevertheless, impulsive background noises might have affected the results for the softer tracks.
- The number of participants was relevant, but the limited variability of the personal data might have not allowed specific features to emerge.

5. CONCLUSIONS

The present study aimed at testing the perceptual effects of noise propagating through lightweight timber walls. To this aim, experimental measures of airborne sound insulation were performed on timber frame walls; a few of them were selected, and the amplitude spectra of the recorded signals was used to filter traffic and speech noise and perform listening tests. The results showed that there is a significant correlation between single number rating and annoyance, which is further improved if spectral adaptation constants are used. Nevertheless, walls having the same R_w were rated differently and the signal rated as more annoying was characterized by lower R values in the frequency range. Correlation between single number rating and annoyance was steeper for speech noise compared to traffic noise, indicating narrower acceptability ranges for that sound type.

Further work will be devoted to improving the experiment setup from the side of signal generation and reproduction, to expand the sample to study in detail the effect of personal factors, and to enlarge the number of descriptors used to characterize the listening experience.

6. ACKNOWLEDGMENTS

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