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Acoustic Comfort Investigation in Residential Timber Buildings in Sweden

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This article presents parts of a wide survey on acoustic comfort in Swedish family buildings, specifically with focus on timber light-weight buildings. The scope of the whole research is to investigate acoustic comfort dimensions after collecting and combining data from standardized acoustic measurements and subjective responses from a questionnaire survey. Certain noise sources were reported as dominant within living environments, impact noise from neighbors being the most important. Installation noise from inside the building and outdoor low-frequency noise disturb also a lot. However, the overall level of acoustic comfort in contemporary wooden buildings seems satisfactory.

Keywords: acoustic comfort, field measurements, noise annoyance, subjective responses.

Introduction

This article concerns investigation of acoustic comfort in contemporary Swedish timber buildings. The results presented are part of a wider research project about acoustic comfort in family apartments in Sweden, including timber structures as well as typical heavy-weight concrete or mixed structure types (e.g. steel and concrete). To implement this study data from standardized acoustic measurements in the sample building structures were utilized. Then an acoustic survey was setup for the residents of the test buildings: they were invited to fill in a questionnaire in their living environment. The overall scope of the research project is to collect and combine acoustic data and subjective responses from residents in order to develop approaches for the concept of acoustic comfort.

The only description offered for the concept of acoustic comfort in the existing literature is the following: “a concept characterized by absence of unwanted sound, desired sounds with the right level and quality, opportunities for acoustic activities without annoying other people” as stated by Rasmussen and Rindel (2010). We would also add in that definition: “a concept with opportunities for supportive acoustic conditions according to the activities taking place”. For instance, different demands for acoustic conditions in a flat exist when residents cook, sleep, read or play the piano. Furthermore, the above statements describe how acoustic comfort is relevant to a person as a receiver of sound and a source: somebody can be disturbed by noise from others or by their own

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sounds or by the idea that they might disturb others around them. Consequently, there can be conflicts or discomfort due to various situations related to noise sound in living environments.

Current standardized methods for airborne sound reduction and impact noise measurements have been used to assess sound insulation of building components (ISO717 1996, ISO140 1998, ISO16283 2014, EN ISO12354 2017) but also as means to evaluate acoustic comfort in flats. As we analyzed in a review paper of relevant building acoustic surveys (Vardaxis et.al. 2018), the measured descriptors derived from the ISO standard measurements are highly associated to the subjective noise annoyance responses of the residents in multistory buildings. However, the acoustic indicators represent sound transmission between building elements, they do not represent directly any acoustic comfort index.

For this research project we have setup a questionnaire design which includes noise annoyance from several sources in buildings alongside other important variables such as: size of home, living density in flats, characterization and emotional reaction to acoustic conditions at home and demographic data. In this article we present parts of the collected data with a main focus on noise annoyance in timber buildings; we demonstrate results of the whole sample which includes concrete buildings too, for a comparison of the differences regarding the wooden structures.

Methods

Our research design includes 101 different building units (different addresses) of 34 different structures types: concrete or timber buildings and mixed structures. Thus the sample of buildings is 34 blocks (1 or more units each) with different structures: 25 HW buildings, 7 LW and 2 mixed structures: the term heavy-weight (HW) refers to concrete buildings and the term light-weight (LW) refers to wooden buildings. HW have a structure with concrete beams, floor and support walls: they can have concrete panels, brick walls (any kind or brick) or prefabricated panels (concrete, heavy or light) for walls. LW have wooden beams, floor and support walls: they utilize wooden elements, light bricks or prefabricated light-weight panels for wall components.

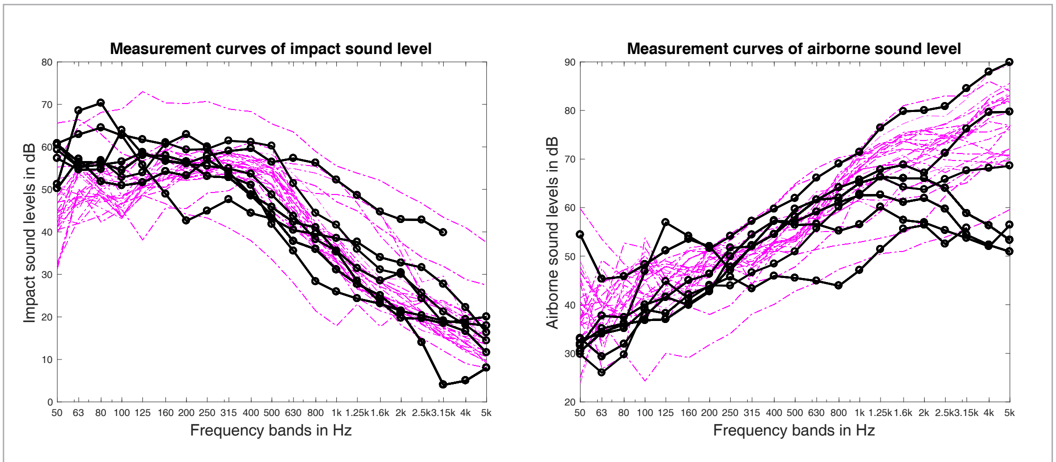


Fig. 1

Impact sound levels $L'_{n,w}$ (left) and airborne sound reduction levels *R'w* (right) for all sample buildings of the research project: HW buildings with purple lines, LW wooden buildings with bold black lines

Following the European or ISO standards and previous research (Negreira 2016, Hagberg 2018, Ljungren et.al. 2014, Hagberg and Bard 2014), sound transmission was measured between two typical adjacent rooms, one above another, always bedrooms or living rooms, typical of the building's floor plan and representative of everyday acoustic conditions. The room above is the sending test room and the one below is the receiving test room; That acoustic data included airborne sound measurements (sound speaker source above, microphone positions below), impact sound measurements (standardized tapping machine or other impact sources above, microphone positions below) and reverberation time measurements (impulse response measurement with sound source and microphones in the same test room) for the receiving room.

Fig. 1 presents the measurement curves for impact sound levels $L'_{n,w}$ and airborne sound reduction levels R'_w for all sample structures. HW concrete buildings follow a similar trend with less dispersion around that except few cases of much higher or lower performance, especially in cases of impact sound which is the most critical for acoustic comfort (Hagberg 2018, Ljungren et.al. 2014). For the LW curves the behavior is dissimilar, with wider dispersion between them in the whole frequency range for both cases of impact and airborne sound. However, the highest and lowest values in curves belong mostly to HW cases, as can be seen in Fig. 1 and also Table 1.

Table 1

Single number quantities of acoustic descriptors for the sample buildings

		Impact sound index in dB			Airborne sound reduction index in dB		
		$L'_{n,w}$	$L'_{n,w} + C_{50\text{-}2500}$	$L'_{n,w} + C_{100\text{-}2500}$	R'_w	$R'_w + C_{50\text{-}3150}$	$R'w + C_{100\text{-}3150}$
Type:	N	Mean (Range)			Mean (Range)		
Heavy-weight (HW)	25	50 (38-64)	50.2 (40-65)	49.7 (39-64)	59.3 (46-67)	57.7 (44-64)	58.1 (44-65)
Light-weight (LW)	7	48.8 (45-55)	52.4 (49-59)	49.6 (47-54)	58.1 (48-68)	55.5 (48-63)	56.4 (48-65)
All structures	34	49.8 (38-64)	50.8 (40-65)	49.7 (39-64)	59 (46-68)	57.2 (44-64)	57.6 (44-65)

Table 1 presents some statistics for the single number quantities for the sample measurements, the indices for airborne and impact sound characterization calculated according to the relevant ISO standards. Note that measurements in this study have a frequency range between 50-5000Hz and the single number indices are calculated from 50 Hz, which is the standard requirement in Scandinavia. Most data were acquired by a national Swedish research database: the Green Building database. The building regulations in Sweden demand a minimum level of sound level difference of $D'_{nT,w,50}$= 52 dB from the space outside to inside a dwelling and highest impact sound levels of $L'_{nT,w,50}$ = 56 dB. Those descriptors are equal to $R'_w + C_{50\text{-}3150}$ and $L'_{n,w} + C_{50\text{-}2500}$ respectively when no flanking transmission has been measured. However, other European countries have not that strict limits while the official requirement of the ISO standard is 100-3150Hz for airborne sound and 100-2500Hz for impact sound measurements (Boverket, 2016).

Furthermore, self-reported data was collected with the development of a social survey, using a questionnaire for the residents developed according to (ISO-15666 2003). The survey aimed to capture several aspects that we consider part of the overall acoustic comfort concept: there is special focus on targeting all possible noise types and other variables relevant to noise annoyance. The questionnaire was distributed using post mail (one copy for every test flat, a web link was provided too): an invitation letter was sent first with the questionnaire, then two reminder letters followed within a month. The questions analyzed in this article are presented in Table 2, with some statistics which refer to the subjects (residents) living in LW wooden buildings only.

The subjects sample have an age span of 18-85 years and have spent at least 12 months in their flat, which were basic requirements for the survey. Also they should have normal hearing, thus subjects who use hearing aids at home were filtered out of the data. Tenants who live on the top floor were filtered out too, since they do not have neighbors on the floor above and their perception of noise annoyance is probably different. Finally, after filtering, 85 responses for LW subjects were collected: 37 male, 45 female (3 did not report gender). The gender distribution was the same for the 375 subjects of the total sample (LW and HW) split in 43% men and 55% women. The overall response rate was 28% in both cases of LW and HW buildings. Fig. 2 presents the distribution of observations in the overall research sample grouped by structure blocks, so one can see HW and LW observations together.

The distribution of our observations grouped in different structures (or building blocks) is uneven: most blocks have less than 10 observations. However, 5 HW and 1 LW blocks, have 50% of the total observations (187 out of 375). For the case of LW wooden structures, a certain structure provided 59% of the total LW sample: that was a building block of 4 building units (8 separate addresses) of the exact same wooden structure type.

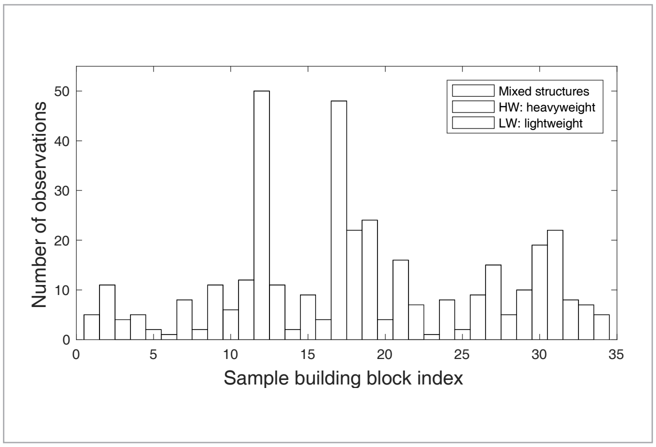


Fig. 2

Histogram of the total research sample: observations grouped in building blocks and different structure types

Results and Discussion

Histograms of questions 1-3 are illustrated in Fig. 3. As can be observed, most subjects stayed at their house for 1-5 years, about 71% while only 9% have lived for more than 10 years. That situation is indicative of mobility in Swedish apartments since there are new buildings erected and inhabited, while in parallel a shortage of house supply makes lots of tenants to rely on short-term rentals and move frequently between rented flats. For the LW cases, tenants have evenly spent from 1-10 years in the building but the wooden structures of our sample are contemporary: the oldest one was finished and occupied in 2008.

Question 2 (Fig. 3) concerns apartment size (in square meters): the distribution of this variable is close to normal, with most flats being between 60 and 80 sq., one third of the total sample. For the wooden buildings case, this is still true: 32 of the 85 LW flats are between 60-80 sq. (ca. 38%) but the overall LW data concern bigger flats. For instance, 37% of the LW flats are bigger than 80 sq. which can be justified as wooden buildings in Sweden are new and have bigger size.

The number of flat tenants is important for the parameter of living density. As illustrated in question 3 (Fig. 3) one or two persons live in most flats in both HW and LW structures, while only 20% of the cases concern 3 tenants or more in a flat. For wooden buildings, it is only 12% of flats with 3 or more tenants, while 34 persons live alone (40%).

Then, question 4 deals with the presence of children in the house, which is an important factor for the status of the tenants (family with children at home), the living density and the possible presence of noise at their own home due to children. Overall, 23% of the survey flats have children at home, while for the wooden buildings sample this percentage is almost half namely 14% (12 out of 85).

Question 5 aimed at nuisances that affect the decisions of the tenants that much as to move out from a residency. About 8% of the total subjects would consider moving out due to noise pollution in their living environment: this corresponds to a small percentage for LW buildings (only 2%) but a considerable percentage for HW concrete buildings (9%). That is a first indication that wooden multistory residencies in Sweden can offer better acoustic conditions compared to typical concrete structures, but they were also designed to fulfil higher acoustic criteria.

Questions 6 and 7 refer to noise sources unmentioned in the questionnaire but might be of concern for the residents in the survey buildings. Specifically, 20% of HW and 22% of LW tenants have alternative sources of disturbance in question 6. Question 7 shows that 56% of those replied being somewhat or fairly annoyed. Additionally, about 30% of those commented on the nature of the additional source: most of them referred to construction noise from building sites next to their house. That refers to a common situation in Swedish housing where new buildings are constructed or existing ones get renovated, thus there are many construction sites producing noise next to dwell-

Table 2

Questionnaire data and initial statistics for the wooden building sample

Questions	N: replies	Mean	Std.
1. How long have you lived in your home? (years)	83	5.96	4.11
2. What is the size of your home? (in square meters)	72	80.10	16.78
3. How many people, including you, are currently living in your home?	80	1.73	0.75
4. Do you have children living with you on a regular basis? (1:No, 2:Yes)	81	1.15	0.36
5. Are you considering moving from your home due to noise pollution? (1:No, 2:Yes)	83	1.02	0.15
6. Is there any other disturbing source of noise in or close to your home that we have not addressed? (1:No, 2:Yes)	84	1.22	0.42
7. If so, please indicate the level of disturbance: (1:Not at all, 2:Slightly, 3:Moderately, 4:Very, 5:Extremely)	23	1.91	0.85
8. How pleased are you with the sound environment in your home? (1:Very pleased, 2:Fairly pleased, 3:Neither pleased or displeased, 4:Fairly displeased, 5:Very displeased)	81	1.75	1.06
9: Thinking about the last 12 months, when you are here at home…			
9.a. ***How much do you think about*** not disturbing your neighbours when you e.g. play music, close doors, or walk around?	82	2.34	1.09
9.b. ***How disturbed/bothered*** do you think your neighbours are from the noise you make? (1:Not at all, 2:Slightly, 3:Moderately, 4:Very, 5:Extremely)	82	1.26	0.58
10: Thinking about the last 12 months, when you are here at home, *with the windows and doors shut, how much* disturbed are you by:			
10.a. **Noise from machines or appliances inside the building**? (Refrigerator, freezer, washer, dryer, lift, AC, ventilation, water pipes, flushing toilets)	82	1.86	0.78
10.b. **Low-frequency noise** from a neighbour's sound system, TV or computer, coming through the walls?	82	1.21	0.51
10.c. **Low-frequency noise** from a neighbour's sound system, TV or computer, coming through the floor or ceiling?	81	1.42	0.69
10.d. **Sound of neighbours talking,** coming through the walls?	82	1.07	0.47
10.e. **Sound of neighbours talking,** coming through the floor or ceiling?	81	1.22	0.63
10.f. **Sound of neighbours walking**, slamming doors and dropping things, thuds from children playing, coming through the floor or ceiling?	82	2.04	1.01
10.g. **Sound of walking** in shared spaces of the building (staircase, hallway, etc.)?	82	1.40	0.78
10.h. **Low-frequency noise** (rumbling, muffled sound) from **outside sources such as music, traffic and ventilation**? (1:Not at all, 2:Slightly, 3:Moderately, 4:Very, 5:Extremely)	82	1.67	0.77
11: How would you rate your normal quality of sleep? (1:Very good, 2:Good, 3:Neither good or bad, 4:Bad, 5:Verybad)	82	2.26	1.05
12: In a regular week, how often does noise disturb your sleep? (1:Not at all, 2:1-2 times/week, 3:3-4 times/week, 4:5-6 times/week, 5:Every night)	83	1.35	0.88
13: Thinking about the last 12 months, when you are here at home with the windows and doors shut, how *much is your sleep disturbed by:*			
13.a. **Noise from machines or appliances inside the building**? (Refrigerator, freezer, washer, dryer, lift, AC, ventilation, water pipes, flushing toilets)	84	1.33	0.55
13.b. **Low-frequency noise** from a neighbour's sound system, TV or computer?	84	1.11	0.35
13.c. **Sound of neighbours talking**?	84	1.10	0.48
13.d. **Sound of neighbours walking**, slamming doors and dropping things, thuds from children playing?	84	1.52	0.87
13.e. **Sound of walking** in **shared** spaces of the building (staircase, hallway, etc.)?	84	1.24	0.70
13.f. **Low-frequency noise** (rumbling, muffled sound) from outside sources such as music, traffic and ventilation? (1:Not at all, 2:Slightly, 3:Moderately, 4:Very, 5:Extremely)	84	1.33	0.71
14. Age (Derived from the question "What year where you born?")	82	58	19.13
15. What is your highest completed level of education? (1:Primary school, : High school, 3:College/University)	83	2.34	0.8
16.What is your current occupation? (1:Student, 2:Stay at home, 3:On sick leave, 4:Leave of absence, 5:Unemployed, 6:Employed currently, 7:Other)	83	6.25	1.14

ings. Other additional noise types were unidentified installation noise and machinery noise (e.g. few tenants commented on some noise types that sound like washing machine or ventilation).

The satisfaction related to the acoustic living environment has been included as a variable (question 8, Fig. 3) which has been used in past surveys too (Bradley 2001, Hongisto et.al. 2015). As illustrated up to 77% of subjects are very pleased or fairly pleased with their sound climate, only 11% are fairly or very displeased. For LW buildings the satisfaction ratings are even better with 80% of LW tenants being fairly or very pleased and 11% being fairly displeased.

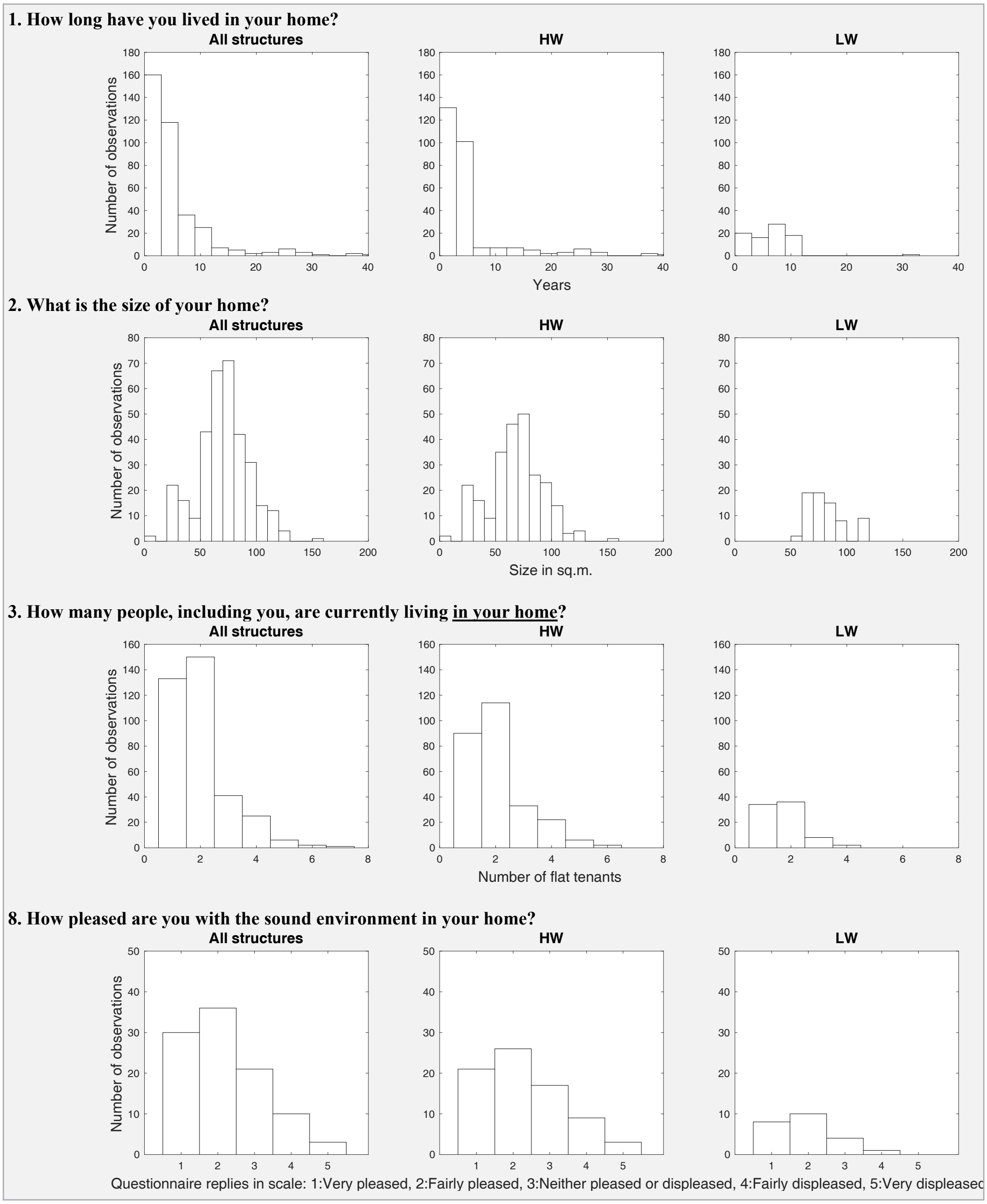


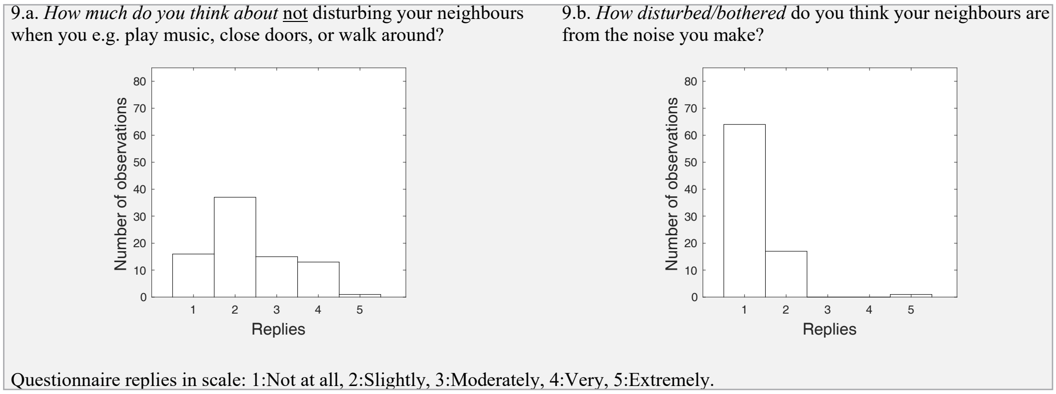
Fig. 3

Questions 1-3 and 8. Histograms of questionnaire replies grouped in different structure types for the sample buildings

Questions 9.a and 9.b, Fig. 4, are inspired by the definition of acoustic comfort provided by Rasmussen and Rindel (2010) and relate to the perception of oneself as a source of noise for others. In 9.a. tenants self-reported that they think, up to some extend, about not causing noise annoyance to their neighbors their own activities. Specifically, 47% of the total subjects replied that they think

Fig. 4

Questions 9.a and 9.b. Histograms of questionnaire replies for the subjects residing in wooden buildings



moderately, very or extremely about not disturbing their neighbors. But the LW percentage is lower at 34%; this happens probably due to increased acoustic comfort sense in wooden buildings so the residents have to think less about noise annoyance in general, both as receivers or sources of noise. Then in 9.b the majority of subjects think that their neighbors are not at all or slightly disturbed by the noise they make: this applies for 93% of the total subjects and 100% of the LW tenants.

In Fig. 5 all the histograms of replies in question module 10 are presented, regarding daytime noise annoyance at home and which noise sources cause higher disturbances. The annoyance ratings were given in a Likert type 5-point-scale with the range: 1-Not at all, 2-Slightly, 3-Moderately, 4-Very, 5-Extremely. Specifically, in 10.a. it can be observed that 51% of LW tenants reported slightly annoyed by machine and installations noise (e.g. washing machine, dryer, water pipes, flushing toilets) in their flat, 33% not at all and 14% are moderately to extremely annoyed.

For question 10.b. (Fig. 5) just 14% of the LW tenants are slightly disturbed by neighbors' low-frequency noise propagating through walls while only 2% are moderately to extremely annoyed. Thus, those neighbors' low-frequency noise types seem to create bigger disturbances through floors in apartments.

In question 10.d. (Fig. 5) it seems that 93% of LW tenants are not at all annoyed by neighbors' talking coming through walls and in 10.e. as well 81% of LW tenants replied as not at all annoyed by neighbors' airborne noise propagating through floors (9% are slightly disturbed, 5% are moderately to extremely annoyed). That is another indication of high acoustic comfort with sufficient airborne sound insulation in Swedish timber buildings.

(80% not at all disturbed, few did not reply). For the same question of sound transmission but through floors, in 10.c, 28% of LW tenants reported slightly annoyed by neighbors' low-frequency noise propagating through floors while 5% are moderately to extremely annoyed (62% not at all).

Impact noise (stepping, kids playing, slamming doors dropping objects) propagating through floors is one of the typical disturbances in family building apartments, known by many previous studies (Vardaxis et.al.). In question 10.f. in Fig. 5, the 46% of the tenants self-reported as slightly annoyed by neighbors' impact sounds while 20% report moderately to extremely annoyed.

Further, in question 10.g. can be observed that 20% of LW tenants are slightly annoyed by noise in shared spaces (hallway, staircases) and 7% are moderately to extremely annoyed. Finally, 10.h. concerns outside low-frequency noise (such as traffic, music, ventilations) for which the responses suggest that 44% of LW tenants are slightly annoyed while 8% are moderately to extremely annoyed: that is another significant high response for a known noise source.

Questions 11, 12 and 13 in Fig. 6 comprise the module in the questionnaire regarding noise annoyance during sleep; it includes the same questions as module question 10 without differentiation

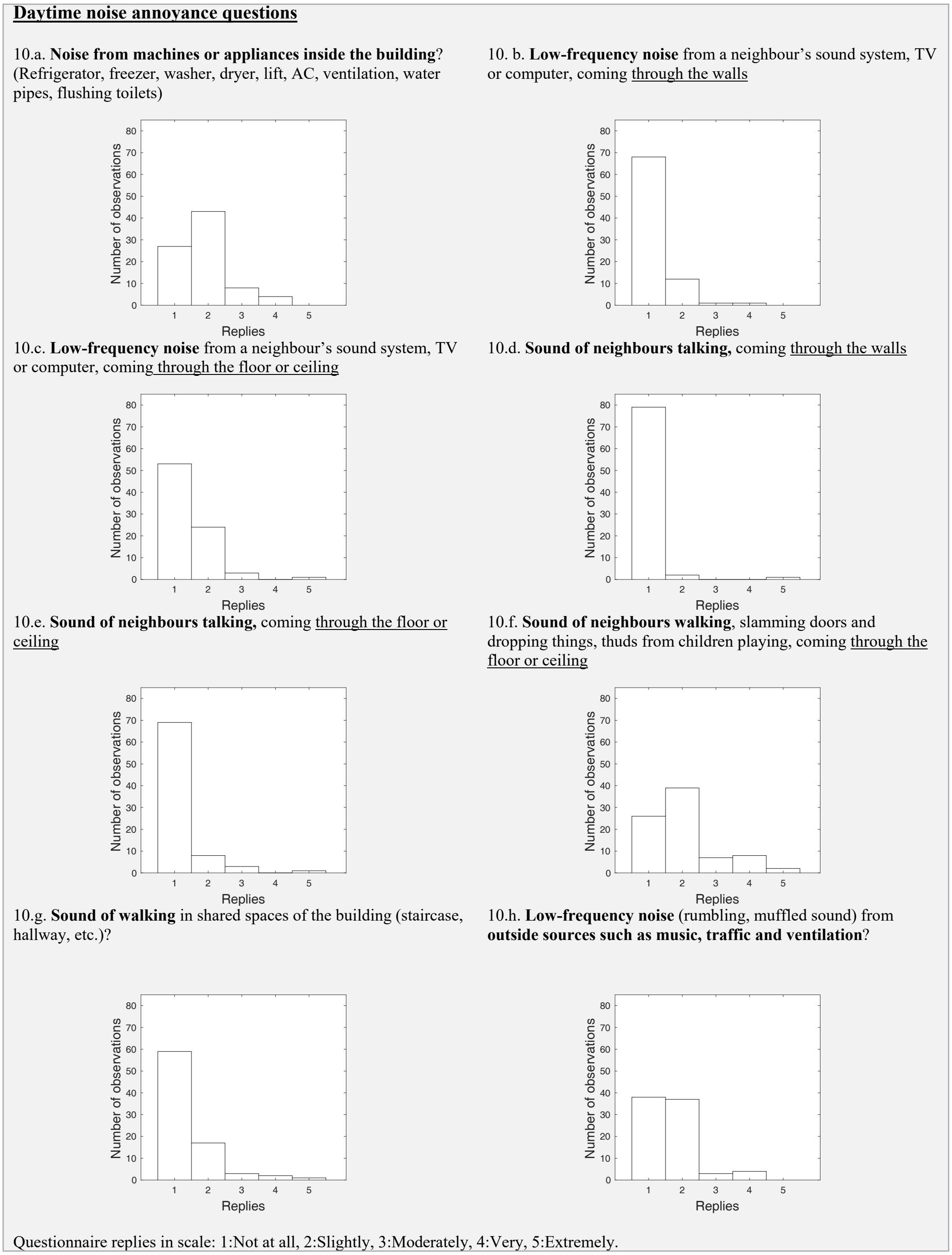


Fig. 5

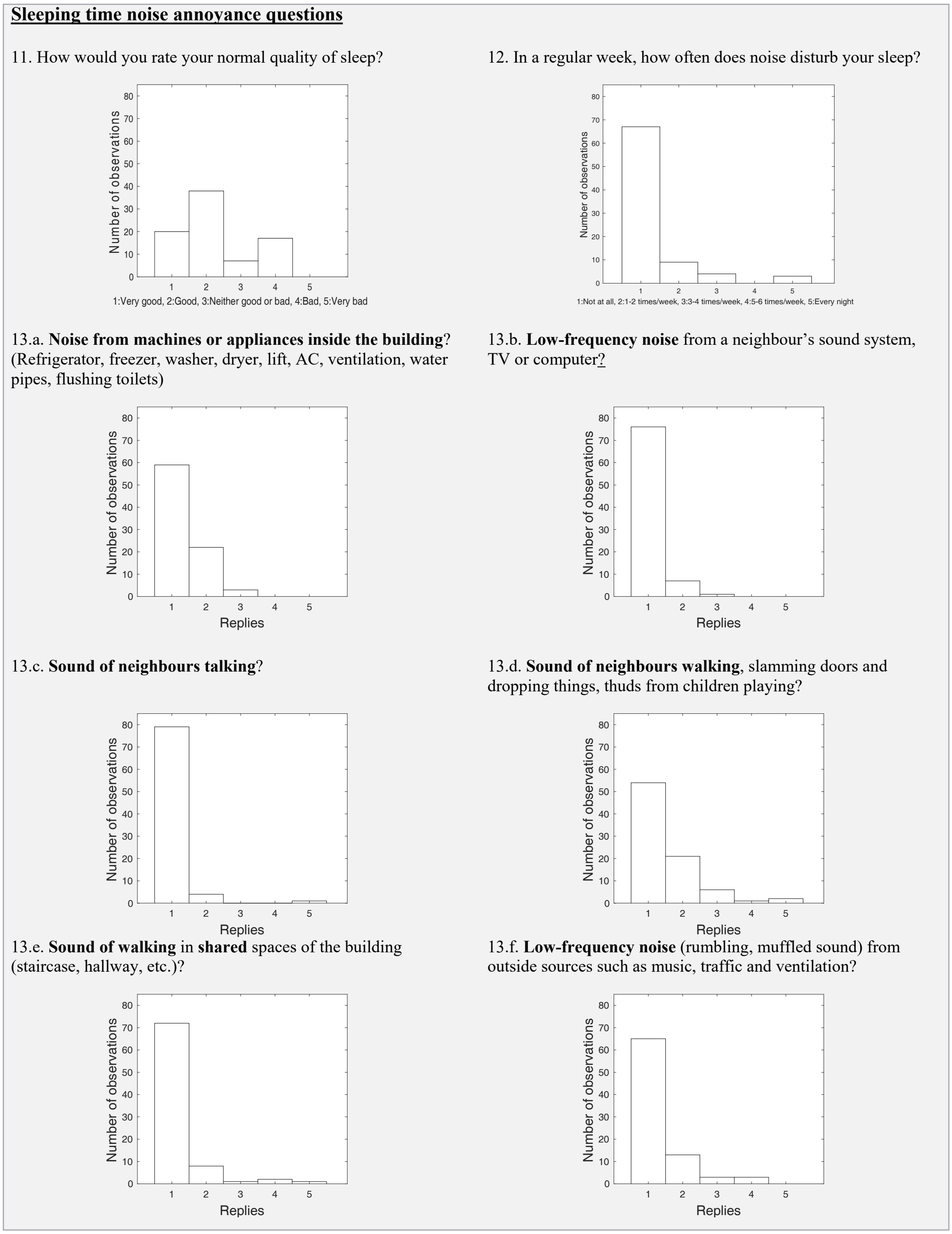
Daytime noise annoyance, Questions 10.a-10.h. Histograms of questionnaire replies for the subjects residing in wooden buildings

between horizontal and vertical sound transmission, i.e. from walls or floors respectively. Question 11 concerns the quality of sleep of the subjects: 20% self-report to have a bad sleep while 68% report having good or very good sleep quality. However, bad sleep quality is not necessarily connected to acoustic conditions. Then, question 12 records how often a subject is annoyed during sleep by any noise: 11% reported disturbed 1-2 times per week and 8% at least 3-4 times per week (79% not at all).

As observed by replies in question 13.a - 13.f in Fig. 6, the same types of noise affect daytime and sleeping time response towards noise disturbance. Specifically, machinery/installations noise

Fig. 6

Sleeping time noise annoyance, Questions 11-13.h. Histograms of questionnaire replies for the subjects residing in wooden buildings



(26% slightly annoyed, 3% at least moderately-extremely annoyed) alongside neighbor's impact noise (25% reported slightly annoyed, 9% moderately-extremely) and outside low-frequency noise (15% slightly and 6% at least moderately annoyed.

Furthermore, some personal and socioeconomic data was gathered in the questionnaire as well. Regarding question 14, the distribution of age for the whole sample is close to a balance where at least 40 observations exist for every category of ages between 20-80 years old. Only subjects of age 18-85 years old were allowed to take part in the study. About 40% of the total subjects are below 40 years old, 30% are between 40-60 and 30% are older than 60. However, residents of LW buildings are older than HW buildings: specifically, 25% of LW residents are below 40 years old, 22% are between 40-60 and 53% are older than 60.

The education status of tenants was recorded too: most subjects have completed university studies (53%) in both cases of HW (54%) and LW (53%) buildings. The occupation status is the topic of question 16: most participants are in the categories of currently employed or reported "other", which mostly means pensioner as it was commented. Again it is observed the for the total sample there are 57% employed tenants and 24% pensioners while for the LW buildings there is only 43% of currently working tenants and 48% of pensioners.

Conclusions

This study presents data from a building acoustic survey in contemporary Swedish structures: the aspects of acoustic comfort in wooden buildings are in the focus of the research, as well as relevant information on light-weight (LW) family residencies in Sweden. The study sample of wooden buildings contains 7 different structures and questionnaire responses from 85 tenants. An overall level of high acoustic comfort is indicated by the self-reported data of LW tenants, with low annoyance responses and only few complaints about the acoustic environment at home.

The timber buildings of our sample were maximum 10 years old at the time of the data collection; the Swedish timber dwellings are also bigger than the average size suggested by a total research sample including many concrete structures. Additionally, most LW residents live alone or with another tenant and only 14% of them have children at home. The situation is different in concrete HW buildings, were 23% of subject have children at home and the living density is higher. Consequently, the practical conditions for LW tenants are better to ensure less noise annoyance from others inside their own flat. The self-reported satisfaction for LW buildings is very high: 80% of LW tenants being fairly or very pleased.

Summing up the noise types that cause the biggest annoyance for residents in the wooden buildings of our sample are: home machinery and installations, impact noise caused by neighbors and outside low-frequency noise; the latter concerns mostly noise sources such as road traffic (vehicle sounds), music from cars, shops, cafes, bars or outer installations such as ventilation from shops, restaurants etc. There is emphasis on the low frequency content of outside noise sounds because that can still propagate in the form vibrations inside apartments with closed windows and doors, while the middle and higher frequencies are usually filtered out from the building façade.

Additionally, if we consider that it is acceptable or at least unavoidable for some residents to be slightly annoyed by a certain noise type in their living environment then we could rank the most disturbing noise source according to the amount of subjects that self-report to be moderately, very or extremely annoyed. That would make sense since for the above three noise types the percentage of subjects reporting slightly annoyed varies between 44-51%, so there is no extreme difference in those cases for a sample of 85 subjects. Consequently, impact noise from neighbors (through floors) would be summarized as the most important noise type (20%), home installations (14%) would be the second biggest annoyance and outside low-frequency noise would come third (8%).

The questionnaire data indicates also some disturbance due to: low-frequency noise from neighbors' sound system (TV or computer) through floors or ceilings and noise in common spaces of the building (corridors, staircases). All the analyzed noise disturbances are typical noise problems in living environments (Ljungren et.al. 2014, Ljungren et.al. 2017, Vardaxis et.al. 2017).

Similar responses were recorded for sleeping time noise annoyance. Most tenants did not report any sleep interruptions in Swedish wooden buildings (79%) but some reported frequent annoyance during sleep (8%). With a ranking approach as before, impact noise from neighbors (through floors) remains the most important noise type (9%), outside low-frequency noise is second highest this time (6%) and installation noise comes third (3%).

Finally, it is important to notice that in our study sample the tenants of wooden buildings are of higher age (53% older than 60) than those in typical concrete Swedish buildings; additionally, most of them are pensioners or not currently employed. Thus there is an imbalance concerning age distribution in the LW sample presented here: it might not be representative of the whole population of wooden building tenants in Sweden.

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