Physical and psycho-vibratory testing of wooden floors

Delphine Bard
Kirsi Jarnerö
Juan Negreira
Lars-Göran Sjökvist
Arnaud Trollé

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Delphine Bard, Juan Negreira and Arnaud Trollé
LTH Lund Technical University

Kirsi Jarnerö and Lars-Göran Sjökvist
SP Wood Technology

Abstract

This report contains results of physical and psycho-vibratory testing of five different wooden floors.

The results of the physical testing indicate that the size of the floors has a great impact on the vibration performance parameters.

The psycho-vibratory tests performed at two locations show that there are large differences between the judgments uttered by the test participants for each floor. The vibrations are considered less annoying/more acceptable when people are walking on the floors than when seated. The differences in subjective response from impact sound between the floors are negligible.

The findings of the physical testing of the floors seem to support the psycho-vibratory results, but the relationships need to be analyzed in more detail and will be presented in a separate report.

Key words: building acoustics, vibrations, springiness, subjective response, annoyance.

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Preface

This report presents results that have been produced within the national Swedish project AkuLite – Acoustics and vibrations in light weight buildings. AkuLite involves all Swedish research institutions active in the field, leading industries and consultants. Vinnova and Formas are the public funders. The project started in late 2009 and will be finalised in early 2013.

The work reported here has been performed in cooperation between Delphine Bard, Juan Negreira Montero and Arnaud Trollé at LTH Lund Technical University and Kirsi Jarnerö and Lars-Göran Sjökvist at SP Wood Technology in Växjö.

The test results will be analyzed in more details and presented in a separate report.

Klas Hagberg

AkuLite project manager
SP Wood Technology and WSP Acoustics

Birgit Östman

Senior advisor
SP Wood Technology

Content

Summary

This report contains results of physical and psycho-vibratory testing of five different wooden floors. The tests have been performed both in Växjö and Lund.

In the physical testing, the one- and two-point deflection tests give different values of deflection but, when sorting the values in increasing order, one can observe that the rankings of the floors are the same for both tests. Floor 1 has the lowest deflection value and floor 2 the highest. Floor 1 also has the lowest impulse velocity response, which could be an indication of good performance regarding vibration annoyance.

When looking at the driving point velocities of the floors, one can observe that there are some clear differences between the floors. The characteristics of floors 2 and 4 are clearly different from those of the other floors: the former floors have the highest number of modes below 50 Hz. Floor 2 also has the lowest damping ratio, longest span and highest mass. Floor 3, on the other hand, has the highest first eigenfrequency, highest damping ratio, lowest number of modes below 50 Hz, shortest span and lowest mass.

These results of the physical testing indicate that the size of the floors has a great impact on the vibration performance parameters and therefore the floor structures are not comparable in such a way that it is possible to rank them as better or worse when completely installed in a building.

At both locations, in Växjö and Lund, the tests show that, for each floor, within each subtest, there are large differences between the judgments uttered by the test participants. Still, there are detectable differences between the floors in terms of performance regarding springiness, vibration annoyance and vibration acceptability. The subtest condition, seated or walking, has a great effect on the subjective responses. The vibrations are considered less annoying/more acceptable when people are walking themselves on the floors.

Regarding noise annoyance from impact sound, the differences in subjective response between the floors are negligible, i.e. the floors are not discriminated in terms of noise annoyance.

Regarding vibration annoyance and vibration acceptability, the results from Lund show that the vibrations of floor 3 are considered the most acceptable / least annoying and the vibrations of floors 2 and 5 the least acceptable/most annoying. In Växjö, the test participants favored floor 1, it had the most positive response on all questions regarding vibrations, springiness and noise. On the contrary, floor 2 had the most negative response.

The findings of the physical testing of the floors seem to support the psycho-vibratory results, but the relationships between the results from the physical testing and the subjective responses need to be analyzed in more details and will be presented in a separate report.

The aim is to find a vibratory indicator for each of the attributes, i.e. springiness, vibration annoyance and vibration acceptability, that would make it possible to predict at best the subjective responses.

Sammanfattning

Denna rapport redovisar resultat från provning av fysiska egenskaper och subjektiv upplevelse av vibrationsegenskaper(psyko-vibrationsegenskaper) för fem olika träbjälklag. Provningarna har utförts i Växjö och i Lund.

Den fysiska provningen med en- och tvåpunkts nedböjning ger olika resultat, men rankingen av bjälklagen är densamma enligt båda metoderna. Bjälklag 1 har den lägsta nedböjningen och bjälklag 2 den högsta. Bjälklag nr 1 har också den lägsta impulshastighetsresponsen, vilket kan vara en indikation på låg vibrationsstörning.

Bjälklagen har olika beteende med avseende på mobiliteten i exciteringspunkten, där bjälklag 2 och 4 avviker från övriga och har högsta antalet moder under 50 Hz. Bjälklag 2 har också lägst dämpning, störst spännvidd och högst massa. Bjälklag 3 har å andra sidan högst egenfrekvens, högst dämpningsförhållande, lägst antal moder under 50 Hz, kortast spännvidd och lägst massa.

Resultaten från den fysiska provningen indikerar att bjälklagens storlek har stor inverkan på vibrationsegenskaperna. Därför är bjälklagen inte jämförbara så att de kan rankas före installationen i en färdig byggnad.

Provning av psyko-vibrationsegenskaper utfördes både i Växjö och i Lund. Resultaten visar i båda fallen att det är stora skillnader upplevelsen hos försökspersonerna. Men det finns också skillnader mellan bjälklagen avseende svikt, vibrationsstörning och vibrationsacceptans. Vibrationerna anses mindre störande när försökspersonerna själv går på bjälklagen än när de sitter ner och någon annan går på bjälklaget.

Skillnaderna i uppfattad ljudstörning från stegljud för de olika bjälklagen är försumbara.

Vibrationsstörningar och vibrationsacceptans i Lund visar att egenskaperna för bjälklag 3 är minst störande och att de för bjälklag 2 och 5 är mest störande. I Växjö bedömdes egenskaperna för bjälklag 1 som bäst med mest positiva resultat för vibrationer, svikt och ljud. Å andra sidan fick bjälklag 2 mest negativa svar.

Resultaten från de fysiska provningarna verkar överensstämma med psyko-vibrationsegenskaperna. De kommer att analyseras vidare och presenteras i en separat rapport.

Målet är att finna en vibrationsindikator för vikt, vibrationsstörning och vibrationsacceptans, som kan prediktera den subjektiva upplevelsen.

1 Introduction

When increasing the use of wood in building the structural use of wood is broadened and demands on performance of the structural parts are changed. Structural solutions suitable for one family and row houses have to be modified when applied in multistorey residential buildings. Demand on use and performance in office buildings and other public buildings are also completely different when concerning say layout. Designs with large open spaces that are easy to change if the use is changed are common. An open space layout often imply long spanning floors that will be more easy to excited by human activities when made of lightweight wooden structures than heavier concrete ones. Therefore annoyance due to human induced vibrations has to be taken in consideration when designing wooden floors. In the present work the human perception and annoyance of vibrations in wooden floors are investigated.

In order to assess how people perceive floor vibrations, five different prefabricated floor structures were used to carry out psycho-vibratory tests in Växjö and in Lund. The tested floor structures were delivered from five suppliers that provide prefabricated floor elements for residential buildings. Each supplier adopts its own concept of structural design, which results in differences in the floor design. For instance there are both box and surface unit concepts. The use of each floor may also be intended for slightly different building design and construction. The most desirable situation for the psycho-vibratory tests would perhaps have been to have a range of floors with clearly different vibration performance spanning from clearly not acceptable to very good vibration performance. The presently tested floors have different vibration properties but the vibration performance range is narrow, as each supplier in large extent did choose themselves the sizes and designed the floor to have acceptable vibration performance with regard to that size. This makes it harder for the people participating in the test as test subjects to judge the floor vibration performance.

In Växjö 29 persons and in Lund 31 persons participated in the tests as test subjects. All the floors were tested by all the subjects and the floors were presented to them in random order. The test has been divided into two subtests, both in Växjö and in Lund; a seated subtest, during which the subject was seated in a chair on the floor and a walking subtest, during which the subject was asked to walk on the floor. A questionnaire was presented to the subjects during the test. The used questionnaire was different in Växjö and in Lund, see Appendix A and B respectively.

During the psycho-vibratory tests objective measurements were also carried out on the floors, in order to assess accelerations and deflections experienced by the subjects. Accelerations were measured in several points on the surface of the floor and deflections were measured on the bottom side of the floor. To evaluate physical measurable properties of the floors, i.e. properties not dependent of the test subject, both static and dynamic tests were carried out.

The performed physical properties tests and the psycho-vibratory tests with findings are presented in separate sections of this report. The tests for the physical properties are described independently of locality, Växjö or Lund. The psycho-vibratory tests are on the other hand presented separately for each locality in two separate sections.

2 Tested floor structures

The tested floor elements were delivered by five suppliers that are active on the Swedish construction market. All of the suppliers provide floor elements for residential buildings, but the total structural building concept, which the floors are a part of, may differ. The use of each floor element may also be intended for slightly different building design and construction. The fact that the floors included are not designed to meet any common set requirement when it comes to performance or to other quality properties means that the results presented here are not comparable in such a way that it is possible to rank them as better or worse when completely installed in a building.

A floor designed for an intended use, in a specific location and completely installed in a building structure would behave differently than as here installed on supports in a laboratory. In a finished building the boundary conditions and added structural parts change the vibration performance of a floor.

The floors when tested in Växjö were labeled with numbers according to Table 1 and when tested in Lund labeled with characters also according to Table 1. Hereafter the floors will be referred to using the appropriate number or character. In Table 2 information about the structural parts of the floors and about whether ceiling or supplementary flooring were installed or not are presented. In Figure 1 to Figure 5 section drawings of each floor is presented.

Table 1. Floor suppliers and floor labeling according to tests performed in Växjö and in Lund

Supplier	**Floor Number**	**Floor Character**
Moleven Töreboda	1	A
Martinsons Byggsystem	2	B
Lindbäcks Bygg	3	C
Masonite Beams	4	D
Masonite Lättelement	5	E

Table 2. Floor design, all sizes in mm

	Floor number 1	**2**	**3**	**4**	**5**
Total length	6800	8500	3700	7966	8100
Total width	2x2400 4800	4x1200 4800	2400	2x2402 4804	2x2424 4848
Flooring	-	-	13 flooring gypsum board		13 flooring gypsum board
Sheathing	33 Kerto Q511	73 CLT, cross laminated timber	22 flooring chipboard	43 plyboard	43 plyboard
Beams	Web: Kerto S80 51x360 s587 Flange: Kerto S16 45x300	Web: Glulam C40 42x220 s460 Flange: Glulam C40 42x180	Web: Glulam 42x225 s600 Flange: Plywood 12x300	Masonite beam HB 350 C24 s480 Flange width 98	Masonite beam H300 C24 s585
Remarks	-	-	-	Beam in one of the long sides H350 C24 flange width 45	Tension flange 0.7 mm perforated steel sheet
Strutting	2 rows of beams Kerto S75 51x360 L1 = 2392 L2 = 4362	-	-	2 rows of Masonite beams H350 K24 L1=3079 L2=6079	2 rows of Masonite beams H300 K24 L1=3079 L2=6079
Junction between floor elements	WT-T screw 6.5x130 s300 every second from left and right element respectively	Plywood strip 12x160 P30 screwed with WFR 4x50 s125	-	Glued with SikaBond-540 Chipped nails 34x45 s300	Overlapping plyboard screwed with 5x90 s300
Number of elements	2	4	1	2	2
Ceiling	-	-	-	2x 13 gypsum board	13 gypsum board
Weight (kg/m^2)	59.5	67	43	48	53

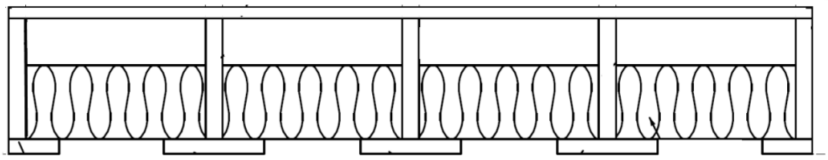


Figure 1. Floor 1, Moelven Töreboda

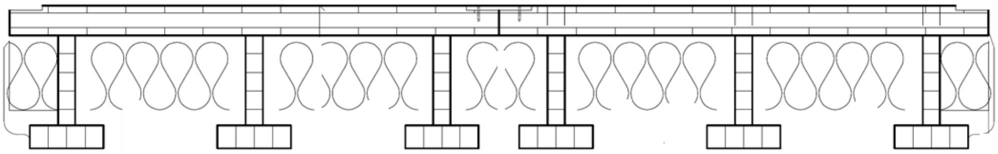


Figure 2. Floor 2, Martinsons Byggsystem

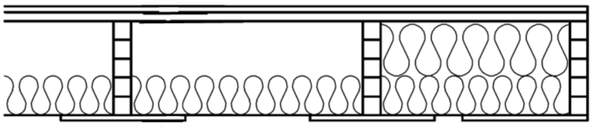


Figure 3. Floor 3, Lindbäcks Bygg

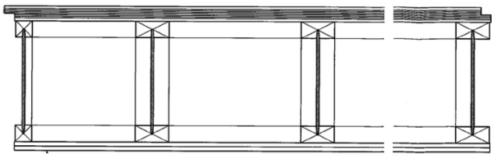


Figure 4. Floor 4, Masonite Beams

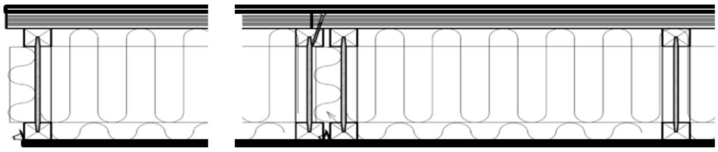


Figure 5. Floor 5, Masonite Lättelement

2.1 Test setup

Each floor element was simply supported on two sides on glulam beams with dimensions 90x180 mm^2. The beams were supported by studs with a center distance of 600 mm. The studs were stabilized with plywood slabs, as shown in Figure 6. This support structure was bolted to the laboratory concrete floor. The attachment of the floor elements to the supports was performed according to the suppliers instructions by a construction company. The sides of the elements and the supporting structure were covered with black plastic down to floor level so that the visual impression of all test setups was fairly equal.

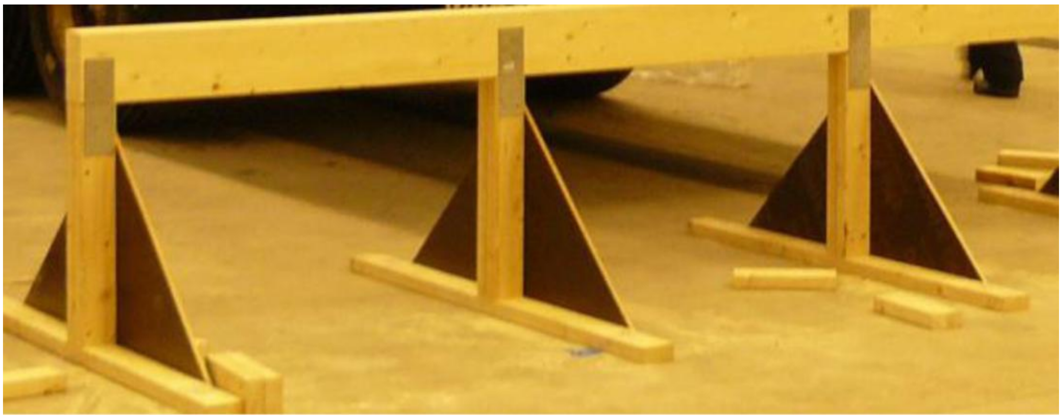


Figure 6. Floor element supporting glulam beam, studs and stabilizing plywood slabs.

3 Physical property test

In order to evaluate physical and measurable parameters such as stiffness, resonance frequencies, damping and mode shapes of the floors, both static and dynamic tests were carried out. The testing of floor stiffness was carried out by measuring the vertical deflection of the floor surface at one or two points when loading the floor with a point load. The dynamic testing was carried out with shaker excitation. The vertical response accelerations were measured at several points with accelerometers. The eigenfrequencies, damping ratios, mode shape and modal densities were extracted from the measured frequency response functions (FRF:s). From the driving point mobility the impulse velocity response also was calculated. The impulse velocity response is the vertical vibration velocity due to an excitation by a 1 Ns impulse of the floor at the loading point. This parameter gives an idea about the vibration performance of the floor and is used in EC 5 used as a floor design parameter.

3.1 One-point deflection measurement

The static deflection due to a 1 kN point load was measured at three points on each floor. The loading was the weight of a person standing at the loading point. The obtained deflection value was extrapolated to be equivalent to a deflection due to a 1 kN point load. The deflection was measured in the following three points:

1. At the centre of the floor at point 4, shown in Figure 7.

2. Near the free long side edge, at point 1 which is under the chair in which the person taking part of the psycho-vibratory test sat during testing, as shown in Figure 7.

3. At point 2 as shown in Figure 7, this is a point along the walking line used by the test leader during the subjective psycho-vibratory test.

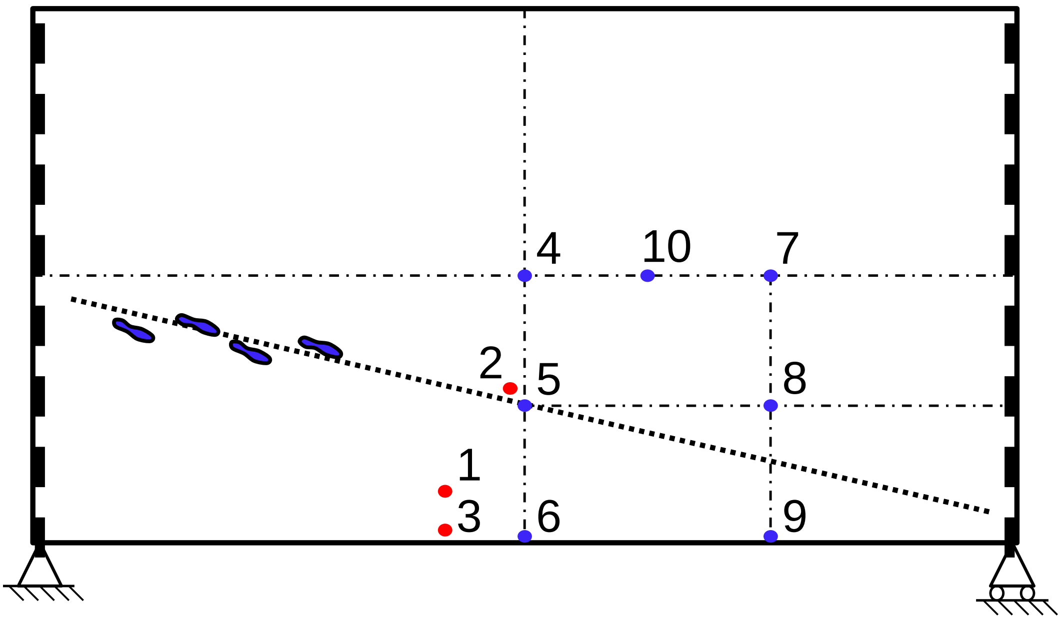


Figure 7. Location of points where excitation and acceleration measurements were performed during the tests. The red color indicates measurement points used for the acceleration measurements during psycho-vibratory tests and the blue color indicates additional measurement points used during the physical property tests.

3.1.1 Method

The floors were loaded by the weight of a person standing with the feet on each side of the measurement point and in the direction of the load bearing beams in of the floor. Before performing the measurement, a walking path to and back from the loading point was evaluated so that the deformation reverted to the starting value i.e. the measured deflection was not affected by the walking to and back from the loading point. The displacement gauge, a Mitotoyo absolute digimatic indicator model ID-C150B, was fastened on a magnetic stand that was attached to a metal weight hung from an overhead crane. The displacement gauge was connected to a PC via cable and a trigger device was used to enable triggering and reading of the deflection values from a distance, without loading the floor. To eliminate the effect of possible unevenness in the floor surface a small slice of plexiglass slice was placed on top of the floor and the tip of the gauge was placed on the slice. Each floor was measured five times as follows:

1. Standing beside the floor, not loading it, reading the starting deflection value three times with a few seconds between each reading.
2. Transfer to the loading point along the evaluated walking path.
3. Loading the floor by standing still, with the feet placed on each side of the measurement point and parallel to the supporting beams, without harming the measurement gauge or its suspension.
4. Reading the deflection value four times with a few seconds between each reading.
5. Transfer back off the floor along the evaluated walking path and reading the final deflection value three times with a few seconds between each reading.

3.2 Two-point deflection measurement

For each wooden floor, two displacement gauges measuring the vertical deflection of the floor were placed on top of the floor surface. More precisely, the gauges were placed:

- at the midpoint of the floor as shown in Figure 8 and Figure 9, and
- at a point 0.6 m away from the midpoint.

The gauges were attached to a rigid steel portal frame that was moved from one floor to another between the tests. This test setup was the same for each floor. The data acquisition was performed using Spectrum SBench 6.1 software.

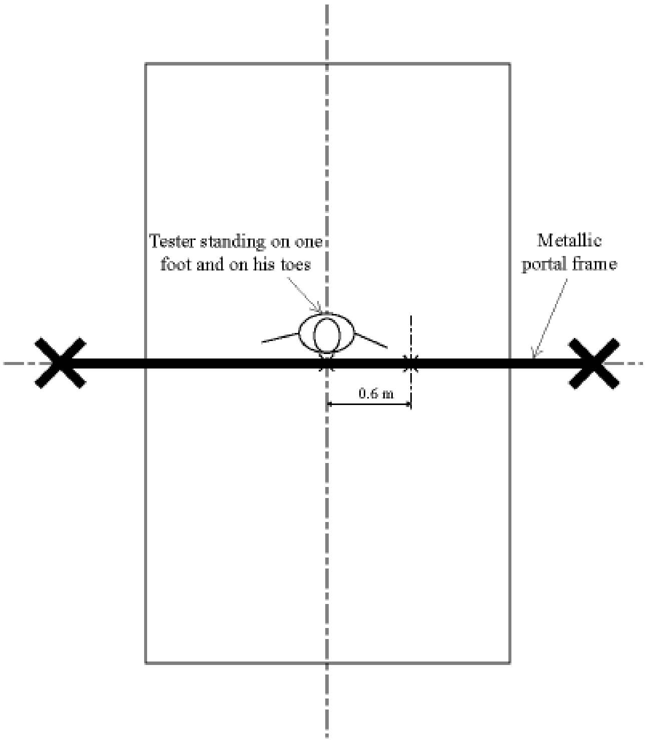


Figure 8. Plan view of the two-point deflection measurement setup.

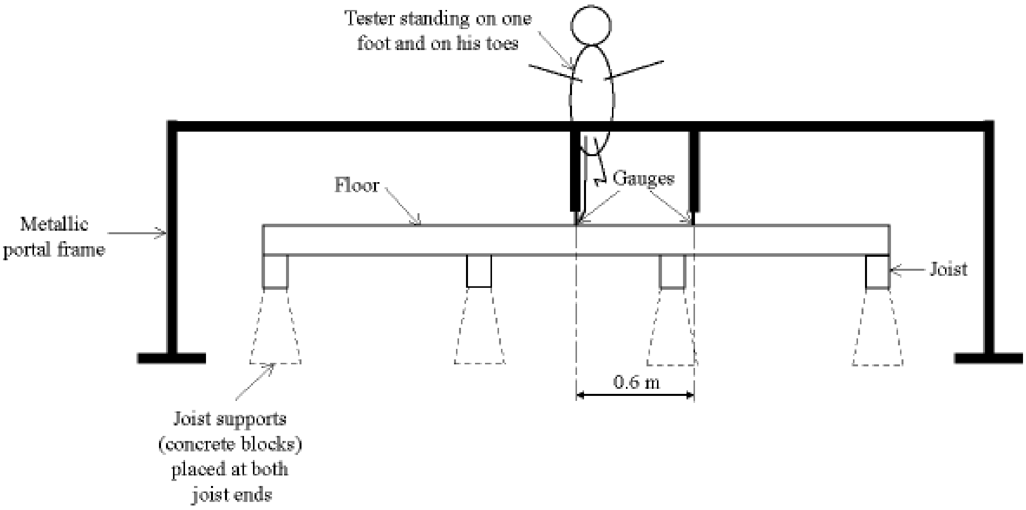


Figure 9. Side view of the two-point deflection measurement setup.

3.2.1 Method

The used measurement procedure was based on one proposed by Talja [Talja, 2000]. The midpoint of the floor was loaded, as shown in Figure 8 and Figure 9, by the test leader's weight, which was about 80 kg. The test leader stood on one foot and on his toes. The displacement during loading has been recorded simultaneously by both gauges. Three trials of loading were carried out for each floor.

3.3 Eigen frequencies, damping ratios and modal density

In Växjö the excitation of the floor was performed with the shaker driven by a pseudo random signal. The excitation force was measured with a force transducer attached to the floor by a wood screw and to the shaker by a threaded rod, as shown in Figure 10 (left side). The shaker was suspended from an overhead crane. Three different measurements with different driving points were carried out. The driving points were points 2, 4 and 8 shown in Figure 7. Point 2 was placed at the walking line used during psycho-vibratory tests, as close as possible to the chair where the test subjects sat. Loading at point 4 efficiently excites the first order bending modes and loading at point 8 the second-order bending modes. The response accelerations were measured with accelerometers in seven points on the floor surface, marked blue in Figure 7.

Figure 10. Shakers used to excite the floors to the left dynamic tests performed in Lund and to the right in Växjö.

3.3.1 Linearity and reciprocity

In order to verify that the performance of the floors at the used excitation levels was linear a linearity check of was carried out. This linearity check was performed by loading the floors at two different excitation levels, a higher and lower level, the latter being approximately half of the former. A linear system would give exactly the same FRF:s regardless of excitation level. The check showed that the performance of all the floors was sufficiently linear for the used excitation levels.

The reciprocity of the floor response was examined from the FRF:s computed for each couple of excitation points. As reciprocity is one property of a linear systems, the reciprocity check is a way to further check the linearity of the tested system. Reciprocity means that the FRF for an excitation at e.g. point 2 and a measurement of the response at point 8 is the same as that for an excitation at point 8 and a measurement of the response at point 2. The results of the reciprocity test for floor 5 are shown in Figure 11.

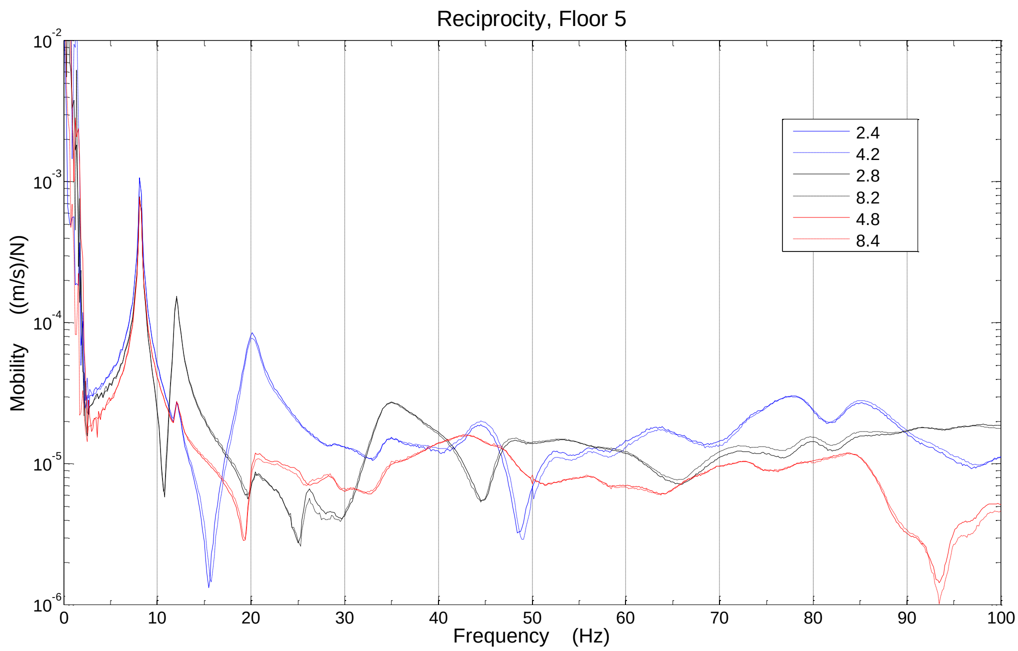


Figure 11. Result of the reciprocity check for floor 5.

3.3.2 Technical equipment

- FFT-analyser with 16 channels, Dataphysics Abaqus Mobylizer.
- Data acquisition with Signal Calc Mobylizer software
- LDS V406-PA500 Shaker and amplifier
- Force transducer Kistler type 9301B with signal amplifier Kistler type 5015A10X0.
- Accelerometers Kistler 8772A 5T and 50T with associated cables.
- Wax and hot-melt adhesives for fastening accelerometers.

3.4 Mode shapes

In Lund, in order to determine the mode shapes of each floor, the response accelerations of the floor were measured at 28 positions, evenly distributed along 4 lines over the short side and along seven lines along the long side. The measurement was performed with MEMS (microelectromechanical system) accelerometers attached on the floor surface. The excitation of the floor was performed with the shaker driven by a chirp signal swept from 5 to 200 Hz during one minute. The shaker was suspended and attached as shown in Figure 10(right side). The data was acquired by Spectrum SBench software.

3.5 Physical properties - results

3.5.1 One point deflection measurement

The results of the floor deflection measurements carried out at three different points are presented in Table 3.

Table 3. Deflection due to a 1 kN point load at point 4, at the center of the floor as shown in Figure 7, at point 1, under the backrest of the chairs, and at point 2, on the walking line.

Floor	d_4 (center of the floor) (mm)	d_1 (under backrest of the chair) (mm)	d_2 (in the walking line) (mm)
1	0.26	0.67	0.49
2	0.66	1.05	0.58
3	0.56	0.84	0.77
4	0.53	1.13	0.53
5	0.44	0.88	0.70

3.5.2 Two-point deflection measurement

The two-point deflection value was calculated as proposed by Talja (Talja, 2000).

The maximum displacements recorded by each gauge were averaged across the three trials performed. These average maximum displacements, were subtracted and the difference was scaled, to get the final deflection value. The results are presented in Table 4.

Table 4. Two-point deflections [mm/kN] due to a point load.

Floor	Max. displacement – Middle gauge [mm]	Max. displacement – Side gauge [mm]	Difference [mm]	Two point deflection [mm/kN]
A	0.04246	-0.05619	0.09865	0.101
B	0.2523	-0.2665	0.5188	0.529
C	0.2173	-0.1117	0.329	0.335
D	0.1518	-0.162	0.3138	0.320
E	0.07235	-0.1533	0.22565	0.230

3.5.3 Eigen frequencies, damping ratio and modal density

The analysis of measurement data was carried out with a MATLAB toolbox, The VibraTools Suite, with functions for modal analysis. For each floor the eigenfrequencies, the damping ratio, ζ(%), and number of eigenfrequencies below 50 Hz, n_{50}, were extracted. In order to evaluate the eigen-frequencies and damping ratio from the measurement data a poly-reference time domain method was used for determining poles and modal participation factors, and then a least squares frequency domain method was used to fit estimated to measured data. The work was carried out for smaller parts of the frequency span at a time with one or several excitation points included.

The results that are presented here contain some uncertainties since they are based on measurement data that are only measured in the vertical direction. Local modes in the floor, e.g. in the beams of the floor, complicate the analysis as they influence the FRF:s, but can't be separated from the vertical modes as the horizontal movements of the beams are not measured. The assessment of the number of eigenfrecuencies below 50 Hz was done by combining visual evaluation of the FRF:s with the poly-reference time domain method. Large numbers of resonance frequencies, closely spaced modes and high damping values make the visual evaluation more difficult, meaning that the value of n_{50} should be considered as an approximate number. The fact that the analysis is not a complete modal analysis with measured responses from all over the surface also supports the fact, as it makes it hard to say if a resonance is coupled to a vertical movement in the surface of the floor or maybe a horizontal movement of a beam.

The extracted eigenfrequencies and the number of eigenfrequencies, n_{50}, below 50 Hz for each floor is presented in Table 5 and Table 6 respectively. The corresponding damping ratios are presented in Table 7. In Figure 12 the different examples of synthesized FRF:s and measured FRF:s are plotted. The three examples show measurements with the excitation located in the different points 2, 4 and 8 and the examples are chosen for the purpose of showing a good, a medium and a less good fit of synthesized to measured FRF:s. In Table 8 the differences in percentage between the synthesized and the measured FRF:s are presented.

Table 5. Extracted eigenfrequencies, f.

Floor	**Mode**															
	1 (Hz)	**2** (Hz)	**3** (Hz)	**4** (Hz)	**5** (Hz)	**6** (Hz)	**7** (Hz)	**8** (Hz)	**9** (Hz)	**10** (Hz)	**11** (Hz)	**12** (Hz)	**13** (Hz)	**14** (Hz)	**15** (Hz)	**16** (Hz)
1	16.3	17.7	18.3	30	36	44										
2	9.9	10.5	11.1	17.3	24.2	27.8	29.5	33.7	36.6	38.9	39.6	42	44.2	45.4	48	49.4
3	24.3	26.1	36	49												
4	8.8	9.9	14	22.7	24	28.3	31.7	37	40.5	44.9						
5	8.2	12	20.2	25.9	28.4	34.1	45.1									

Table 6. Number of eigenfrequencies below 50 Hz, n_{50}.

Floor	**1**	**2**	**3**	**4**	**5**
n_{50}	6	16	4	10	7

Table 7. Extracted damping ratios, ζ.

Floor	**Mode**															
	1 (%)	**2** (%)	**3** (%)	**4** (%)	**5** (%)	**6** (%)	**7** (%)	**8** (%)	**9** (%)	**10** (%)	**11** (%)	**12** (%)	**13** (%)	**14** (%)	**15** (%)	**16** (%)
1	1.6	1.5	1.5	8	5											
2	0.7	1.1	0.9	1.2	1.1	1.4	1.6	1	1.2	2.1	1.3	2.2	1.4	1.4	1.8	1.2
3	2.3	2.6	5	8												
4	1.8	2.1	2.2	2	2	1.5	1.6	2	1.4	1.5						
5	1.1	1.8	3.5	2.6	3.2	4	4.5									

Table 8. The difference in percentage between the synthesized FRF:s and the measured FRF:s.

Δ between curve fitted data and measured data				
Floor	**Point 2** (%)	**Point 4** (%)	**Point 8** (%)	**Average** (%)
1	17.7	14.5	15.1	15.8
2	20.9	19.8	22.9	21.2
3	9.4	10.1	12.4	10.6
4	36.3	25.6	32.3	31.4
5	29.3	24.6	29.4	27.8

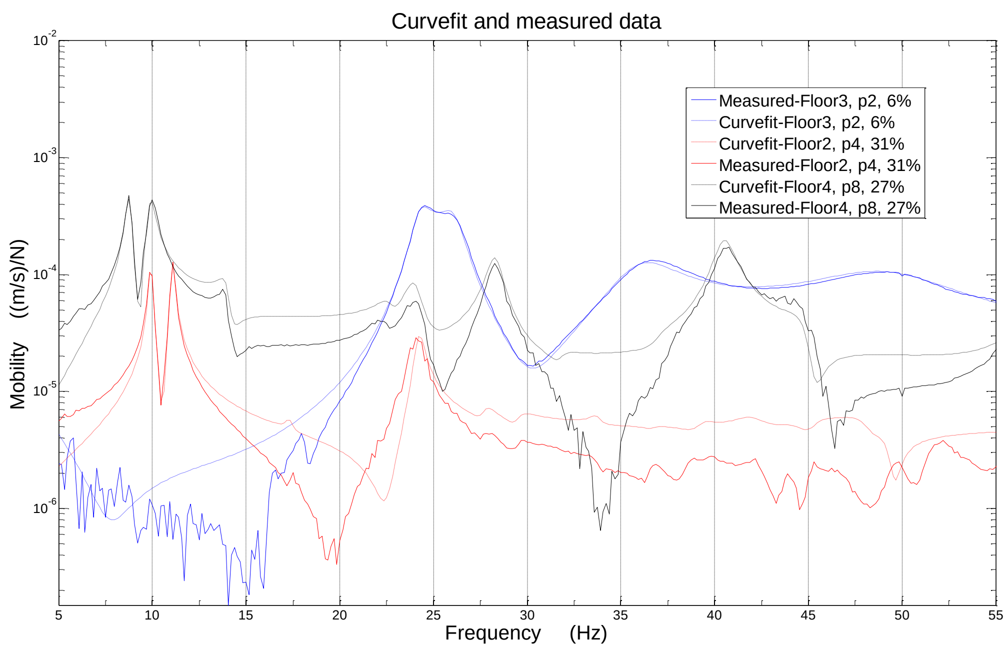


Figure 12. Examples of different qualities of synthesized FRF:s.

3.5.4 Mode shapes

The data acquired data from the 28 measurement points were analyzed using a homemade MATLAB program, with which the eigenfrequencies and mode shapes were extracted. The first eigenfrequency and mode shape for all the tested floors is presented in Figure 13.

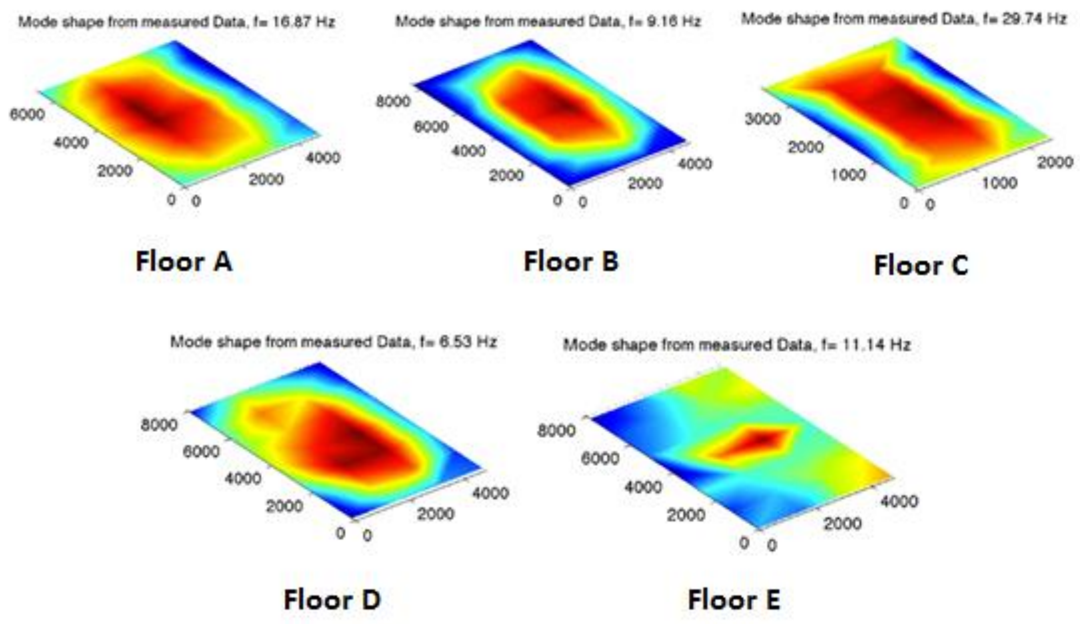


Figure 13. First eigenmode (modal shape and eigenfrequency) for the different floors.

3.5.5 Impulse velocity response

The velocity was extracted by integrating the measured acceleration data in MATLAB. In Figure 14-Figure 18 the driving point mobility, i.e. the velocity in the excitation point, for all tested floors and excitation points is presented.

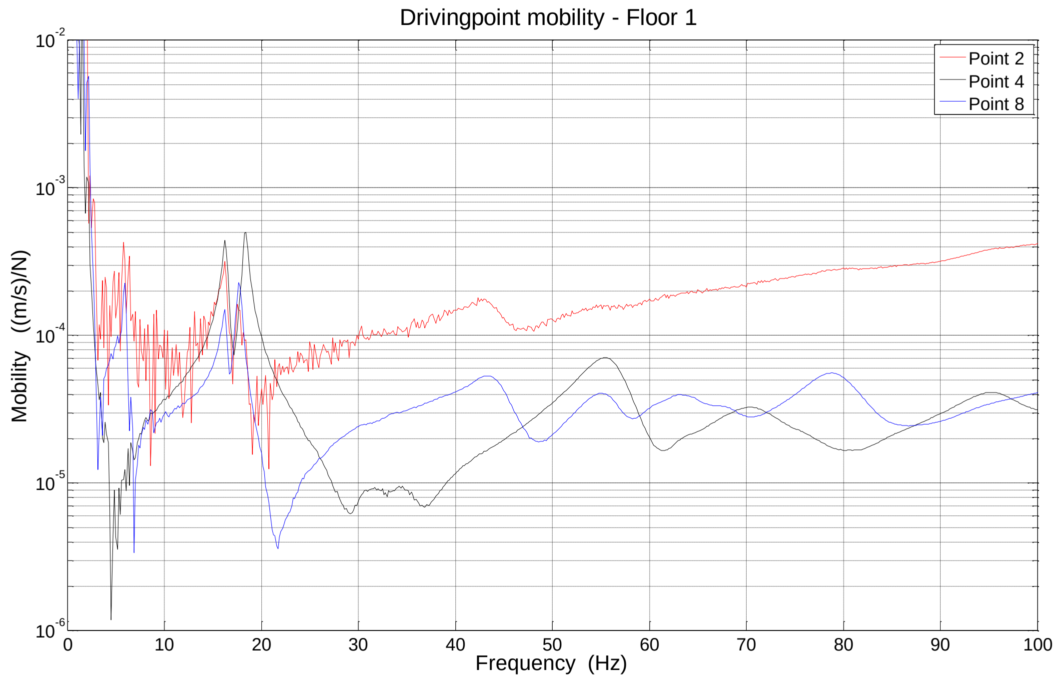


Figure 14. Driving point mobility floor 1.

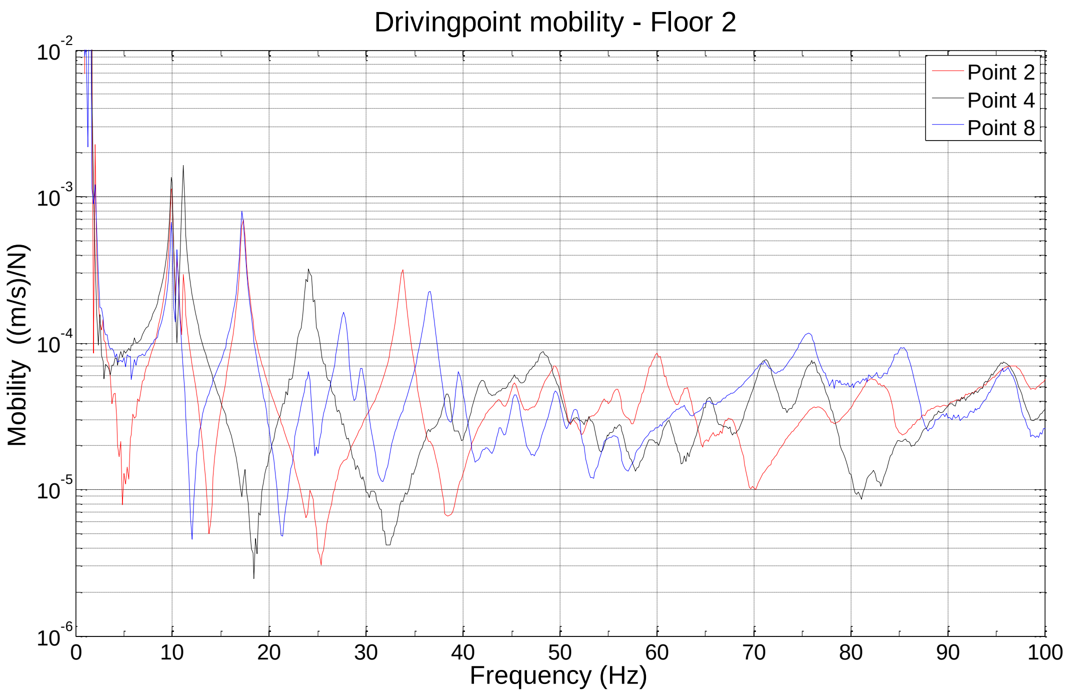


Figure 15. Driving point mobility floor 2.

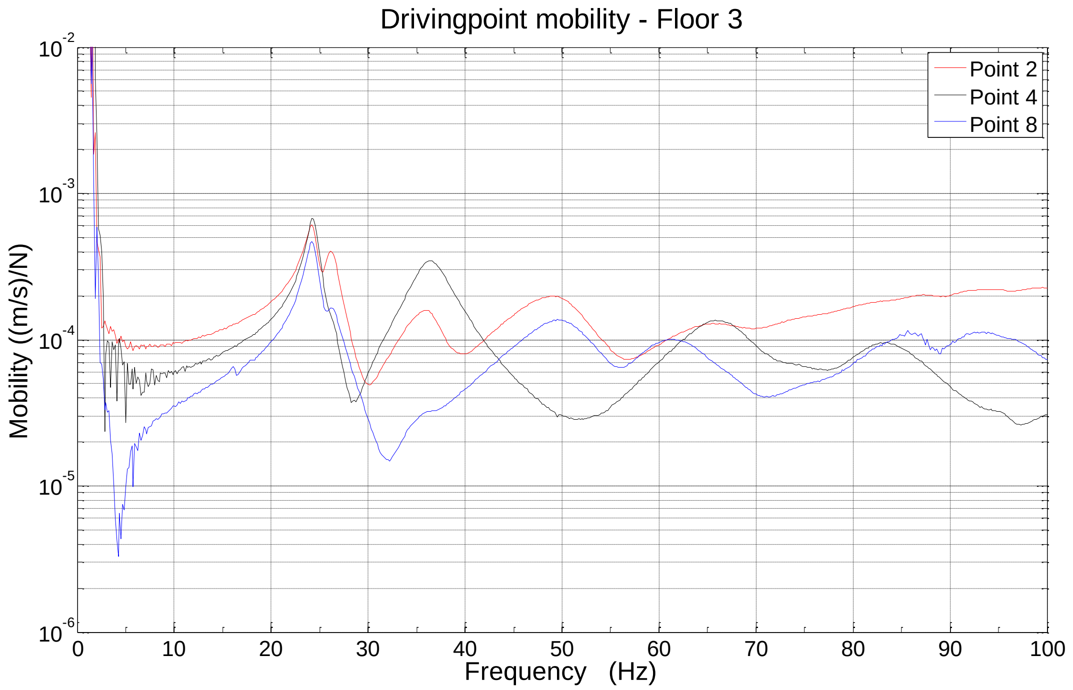


Figure 16. Driving point mobility floor 3.

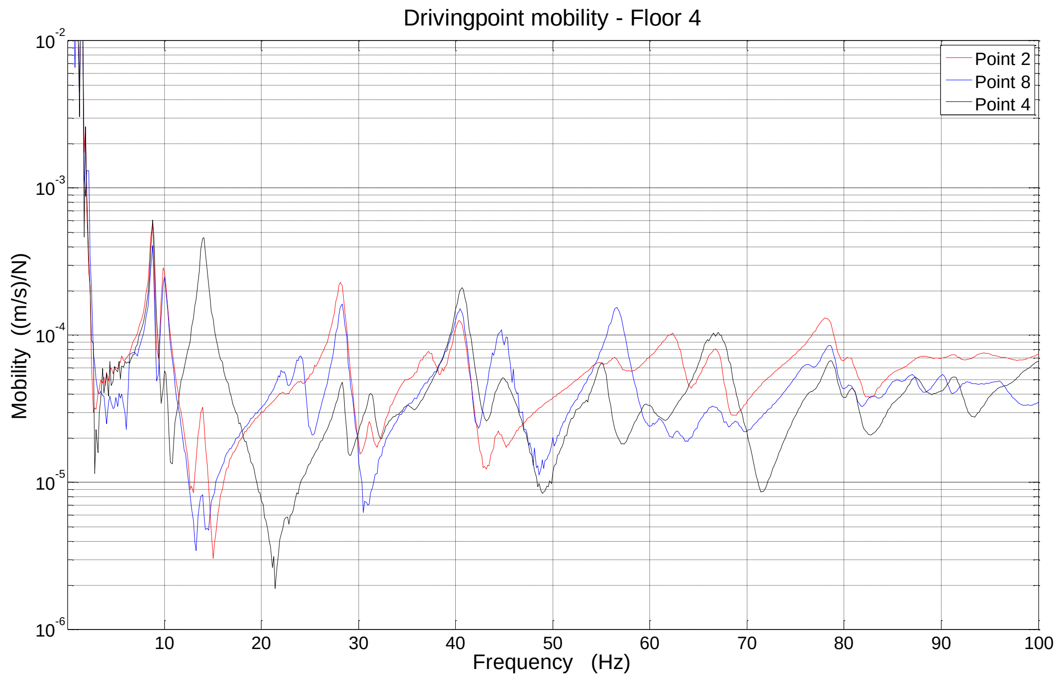


Figure 17. Driving point mobility floor 4.

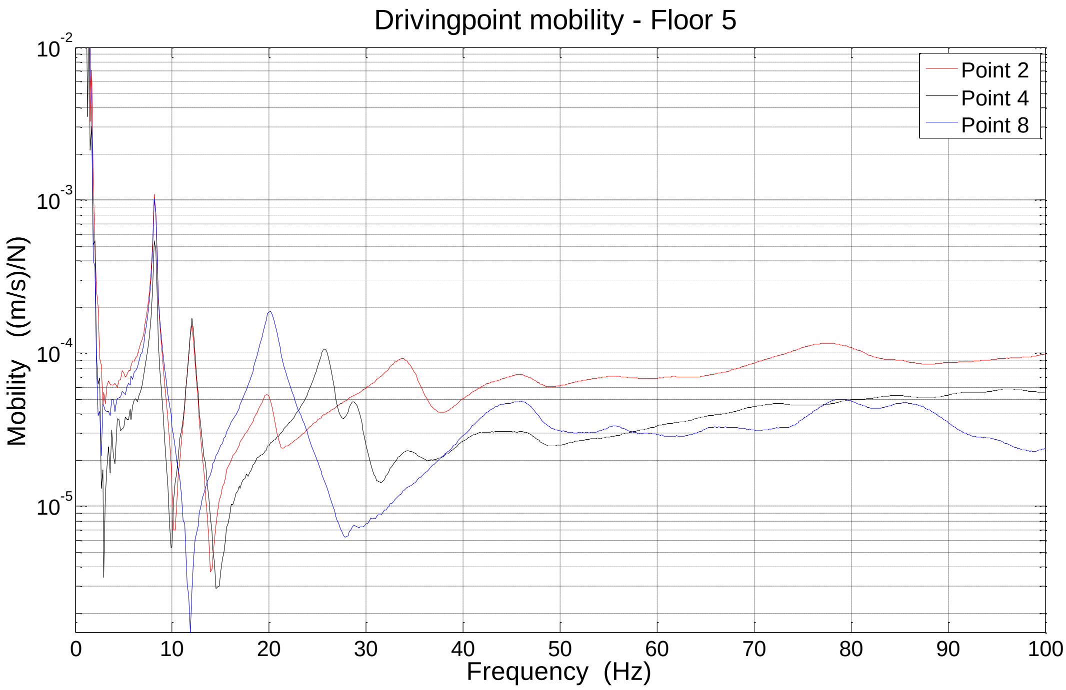


Figure 18. Driving point mobility floor 5.

The frequency range up to 5 Hz shows high mobility values due to the performance of the shaker, as it is not able to excite frequencies below 5 Hz. The values below 5 Hz should therefore not be taken into consideration. In Figure 14, the mobility of floor 1 in driving point 2 shows high values and should be considered with caution, since there might be a problem with the measurement due to shaker attachment. In the shown graphs the earlier extracted parameters, as resonances and damping, are put together graphically and shows the characteristics of each floor. From the driving point mobility the impulse velocity response, i.e. the vertical vibration velocity due to an excitation by a 1 Ns impulse, was calculated for all the floors at the different excitation points. In the calculated value, the contributions from frequencies up to 50 Hz are included. The results are presented in Table 9.

Table 9. Impulse velocity response in excitation points for frequencies up to 50 Hz.

Point no.	**Floor**				
	1 (m/Ns^2)	**2** (m/Ns^2)	**3** (m/Ns^2)	**4** (m/Ns^2)	**5** (m/Ns^2)
2	1.36	0.43	1.52	0.50	0.69
4	0.29	0.52	1.75	0.38	0.30
8	0.33	0.42	0.79	0.40	0.36

3.6 Summary of physical tests

The one- and two-point deflection tests (see Table 3and Table ***4***) give different values of deflection but, when sorting the values in increasing order, one can observe that the rankings of the floors are the same for both tests. Floor 1 has the lowest deflection value and floor 2 the highest. Floor 1 also has the lowest impulse velocity response, which could be an indication of good performance regarding vibration annoyance.

When looking at the driving point velocities of the floors (see Figure 14 to Figure ***18***), one can observe that there are some clear differences between the floors. The characteristics of floors 2 and 4 are clearly different from those of the other floors: the former floors have the highest number of modes below 50 Hz. Floor 2 also has the lowest damping ratio, longest span and highest mass. Floor 3, on the other hand, has the highest first eigenfrequency, highest damping ratio, lowest number of modes below 50 Hz, shortest span and lowest mass.

These results indicate that the size of the floors has a great impact on the vibration performance parameters and therefore the floor structures are not comparable in such a way that it is possible to rank them as better or worse when completely installed in a building.

4 Psycho-vibratory tests

To assess people's perception of floor vibrations the floors were used to carry out psycho-vibratory tests in Växjö and in Lund. In Växjö 29 persons and in Lund 31 persons participated as tests subjects. All the floors were tested by all the test subjects and were presented to them in random order. Both in Växjö and in Lund cases the test was divided into two subtests a seated subtest during which the test subject was seated on a chair placed on the floor, and a walking subtest during which the test subject was asked to walk on the floor. A questionnaire was presented to the subjects during the test. The used questionnaire was different in Växjö and in Lund.

During the psycho-vibratory tests objective measurements were also carried out on the floors, in order to assess accelerations and deflections experienced by the subjects. Accelerations were measured at several points on the surface of the floor and deflections were measured on the bottom side of the floor.

The testing procedure, questionnaires and findings from the tests are presented in the following sections separately for each locality.

4.1 Psycho-vibratory tests performed in Växjö

In Växjö the subjective response from vibrations were evaluated by 29 subjects who were asked questions. The subjects were subjected to two subtests per floor: a seated subtest in which the person was sitting on a chair while the investigator walked on the floor along a fixed walking line, and a walking subtest were the subject himself walked on the floor. After each subtest, the subjects answered questions put by the test leader. The test was conducted by the 29 subjects.

4.1.1 Questionnaires

The questionnaire was developed in cooperation with Pontus Thorsson (Akustikverkstan) and Anders Olsson (LNU). It was agreed to use the categories of terms with six levels for the subjects to explain their experiences. Experience from other tests suggests that the best thing is that the investigator asks questions and writes down the answers, the present tests were made like that.

Questions that were asked during the tests were divided into four sections. A general section to document basic data about the subject, a second part for the walking test, a third part for the sitting test, and finally a closing question in which subjects would rank the floors. Appendix A presents all the parts of the questionnaire.

4.1.2 Testing procedure

The experience of the vibrations from the floors was tested at Linnaeus University's laboratory hall. All five floors could there be mounted simultaneously and the test was therefore easy to implement, since the test subjects were able to compare all the floors during one test session. In this way each test subject probably had more homogenous answers than if the tests were to be made with several days in between.

Each subject tested all five floors and followed the same test procedure except that the floors were tested in different order. The complete test was conducted within approximately 50 minutes and carried out as follows:

1. ***Introduction***

   The test subject were given a quick review of why the test is carried out, and what significance it has for the future quality of wooden houses. The subjects were then instructed to move on the five floors for about five minutes. During this time they attended the floor without any further instructtions. Most of the subjects walked the floors slowly and made some minor jumps. The test leader explained what vibrations are and started afterwards with the general questions. When the introduction and general questions was completed, the test of the first floor began.

2. ***Walking subtest***

   The subjects were asked to move over large parts of the floor area and freely test the floor. The subjects then tended to walk a bit harder and jump more heavily than during the introduction. While the subjects still were on the floor, the investigator asked questions under the heading "Subject Walking" in the questionnaire.

3. ***Seated subtest***

   When the walking subtest was finished, the subjects were asked to sit on the chair. The test leader explained that they would now evaluate the vibrations they feel in the body when a person walks on the floor. Thereafter the test leader walked back and forth along the walking line in front of the subject, see Figure 19. The test leader then asked questions under the heading "Sitting on the chair" in the questionnaire. For every question the test leader walked once or twice along the walking line again, so that the subject could feel the vibrations and answer the question simultaneously.

The positions of chair and walking line are shown in Figure 19. The chair was placed in such a way on the floor that the subject would experience many vibrational resonances. The walking line's location was chosen so that the shortest distance to the chair was about 1 meter in order to reduce direct field from footsteps. Walking line's route was chosen so that the excitation happened across multiple beams and along large parts of the floors. Walking was also avoided along major nodal lines.

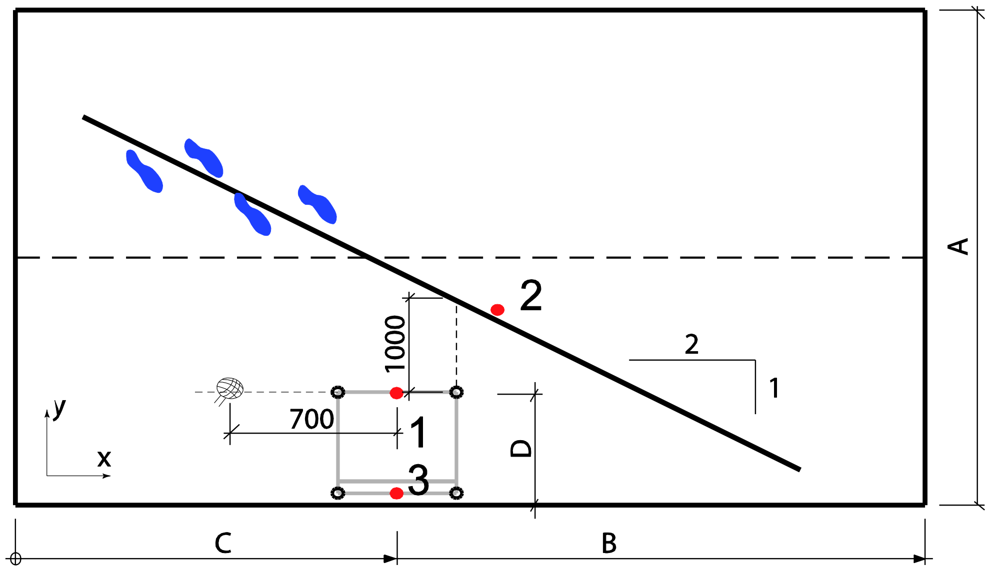


Figure 19. Position of the chair, walking line, microphone and accelerometers during test with seated test person. Sizes of labels A, B, C and D according to Table 10.

Table 10. Floor dimensions and distances in Figure 19 with sizes in mm

Floor no.	A	B	C	D
1	4800	6800	2830	815
2	4800	8500	3540	800
3	2390	3890	1620	790
4	7960	4800	3320	730
5	7940	4780	3310	775

4.1.3 Measurements during testing

During the subjective tests vibrations were measured using three accelerometers on each floor. Thereby it is possible to estimate how much vibration each subjects was subjected to. One can also examine how aggressively the subjects themselves walked on the floors. Accelerometers were placed at points 1,2 and 3 as shown in Figure 7 and Figure 19. The sound was recorded during that part of the test where the test person was sitting on a chair. The sound level meter was placed 1100 mm above the floor, as shown in Figure 19. The microphone had the direction (1010, 700, 420) in the coordinate system in Figure 19. The same positions for the accelerometers were used throughout the experiment and a check of the data collection was made at the beginning of each subjects tests. The sound level meter was calibrated once a day.

4.1.4 Analysis and results of the subjective response

4.1.4.1 Bias

There are many things that can interfere with the subjects' perception of vibrations of a floor. One of the most serious bias factors is that subjects can have difficulties to understand the difference between the impact sounds they hear and the vibrations they feel in the body. There is a number of other factors that can affect the experience; Visual impression of the floor, the time the subjects spent on the floors in advance, if they walk before they sit, or vice versa, the order in which the floors were tested. These factors, can be controlled to some extent. There are also factors which we cannot influence, e.g. unexpected disruptions. These can be of different nature; people entering the laboratory, the vibration background varies, background noise varies, phones ringing, somebody starts to talk with the subject or test leader.

The following measures were carried out in order to reduce bias:

- The subjects walk on the five floors for about 5 minutes before the testing begins in order to reduce the bias of preparation time, and simultaneously give people time to get acquainted with the situation.
- Audio and visual effects from the vibrations were further strengthened with use of props, such as coffee mugs and plants that were placed so that they can vibrate and rattle when walking on the floor.
- All subjects first walked on the floors and then sat down on a chair.
- The floors were tested in different order for different subjects.
- During the tests the vibrations at the floors were measured continuously.

4.1.4.2 Discussion and results

The answers to the questions to the subjects are compiled below for one question at a time. The question is seen in the figure title and response options are located on the x-axis. The height of each bar corresponds to how many subjects that selected that x-axis response option. Each floor is represented by a unique color; the colors are explained in Figure 20.

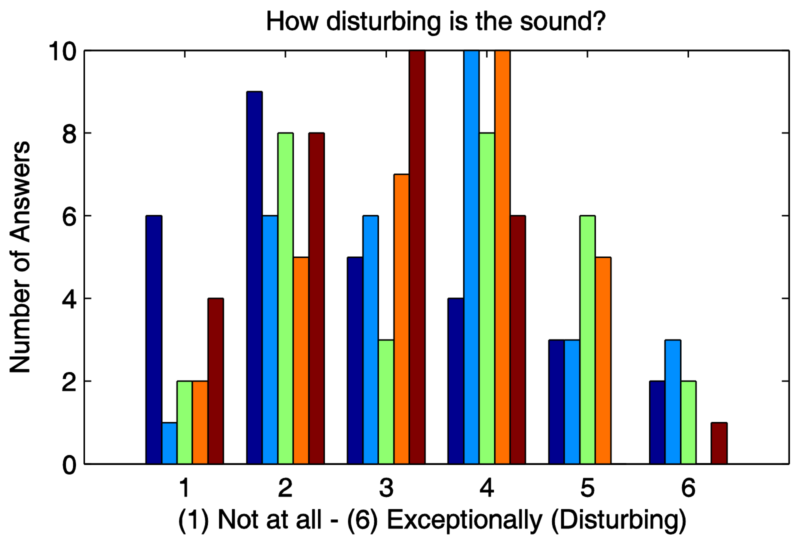
Figure 20. Color schedule for the figures describing the questionnaire answers below

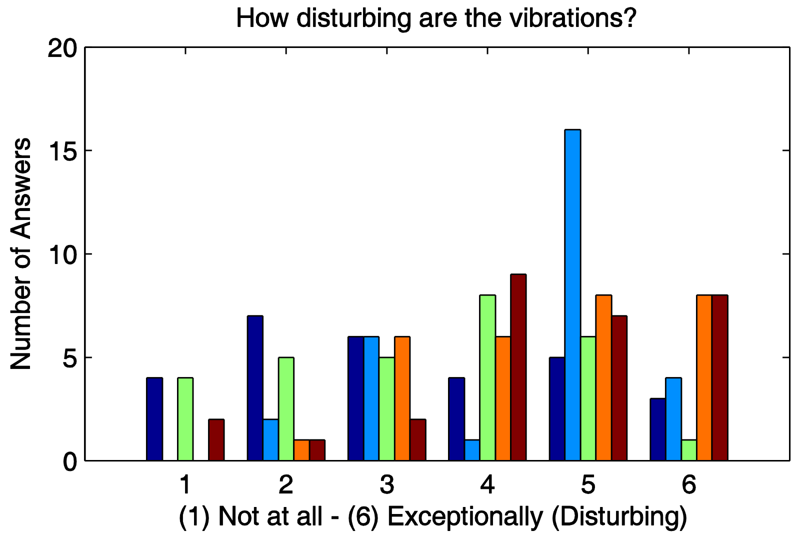
When reading the results, one should bear in mind that the floors not only have different structures, they are also different in size, which greatly affects the vibration performance and how the subjects experience them.

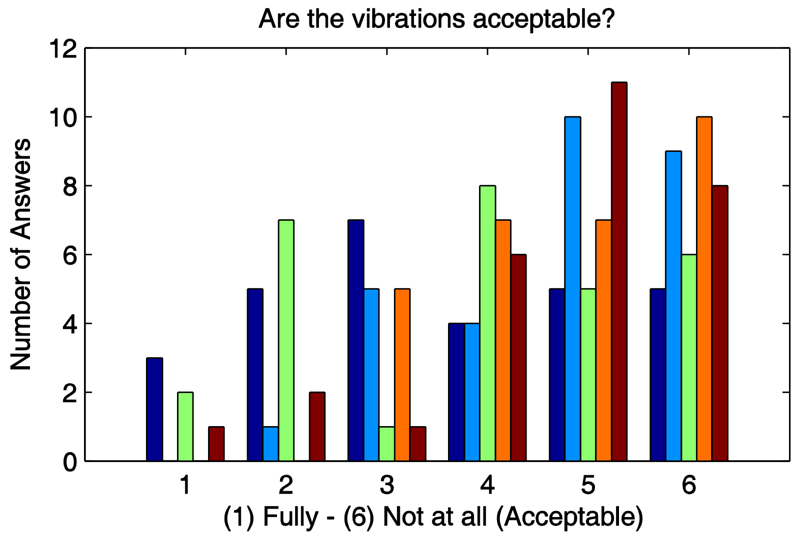
Looking at all the questions, one can observe that:

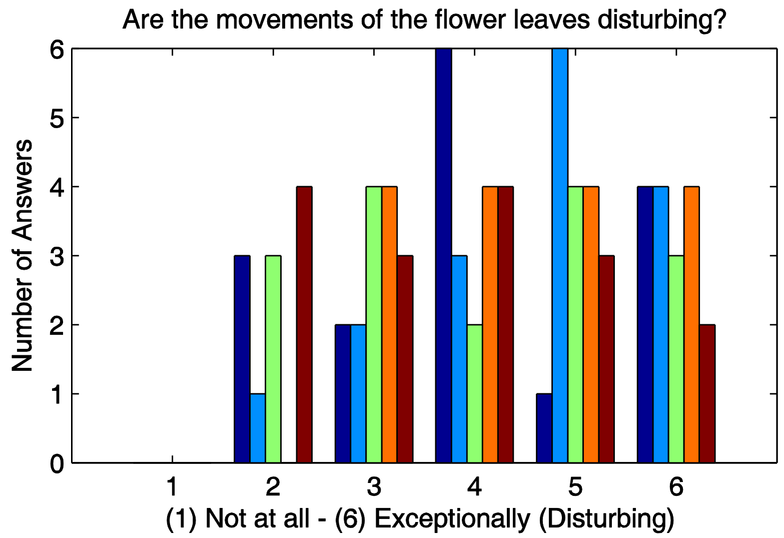
i) The subjects have very different opinions of the floors, but when looking at the answers from the group as a whole there nevertheless are differences between the floors.

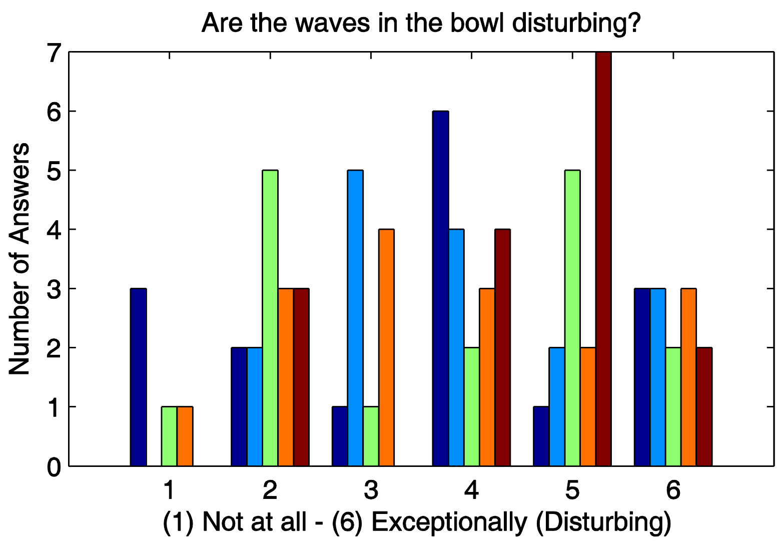
ii) Floor 1 has received the most extremely positive response answers and floor 2 has received the largest number of extremely negative response.

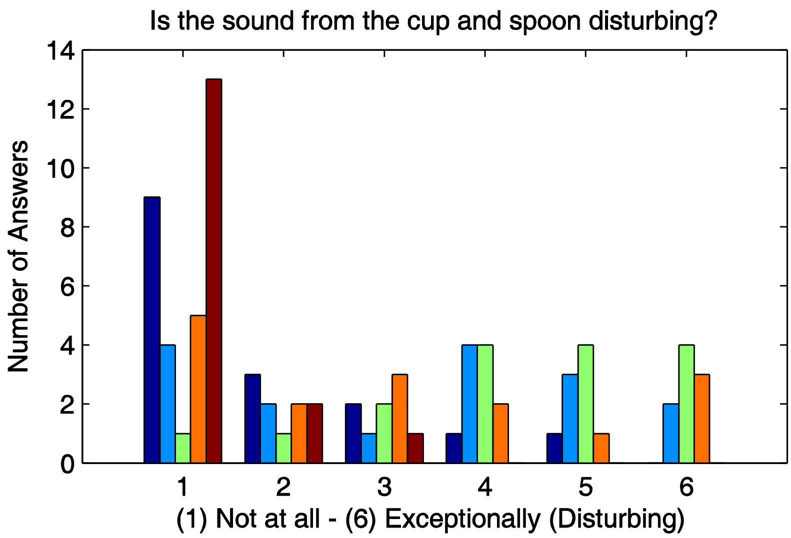


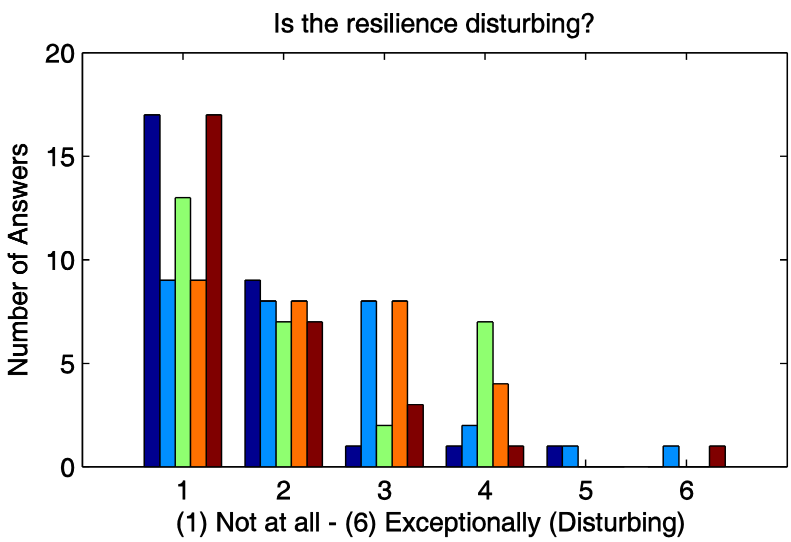

How disturbing are the vibrations?
Number of Answers
0
5
10
15
20
1
2
3
4
5
6
(1) Not at all - (6) Exceptionally (Disturbing)

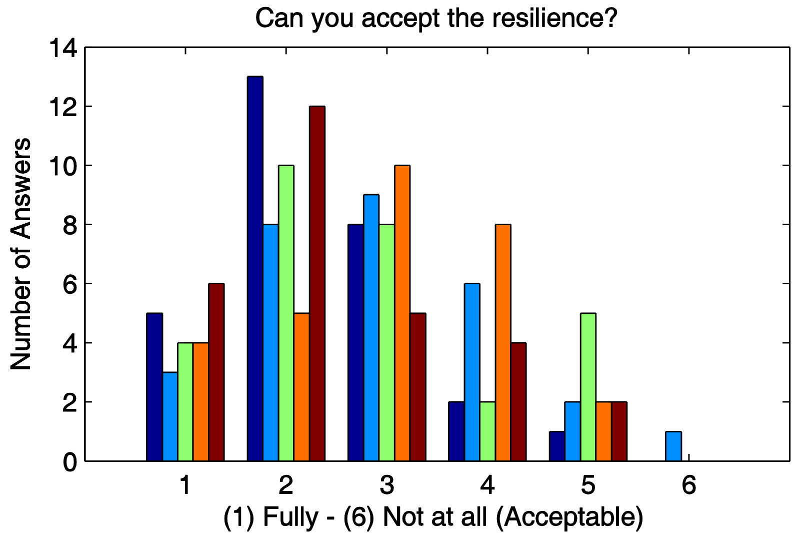

Are the vibrations acceptable?
Number of Answers
0
2
4
6
8
10
12
1
2
3
4
5
6
(1) Fully - (6) Not at all (Acceptable)

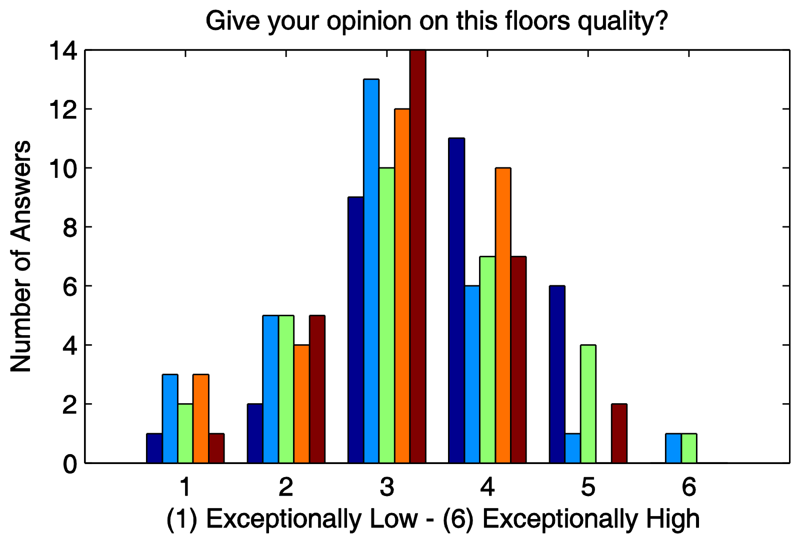

Are the movements of the flower leaves disturbing?
Number of Answers
0
1
2
3
4
5
6
1
2
3
4
5
6
(1) Not at all - (6) Exceptionally (Disturbing)

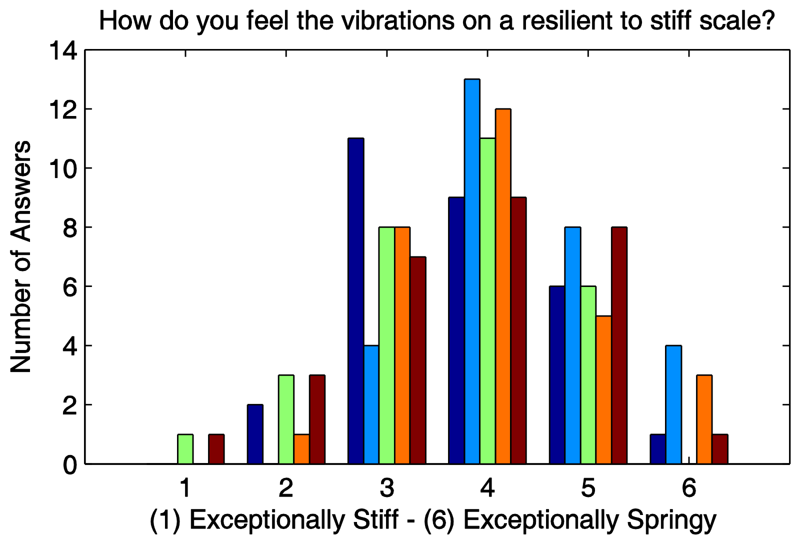

Are the waves in the bowl disturbing?
Number of Answers
(1) Not at all - (6) Exceptionally (Disturbing)

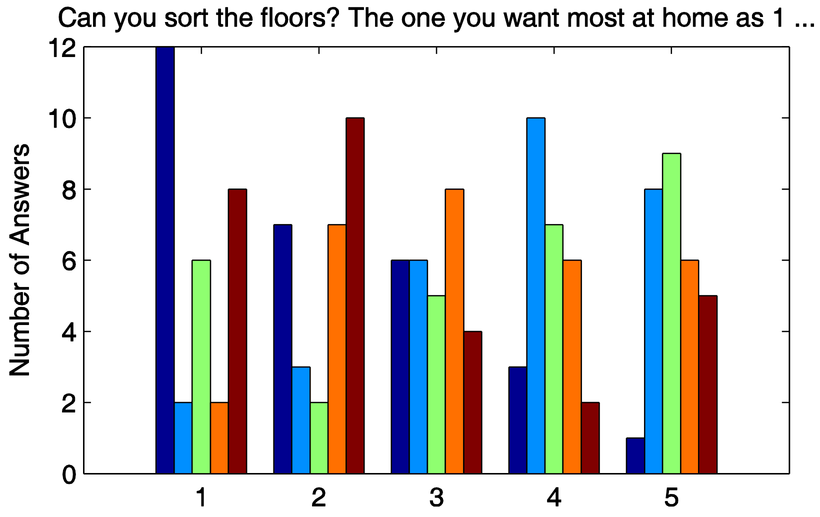

Is the sound from the cup and spoon disturbing?
Number of Answers
(1) Not at all - (6) Exceptionally (Disturbing)

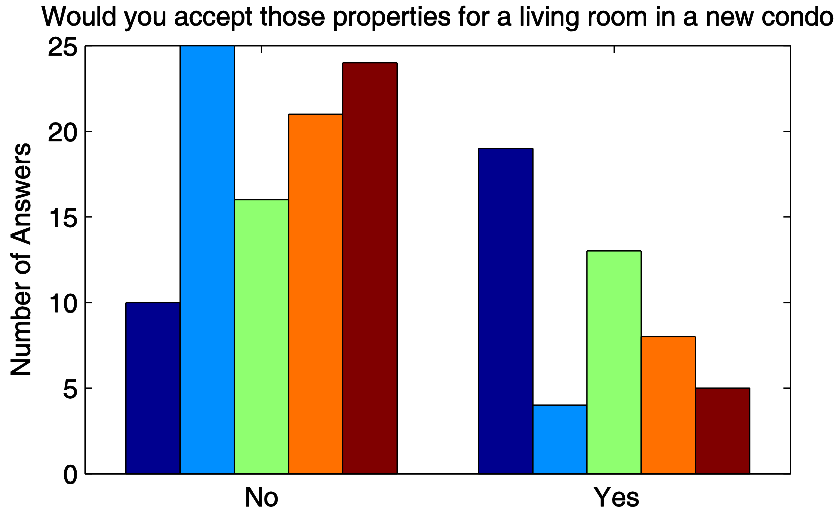

Is the resilience disturbing?
Number of Answers
(1) Not at all - (6) Exceptionally (Disturbing)


Can you accept the resilience?
Number of Answers
(1) Fully - (6) Not at all (Acceptable)


Give your opinion on this floors quality?
Number of Answers
(1) Exceptionally Low - (6) Exceptionally High


How do you feel the vibrations on a resilient to stiff scale?
Number of Answers
(1) Exceptionally Stiff - (6) Exceptionally Springy





4.2 Psycho-vibratory tests performed in Lund

At Lund University the subjective testing of the wooden floors was carried out by 31 persons participating as test subjects. The floors from A to E were tested by all the test subjects and the floors were presented to them in random order. The test was divided into to two subtests; a seated test, during which the subject was seated on a chair placed on the floor, and a walking subtest during which the subject was asked to walk on the floor. After each subtest, a questionnaire about the floor perception was submitted to the test subjects.

4.2.1 Questionnaires

The questionnaire (see Appendix B) was formulated to give information about the perception of floor performance concerning the *attributes*:

- Noise annoyance
- Vibration annoyance
- Vibration acceptability
- Springiness

For the evaluation of noise and vibration annoyance the subjects were asked to utter a judgment on an 11-point numeric scale, ranging from “0” (“not at all annoyed”) to “10” (“extremely annoyed”). For the springiness evaluation, the scale was also an 11-point numeric scale, but ranging from “0” (“very bad”) to “10” (“very good”). Finally, for the vibration acceptability evaluation, the subjects were asked just to utter a binary judgment: “acceptable” or “not acceptable”. The definition of springiness that was given to the subjects during the test was: “resistance of a material to a shock”.

4.2.2 Testing procedure

The complete test was carried out as follows:

1. ***Seated subtest***

   First, the subject was seated on a chair placed at the observation point (located 0.6 m away from the middle line of the floor, as shown in Figure 21), looking in the direction of the walking line. The test leader walked along the walking line with a step velocity of about 2 Hz, between both limits marked by red lines in Figure 21, and passing the observation point three times. The questionnaire after the test included questions concerning the four attributes; noise and vibration annoyance, vibration acceptability and springiness.

2. ***Walking subtest***

   After the seated subtest was finished, the chair was removed and the subject was asked to walk quite freely along the walking line between both limits marked by red lines in Figure 21. No other specific instruction was given to the subject concerning the way of walking. The questionnaire after the test included questions concerning just three attributes vibration annoyance, vibration acceptability and springiness.

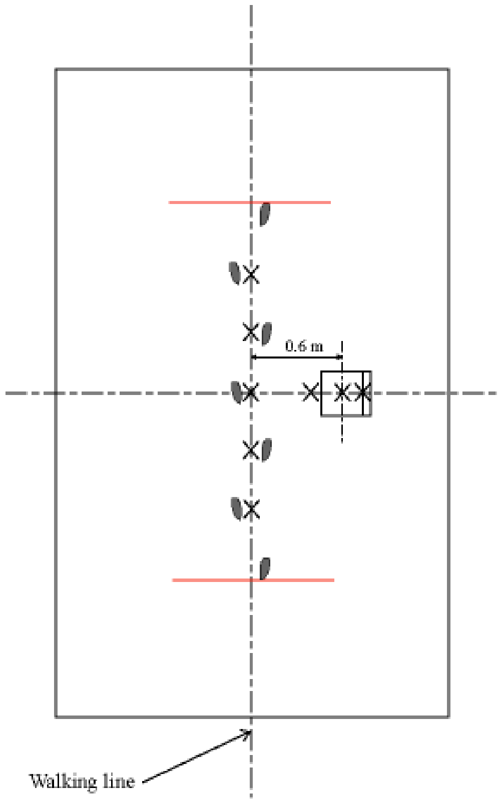


Figure 21. Measurement setup for both subtests X: accelerometer positions.

4.2.3 Measurements during testing

In order to assess accelerations and deflections experienced by the subjects objective measurements were also carried out on the floors during the seated and walking subtests.

4.2.3.1 Acceleration measurements

For each subtest, accelerations were simultaneously recorded using Spectrum SBench 6.1 software. For the seated subtest, 3 accelerometers were used; a first one was placed between the feet of the seated subjects; a second one under the seating plate of the chair and a third one on the backrest of the chair, respectively (see Figure 21 and Figure 22). For the walking subtest, 5 accelerometers were placed along the walking line (see Figure 21 and Figure 23).

Figure 22. Measurement setup for the seated subtests.

Figure 23. Measurement setup for the walking subtest.

Extracted parameters

For both subtests, the following parameters were extracted from the acceleration data for each subject and for each floor:

Overall frequency-weighted RMS acceleration and velocity (basic evaluation method)

For each accelerometer, the frequency-weighted RMS (Root Mean Square) acceleration was computed according to the following formula (see standard ISO 2631-1, section 6.4.2):

$$a_w = \left[\sum_i \left(W_{m,i} a_i\right)^2\right]^{\frac{1}{2}}$$

where a_w is the frequency-weighted RMS acceleration; $W_{m,i}$ are the weighting factors for the different third-octave bands *i* of the acceleration spectrum, given in standard ISO 2631-2, Annex A; and a_i are the RMS values computed for the different third-octave bands *i* of the acceleration spectrum.

In the end, an overall frequency-weighted RMS acceleration was determined from the root sum of squares of the frequency-weighted RMS accelerations computed for the different accelerometers (see standard ISO 2631-1, section 8.2.3).

Furthermore, for each accelerometer, velocity has been determined from the acceleration by integration. Then, the overall frequency-weighted RMS velocity v_w was computed just as the overall frequency-weighted RMS acceleration was (see paragraph above).

Note: Frequency-weighted RMS values are highly dependent on the analysis time window. As a consequence, this time window must be chosen very carefully and stated along with the results. In our case, frequency-weighted RMS values were computed using a time window corresponding to only one out of the three "walking lines" (we define a "walking line" as one "stroll" along the floor). Thus, the time periods during which the subject is just standing on the floor (without walking) were not taken into account in the computation. If these time periods had been taken into account, frequency-weighted RMS values would have been drastically reduced.

Maximum transient vibration value (running RMS method)

For each accelerometer, the maximum transient vibration value was computed according to the following formula (see standard ISO 2631-1, section 6.3.1):

$$MTVV = \max[a_w(t_0)]$$

where *MTVV* is the maximum transient vibration value and $a_w(t_0)$ is defined as follows:

$$a_w(t_0) = \sqrt{\frac{1}{\tau}\int_{t_0-\tau}^{t_0} \left[a_w(t)\right]^2 dt}$$

where $a_w(t)$ is the instantaneous frequency-weighted acceleration, $\boldsymbol{\tau}$ is the integration time for running average (1 second in our case), *t* is the time (integration variable) and t_0 is the time of observation.

In practice, a Matlab code was created in order to calculate *MTVV*. That code sweeps over the entire duration of the recording using a one-second window. All the computed $a_w(t_0)$ values are saved. The given output, *MTVV*, is the "worst" (i.e. the maximum) of these values.

In the end, an overall *MTVV* was determined from the root-sum-of-squares of the *MTVV*s computed for the different accelerometers (see standard ISO 2631-1, section 8.2.3).

The results are presented as a whole for all the subjects and each floor in Table 1 in Appendix C.

4.2.3.2 Floor deflection

During each subtest, a displacement gauge was placed underneath each floor, at its middle point, in order to record the deflection of the load bearing joists in the structure. Hence, it was possible to extract, for each floor and for each subject, the maximum peak deflection when the subject:

i) walked on the floor (walking subtest), and
ii) was seated on the chair (seated subtest).

The results are presented for all the subjects and all the floors in Table 2 in Appendix C.

4.2.4 Analysis of the subjective responses

A preliminary analysis of the subjective responses obtained from the questionnaires was carried out. The analysis involved three steps:

- Step 1: Visual inspection of the data
- Step 2: Cluster analysis of subjects
- Step 3: First assessment of the effects of the floor and subtest condition on the subjective response

The steps are each described in the following sections.

4.2.4.1 Step 1: Visual inspection of the data

Objectives

The first step aimed at getting a quick visual overview of

i) the inter-individual differences, and
ii) the differences between the different floors.

This was carried out for each studied attribute (noise annoyance, vibration annoyance, vibration acceptability and springiness) within each subtest (seated or walking, wherever appropriate). To reach these aims, descriptive statistics were computed and displayed graphically.

Procedure

For each numerical attribute (i.e. assessed on an 11-point numeric scale: noise annoyance, vibration annoyance and springiness), a "box plot" was drawn. The latter here consists of a box and a whisker plot, displayed for each floor and, where appropriate, for each subtest (seated or walking). The box has lines at the lower quartile (blue line), median (red line), and upper quartile (blue line) values. The whiskers are lines extending from each end of the box to show the extent of the rest of the data. Outliers are data with values beyond the ends of the whiskers. If there is no data outside the whisker, a dot is placed at the bottom whisker. Note that, in addition, the individual responses, represented by black dots, are superimposed on the box plots.

For vibration acceptability, for each subtest condition (seated or walking), a histogram was drawn for each floor, showing the respective frequency of "not acceptable" and "acceptable" responses.

Results

Hereafter, the results are presented separately for each attribute.

Springiness

Figure 24 shows the box plots for each floor, a box and whisker plot is displayed for each subtest, i.e. seated (on the left side) and walking (on the right side).

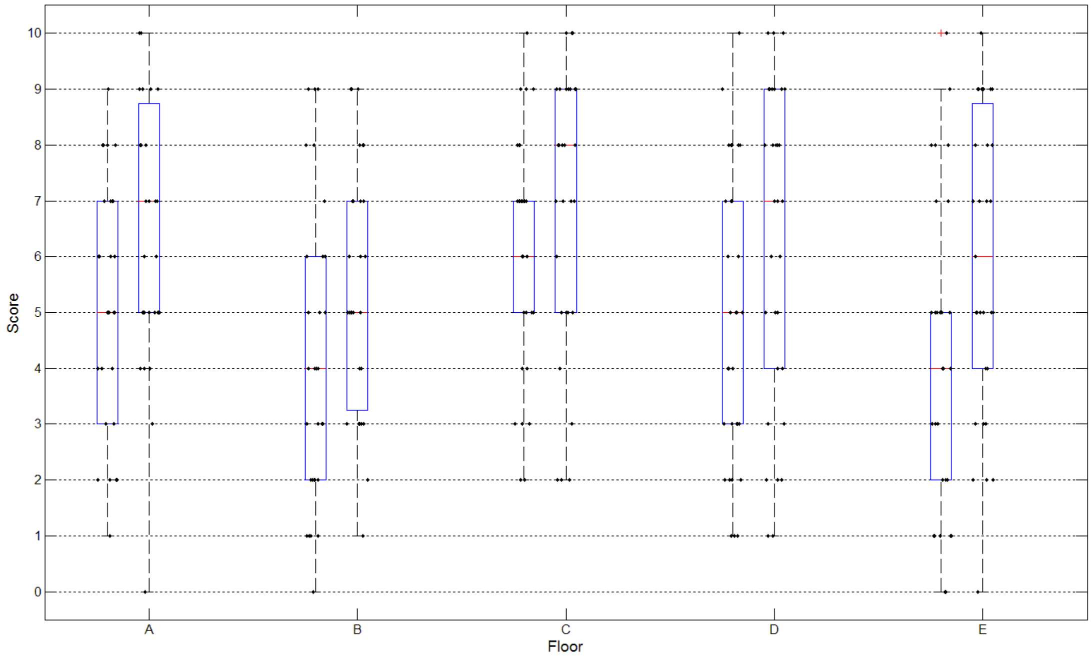


Figure 24. Springiness box plots.

One can observe that:

i) Overall, the dispersion of the individual scores is important;
ii) Whatever the floor, the median scores obtained for the seated and walking subtests appear to be different from each other; notably, the median scores obtained for the seated subtest are lower;
iii) For the seated subtest, there are differences between the median scores of floors: A and B, A and C, A and E, B and C, B and D, C and D, C and E, D and E; floor C obtains the highest median score, B and E the lowest median score;
iv) For the walking subtest, there are differences between the median scores of floors: A and B, A and C, A and E, B and C, B and D, B and E, C and D, C and E, D and E; floor C obtains the highest median score, B the lowest median score;
v) There is one outlier response for floor E, for the seated subtest.

Vibration annoyance

Figure 25 shows the box plots for each floor, a box and whisker plot is displayed for each subtest, i.e. seated (on the left side) and walking (on the right side).

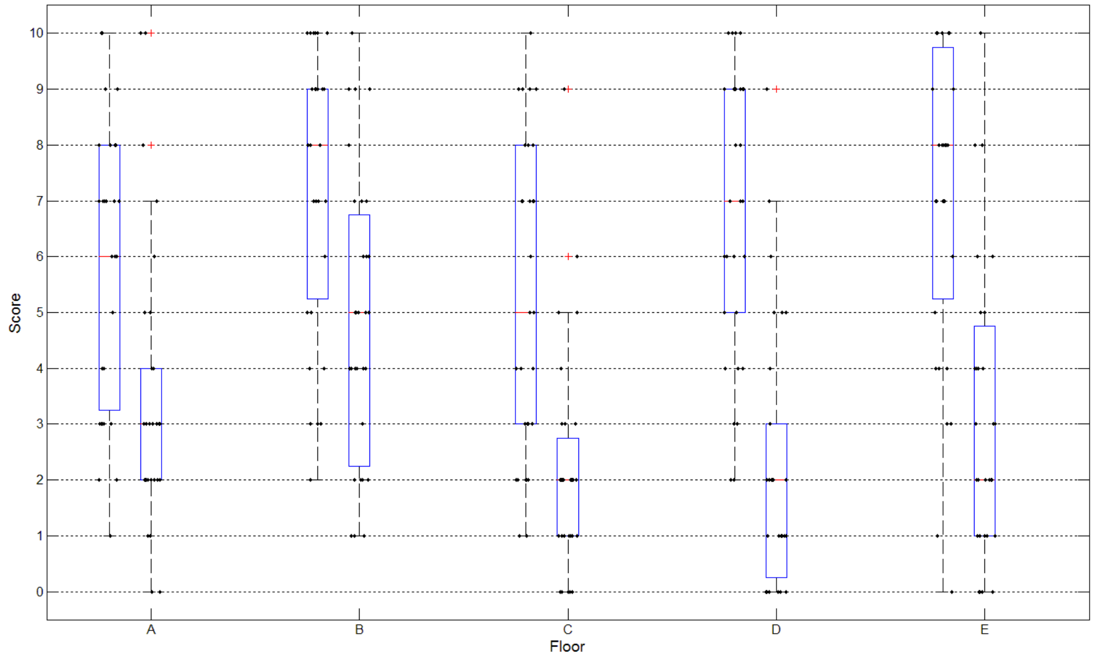


Figure 25. Vibration annoyance box plots.

One can observe that:

i) Overall, the dispersion of the individual scores is still important;
ii) Overall, whatever the floor, the median scores obtained for the seated and walking subtests appear to be different from each other; notably, the median scores obtained for the seated subtest are much higher;
iii) For the seated subtest, there are differences between the median scores of floors: A and B, A and C, A and D, A and E, B and C, B and D, C and D, C and E, D and E; floors B and E obtains the highest median score, C the lowest median score;
iv) For the walking subtest, there are differences between the median scores of floors: A and B, A and C, A and D, A and E, B and C, B and D, B and E; floor B obtains the highest median score, C, D and E the lowest median score;
v) There are outlier responses for floors A, C and D, for the walking subtest.

Noise annoyance

Figure 26 shows the box plots for each floor, one single box and whisker plot is displayed (for the seated subtest).

One can observe that:

i) Overall, the dispersion of the individual scores is still important;
ii) There are differences between the median scores of floors: A and C, A and E, B and C, B and E, C and D, D and E; floors A, B and D obtain the highest median score, C and E the lowest median score.

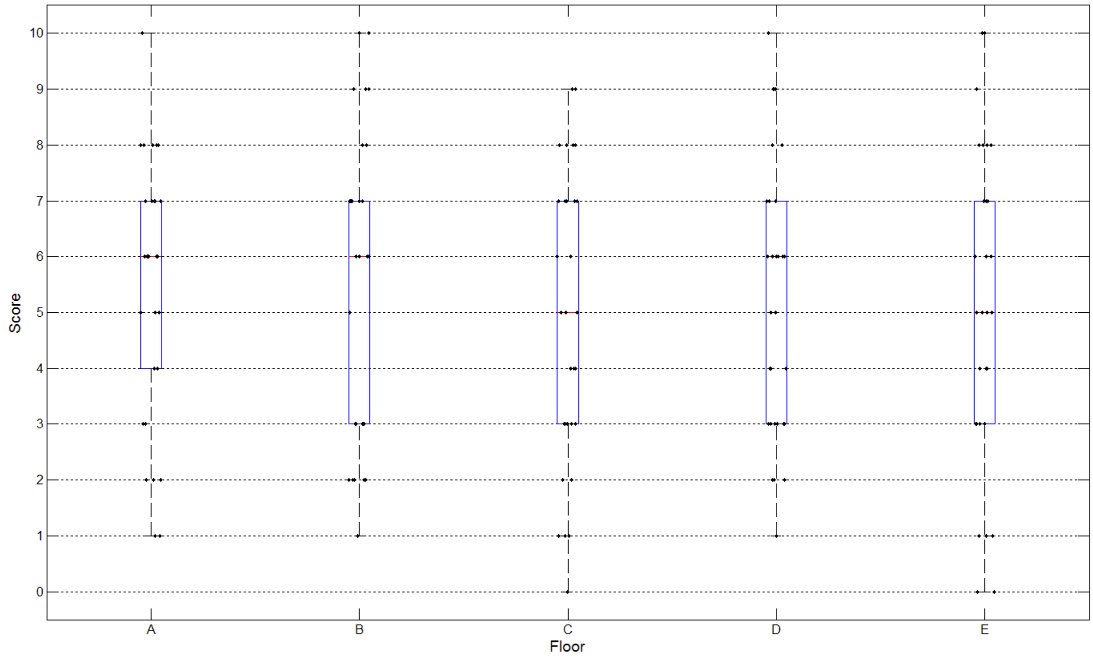


Figure 26. Noise annoyance box plots.

Vibration acceptability

Figure 27 shows the histograms for each floor, for the seated subtest. “0” designates the response “not acceptable”, “1” the response “acceptable”.

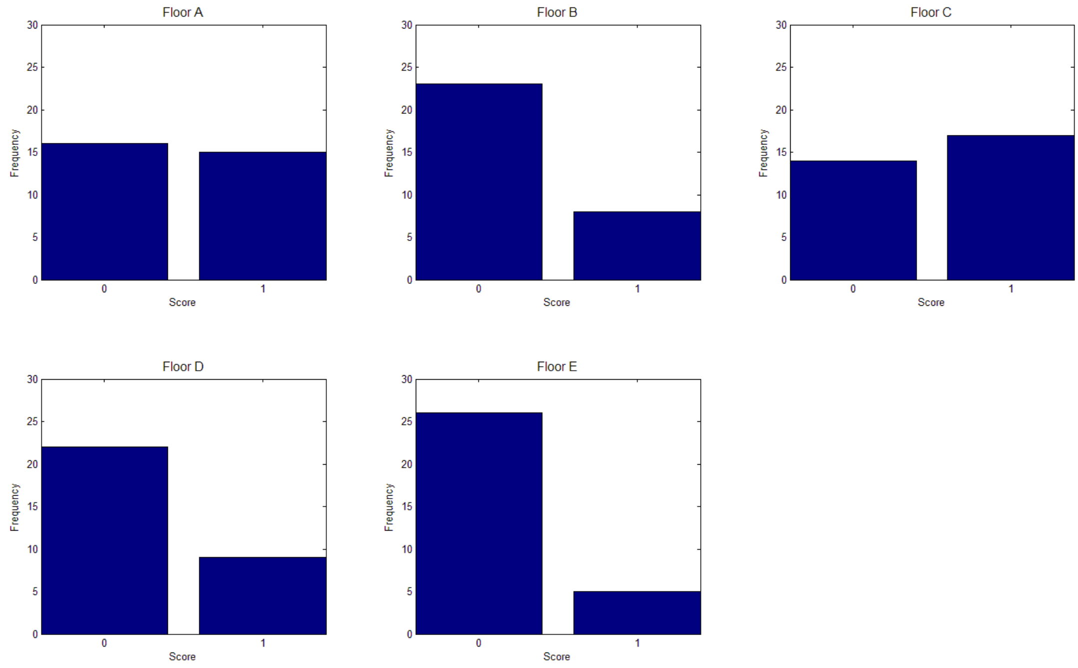


Figure 27. Vibration acceptability response histograms for the seated subtest.

One can observe that:

i) Only floor C is judged as acceptable by the majority of the participants;
ii) Floor E is the least acceptable floor, i.e. for that floor, the frequency of the response "not acceptable" is the highest.

Figure 28 shows the histograms for each floor, for the walking subtest.

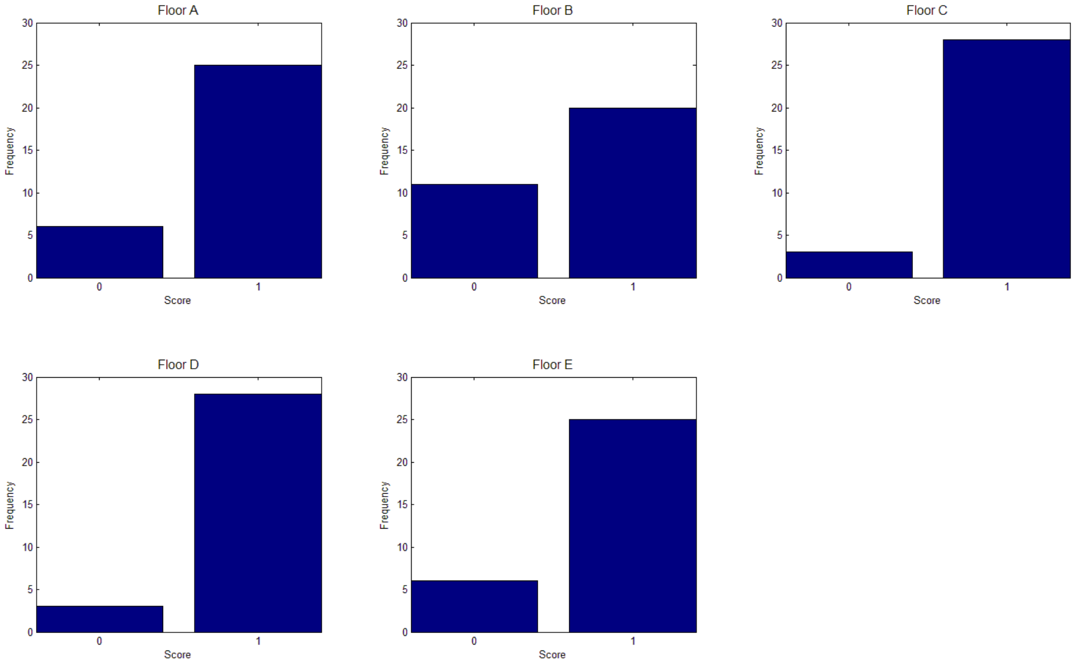


Figure 28. Vibration acceptability for the walking subtest.

One can observe that:

i) All the floors are judged as acceptable by the majority of the participants;

ii) Floor B is the least acceptable floor, i.e. for that floor, the frequency of the response "not acceptable" is the highest.

iii) Floor C is the most acceptable floor, i.e. for that floor, the frequency of the response "acceptable" is the highest.

Summary of results from step 1

The findings coming from this visual inspection can be summarized as follows:

i) For each floor, within each subtest, there are large differences between the scores uttered by the participants.

ii) According to the median scores, it seems that there are differences between floors in terms of performance regarding springiness, vibration annoyance, vibration acceptability and noise annoyance.

iii) It seems that the attributes "vibration annoyance", "vibration acceptability" and "springiness" are correlated with each other. Most of time, when the vibrations from a floor are considered as annoying, these are also considered as less acceptable and performance of the floor regarding springiness is considered worse.

iv) In most cases, it seems that the vibrations are judged as less annoying / more acceptable when people are walking on the floors. Also, performance of the floors regarding springiness is considered better when people are walking on the floors.

v) The vibrations from floor C appear as the least annoying / most acceptable; its performance regarding springiness appears as the best.

vi) In most cases, the vibrations from floors B and E appear as the most annoying / least acceptable; their performance regarding springiness appears as the worst.

All these points shall be further investigated by carrying out a more quantitative statistical analysis (see step 3), notably in order to determine whether the mentioned differences between the floors are statistically significant or not.

4.2.4.2 Step 2: Cluster analysis of subjects

Objectives

From the results of step 1, one could see that there were large differences between the responses uttered by the participants, with sometimes outlier responses appearing. This second step thus aims at:

i) identifying outlier subjects, i.e. the subjects whose responses are abnormally extreme throughout the 5 floors, and also

ii) revealing possible subgroups of subjects with really different response logics.

This was done for each attribute within each subtest. To reach these aims, a cluster analysis of subjects was carried out.

Note that the responses of the outlier subjects have been removed and therefore not taken into account in the following steps of the analysis. In case of the presence of different subgroups, the following steps have been performed separately for each subgroup.

Procedure

To carry out the cluster analysis of subjects, we have recourse to the method of Hierarchical Ascending Classification (HAC). The HAC makes it possible to construct an indexed hierarchical tree, also called dendrogram, from a matrix of dissimilarities between objects (here the subjects). The dendrogram corresponds to “a system of nested clusters whose heterogeneity increases with the size of the clusters” (Nakache, 2005). The different steps of the application of HAC to the data are described hereafter.

Computation of the dissimilarities between subjects

For each attribute within each subtest, the dissimilarities between subjects are computed from their responses given for the different floors. The measure of dissimilarity must be selected with respect to the nature of the data.

Regarding the numerical attributes (i.e. springiness, vibration annoyance, noise annoyance), the responses can be considered as ordinal data. The measure $d_1(k, l)$ adopted to quantify the dissimilarity between two subjects *k* and *l* is the Euclidean distance, defined as follows (Nakache, 2005):

$$d_1(k,l) = \sqrt{\sum_{j=1}^{N} (z_{kj} - z_{lj})^2}$$

where N is the number of floors (i.e. 5), z_{kj} and z_{lj} are transformed scores for floor j, respectively for subjects k and l. The terms z_{ij} are computed as follows:

$$z_{ij} = \frac{r_{ij} - 1}{n_j - 1}$$

where r_{ij} represents the rank of the score uttered by subject i for floor j ($r_{ij} = 1, 2, \ldots, n_j$) and n_j is the number of distinct scores for floor j.

Regarding vibration acceptability, the responses can be considered as nominal data. The measure $d_2(k, l)$ adopted to quantify the dissimilarity between two subjects k and l is defined as follows (Nakache, 2005):

$$d_2(k, l) = \frac{N - s(k, l)}{N}$$

where N is the number of floors; $s(k, l)$ is the number of floors for which subjects k and l uttered a same judgment.

Construction of the dendrogram

For each matrix of dissimilarities between subjects, the dendrogram is constructed by following an algorithmic process. Initially, the same number of clusters and subjects (i.e. the terminal elements of the dendrogram) are defined. In a first stage, the two subjects which are the closest in the sense of the dissimilarity measure adopted are aggregated into a new cluster; on the dendrogram, from the two terminal elements leave two limbs which meet up to form a node. Then, the matrix of dissimilarities is updated; the dissimilarities between the cluster newly formed and the other remaining subjects are computed by using a linkage criterion (see hereafter). From then on, one looks again for the two closest clusters, which one aggregates, and so on until the aggregation of all the subjects into a single cluster (Nakache, 2005). In the end, the algorithm produces a matrix of dissimilarities, called ultrametric distances, which represent the aggregation levels of the different clusters; these levels are carried forward in ordinate on the dendrogram.

Several common linkage criteria are here tested: single linkage criterion, complete linkage criterion, unweighted average linkage criterion, weighted average linkage criterion, Ward's linkage criterion (Gordon, 1999; Nakache, 2005). One finally selects the criterion for which the degree of adequacy between the ultrametric distances and the original dissimilarities is the highest. This degree of adequacy is measured via the cophenetic correlation coefficient (Gordon, 1999; Sokal, 1962) and Goodman-Kruskal's coefficient (Gordon, 1999); the closer from 1 the values of these coefficients are, the higher the degree of adequacy is.

Determination of the optimal number of clusters

The dendrogram provides an important number of possible partitions of clusters[1], ranging from the finest partition, made up of as many clusters as subjects, to the roughest partition, made up of one single cluster gathering together all the subjects. Among all these partitions, the optimal partition, i.e. with an optimal number of clusters, is the partition "the best in terms of density and separability of the clusters" (Nakache, 2005). In order to help to determine the optimal number of clusters, different aid decision indices are computed for each partition with a different number of clusters m:

[1] Every cut of the dendrogram by a horizontal line provides a possible partition.

i) The *quality index.* This index is defined as follows (Nakache, 2005):

$$Q\ m\ = \frac{1}{S}\sum_{r=1}^{m} n_r\, s_r$$

where $Q(m)$ is the quality index (comprised between 0 and 1) of a m-cluster partition; S is the total number of subjects; n_r is the number of subjects within cluster C_r; s_r is the average of the silhouette values within cluster C_r. The silhouette value of a subject i gives an indication about the quality of its classification, see (Nakache, 2005) for its computation formula. The optimal partition is that for which one can observe – ideally – a peak on the quality index curve versus the number of clusters m.

ii) The *ratio intra inertia/total inertia* ($\frac{I_{intra}}{I_{tot}}$). This index is a kind of lack-of-fit measure.

iii) Theoretically, the lower it is, the better the partition is. In practice, the optimal partition is that for which one can observe an elbow on the curve of the ratio intra inertia/total inertia versus the number of clusters m (Nakache, 2005).

iv) The *Semi-Partial R-square (SPRSQ).* This index represents the loss in homogeneity when two clusters are aggregated. The optimal number of clusters is that for which one can observe a strong reduction in *SPRSQ*.

v) The *Root-Mean-Square Standard Deviation (RMSSTD).* This index is the square root of the variance of the responses within a new cluster $C_{k''}$ formed by aggregation of clusters C_k et $C_{k'}$, computed as the sum of the variances of the responses given for the different floors. The more two aggregated clusters C_k et $C_{k'}$ are alike, the more cluster $C_{k''} = C_k \quad C_{k'}$ is homogeneous, and thus the smaller *RMSSTD* is. The optimal number of clusters is that for which one can observe a strong reduction in *RMSSTD.*

Note that the three last indices can only be used when the measure of dissimilarity adopted is the Euclidean distance (Nakache, 2005). In this case, the optimal partition shall be that for which – ideally – the 4 criteria described forth above are fulfilled.

According to the size of the clusters within the partition – whether small or large –, these denote outlier subjects or subgroups of subjects respectively[2].

Results

For an illustration, only the results obtained for the springiness attribute within the walking subtest will be discussed in detail hereafter. Afterwards, the other results will be summarized in a table.

An illustration: results obtained for the springiness attribute within the walking subtest

Figure 29 shows the dendrogram constructed by applying HAC algorithm to the matrix of dissimilarities $d_1(k,l)$ between subjects. The unweighted average linkage criterion was used. Note that the degree of adequacy between the ultrametric distances and the original dissimilarities is moderate according to the values of the cophenetic correlation coefficient and Goodman-Kruskal's coefficient, respectively equal to 0.76 and 0.71.

Figure 30 shows the curve of the quality index versus the number of clusters. One can notice a slight peak for a number of clusters equal to 3. The value of the peak (i.e. 0.36) remains weak in absolute.

[2] We intend to adopt the following convention: i) for a size lower than or equal to 3 (NB : this number corresponds to ca. 10% of the total number of subjects participating in the psycho-vibratory test), the cluster denotes "outlier" subjects, and ii) for a size higher than 3, the cluster denotes a subgroup of subjects.

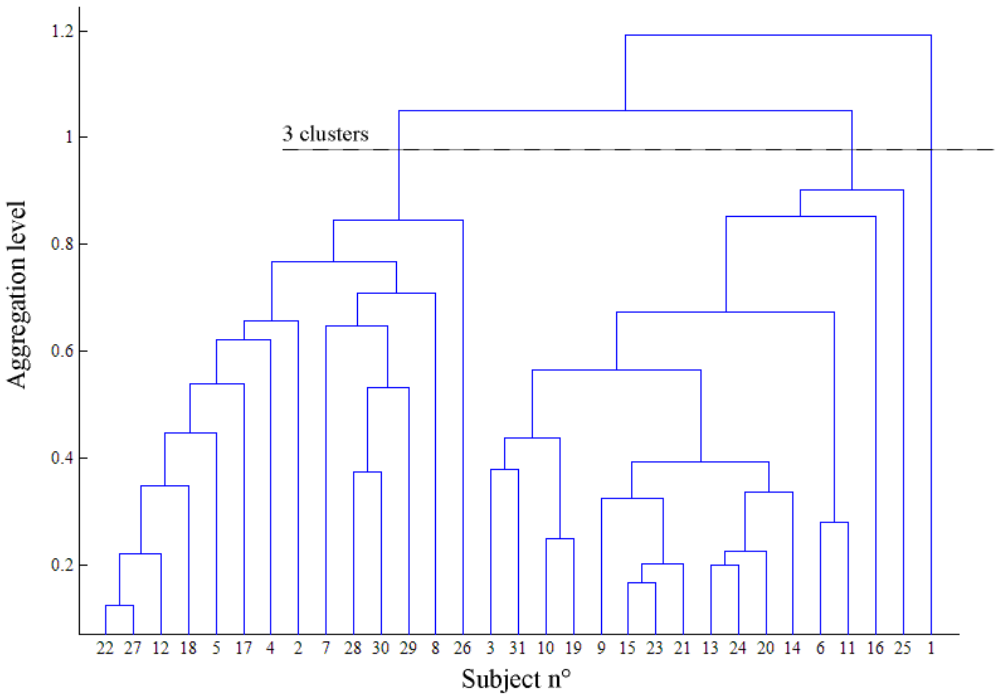


Figure 29. Dendrogram.

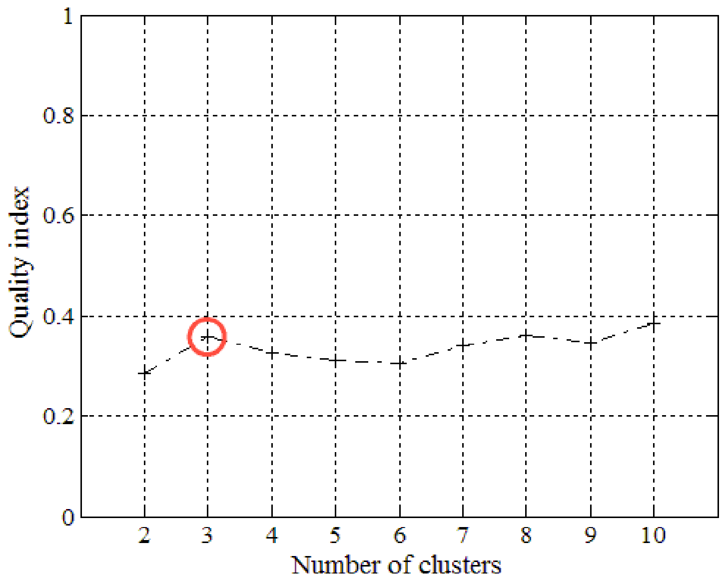


Figure 30. Quality index vs. number of clusters.

Figure 31 shows the ratio intra inertia/total inertia computed for the different numbers of clusters. One can observe an elbow for a number of clusters equal to 3.

Figure 32 shows the curve of SPRSQ versus the number of clusters. One can notice a strong reduction in SPRSQ for a number of clusters equal to 3.

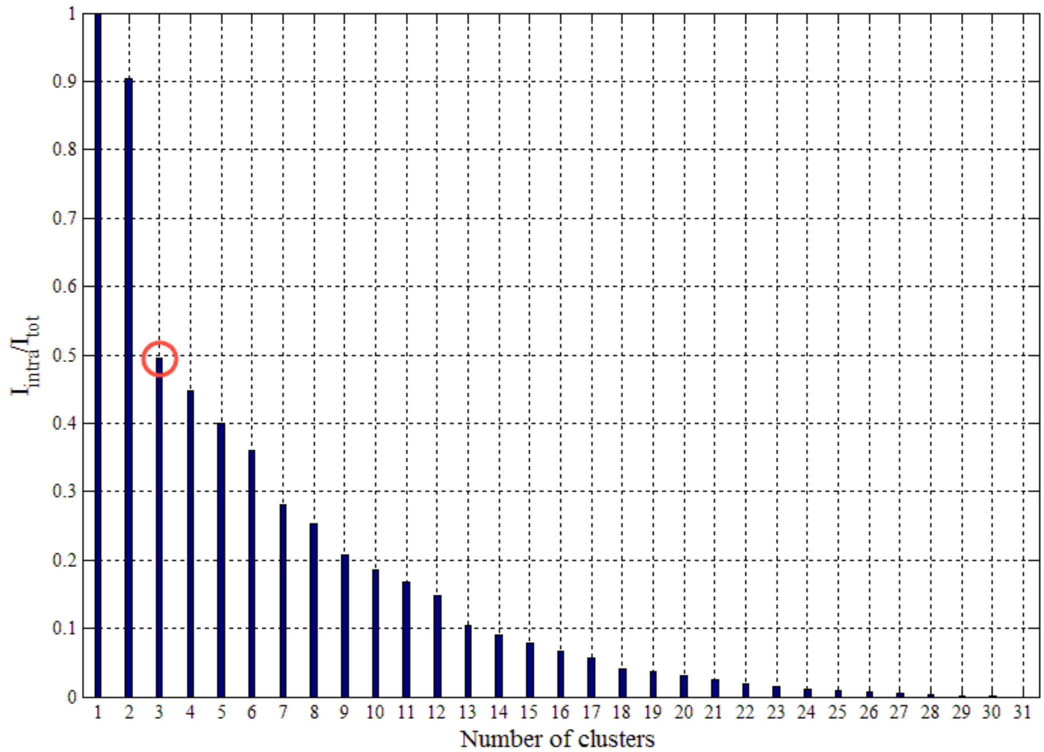


Figure 31. Ratio intra inertia/total inertia vs. number of clusters.

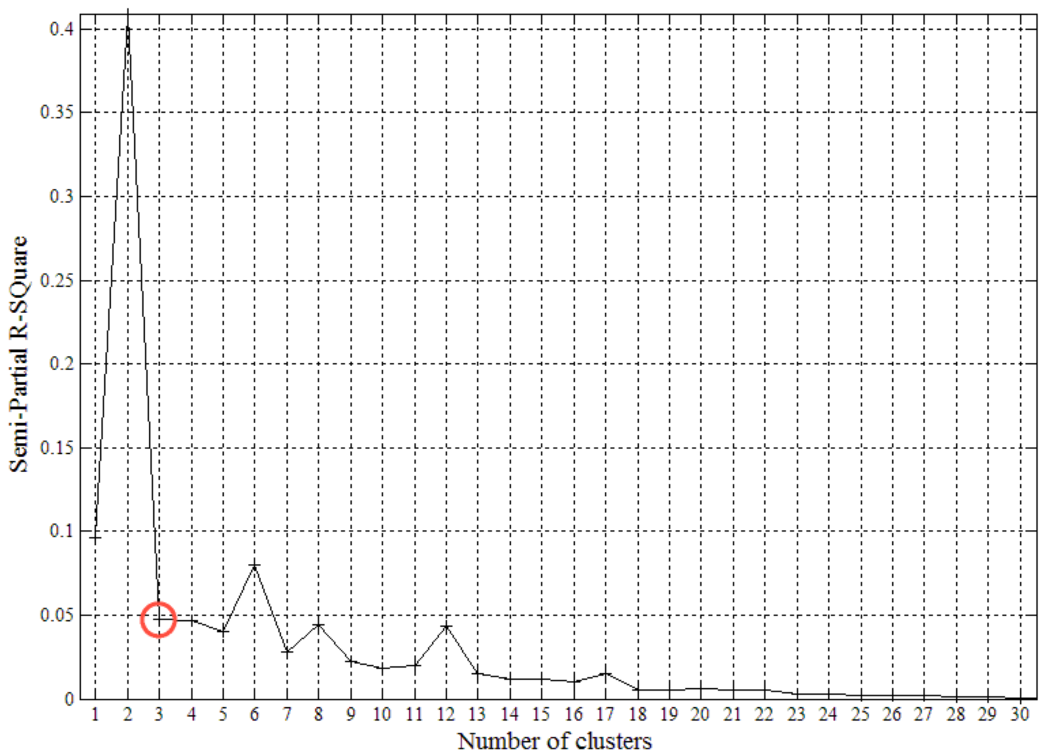


Figure 32. SPRSQ vs. number of clusters.

Figure 33 shows the curve of RMSSTD versus the number of clusters. One can notice a substantial reduction in RMSSTD for a number of clusters equal to 3.

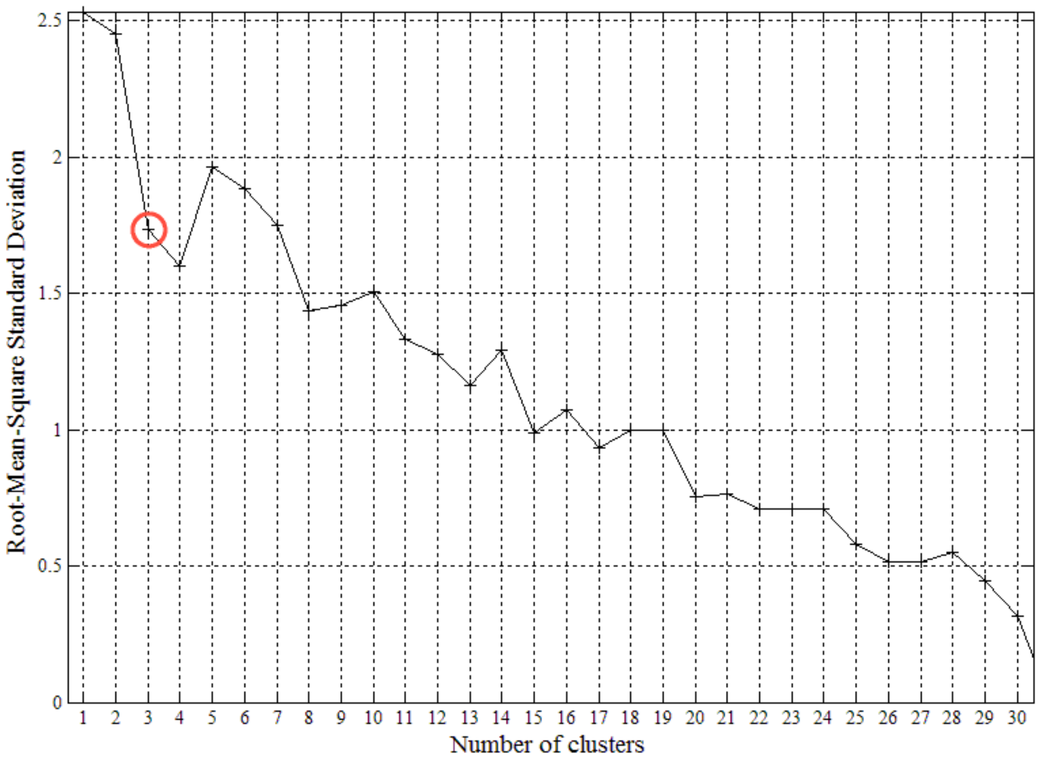


Figure 33. RMSSTD vs. number of clusters.

All the decision aid indices seem to indicate that a partition with 3 clusters is optimal. For this partition (see Figure 29), two clusters are made up of many subjects (respectively 14 and 16 subjects); these clusters represent subgroups of subjects. The last cluster comprises only one subject (i.e. subject n°1); one can consider this subject as an outlier subject.

Summary of results from step 2

Table 11 sums up the results of cluster analysis for each attribute within each subtest.

Table 11. Results of cluster analysis for each attribute within each subtest.

	Seated subtest	**Walking subtest**
Noise annoyance	3 clusters: 2 subgroups (with 15 subjects), 1 outlier subject (subject n°1)	—
Springiness	1 cluster: no subgroup and no outlier subject	3 clusters: 2 subgroups (with 14 and 16 subjects respectively), 1 outlier subject (subject n°1)
Vibration annoyance	2 clusters: 2 subgroups (with 23 and 8 subjects respectively)	2 clusters: 2 subgroups (with 22 and 9 subjects respectively)
Vibration acceptability	2 clusters: 2 subgroups (with 26 and 5 subjects respectively)	2 clusters: 2 subgroups (with 25 and 6 subjects respectively)

Note that, in case where two subgroups are formed, the subgroups are made up of different subjects from one attribute to another and from one subtest to another.

Discussion

In this section, the following questions are addressed after clustering the data into subgroups:

1. are the inter-individual differences still important within subgroups?

2. are there differences in judgment about the floors between the subgroups?

These questions are addressed with respect to the attributes for which one could detect subgroups. To answer these questions, descriptive statistics – box plots and histograms – are used again (see step 1); but this time, these are displayed for each subgroup, for each attribute of interest within each subtest of interest.

Springiness (walking subtest)

Figure 34 shows the box plots for both detected subgroups.

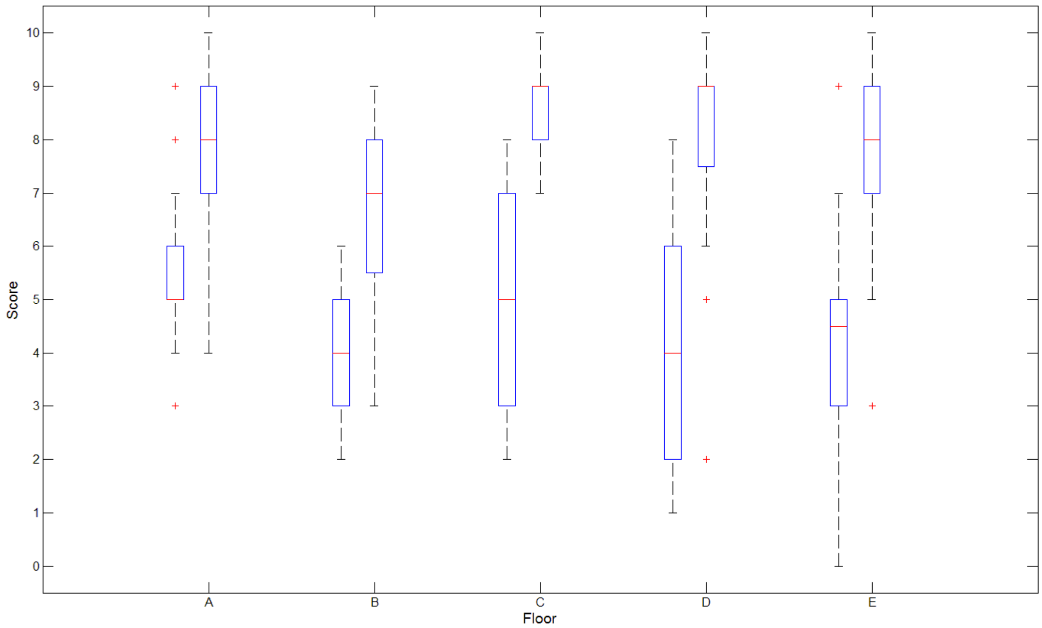


Figure 34. Springiness response box plots for both detected subgroups.

One can observe that:

i) When clustering the data into two subgroups, the dispersion of the individual scores within each subgroup is lower (see Figure 24 for comparison), but still important for some floors.

ii) For subgroup 1 (box plots on the left side), the median scores are lower whatever the floor.

iii) For subgroup 1, floors A and C obtain the highest median score, B and D the lowest median score. For subgroup 2, floors C and D obtain the highest median score, B the lowest median score.

Vibration annoyance (seated subtest)

Figure 35 shows the vibration annoyance response box plots for both detected subgroups.

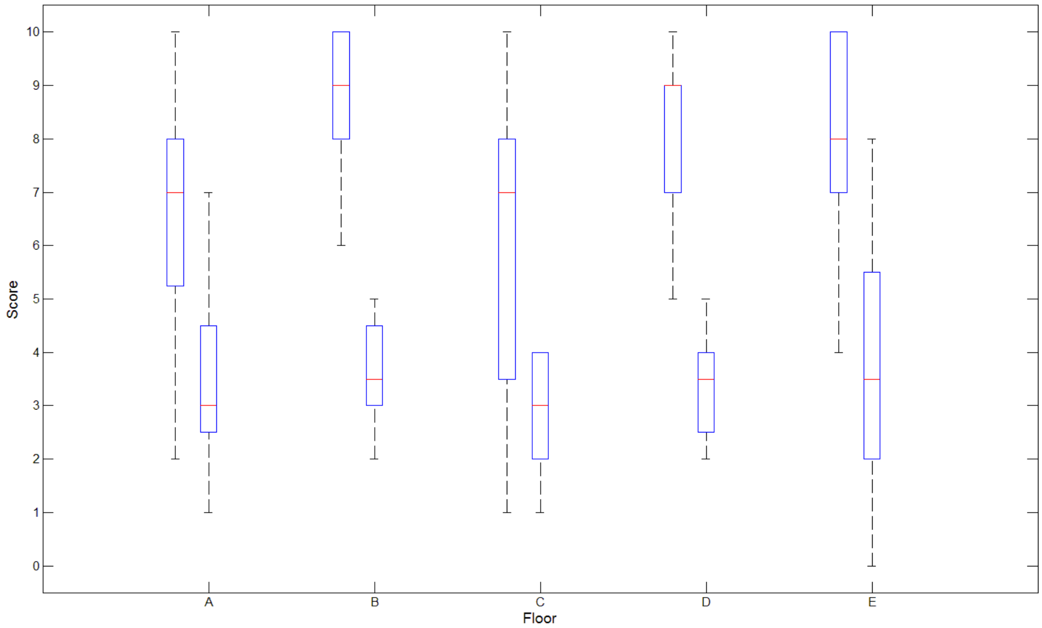


Figure 35. Vibration annoyance box plots for both detected subgroups.

One can observe that:

i) When clustering the data into two subgroups, the dispersion of the individual scores within each subgroup is lower (see Figure 25 for comparison), but still important for some floors.

ii) For subgroup 2 (box plots on the right side), the median scores are lower whatever the floor.

iii) For both subgroups, floors B and D obtain the highest median score, A and C the lowest median score.

Vibration annoyance (walking subtest)

Figure 36 shows the vibration annoyance response “box plots” for both detected subgroups.

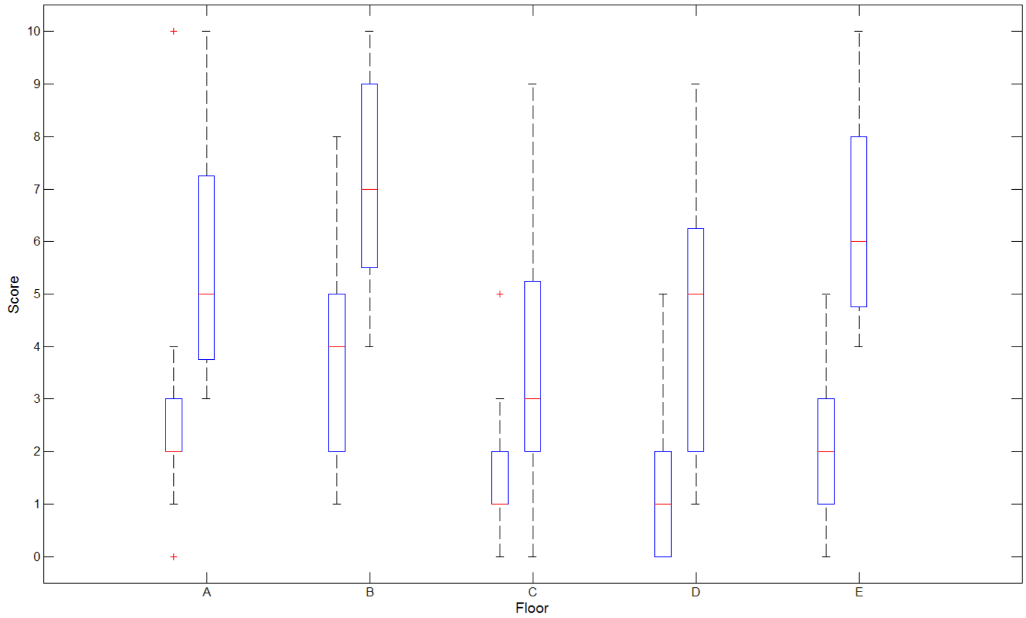


Figure 36. Vibration annoyance response box plot for both detected subgroups.

One can observe that:

i) When clustering the data into two subgroups, the dispersion of the individual scores within each subgroup is lower (see Figure 25 for comparison), but still important for some floors.

ii) For subgroup 1 (box plots on the left side), the median scores are lower whatever the floor.

iii) For subgroup 1, floor B obtains the highest median score, C and D the lowest median score. For subgroup 2, floor B obtains the highest median score, C the lowest median score.

Noise annoyance (seated subtest)

Figure 37 shows box plots for both detected subgroups.

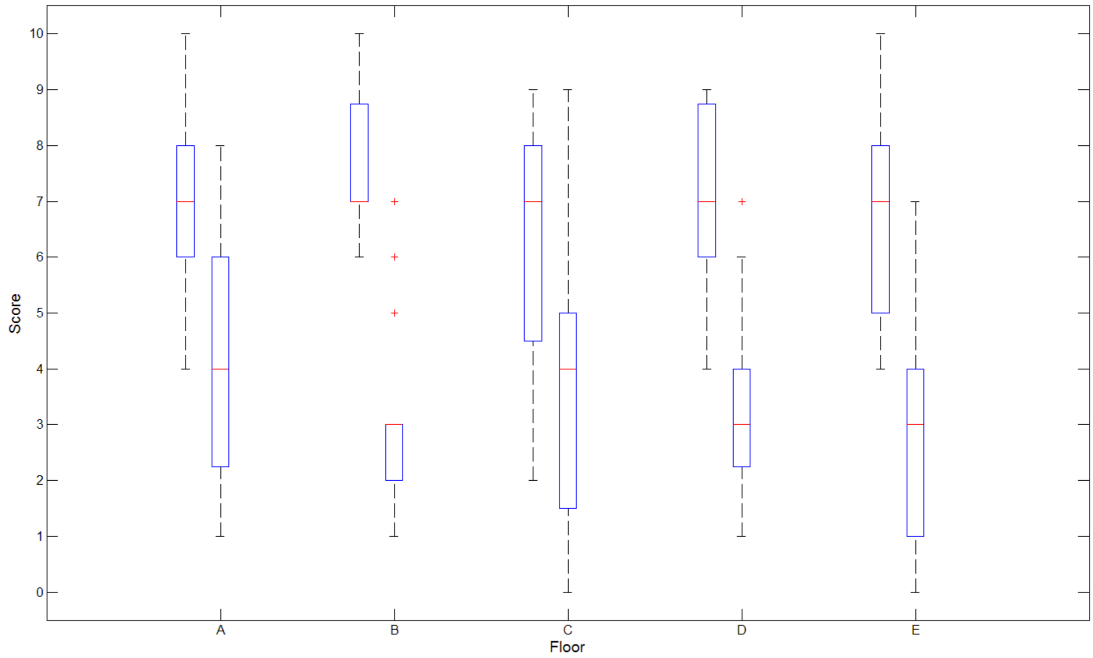


Figure 37. Noise annoyance box plots for both detected subgroups.

One can observe that:

i) When clustering the data into two subgroups, the dispersion of the individual scores within each subgroup is lower (see Figure 26 for comparison), but still important for some floors.

ii) For subgroup 2 (box plots on the right side), the median scores are lower whatever the floor.

iii) For subgroup 1, all the median scores are the same, i.e. it seems there are no differences between the floors. For subgroup 2, floors A and C obtain slightly higher median scores with respect to floors B, D and E.

Vibration acceptability (seated subtest)

Figure 38 shows the histograms for each floor.

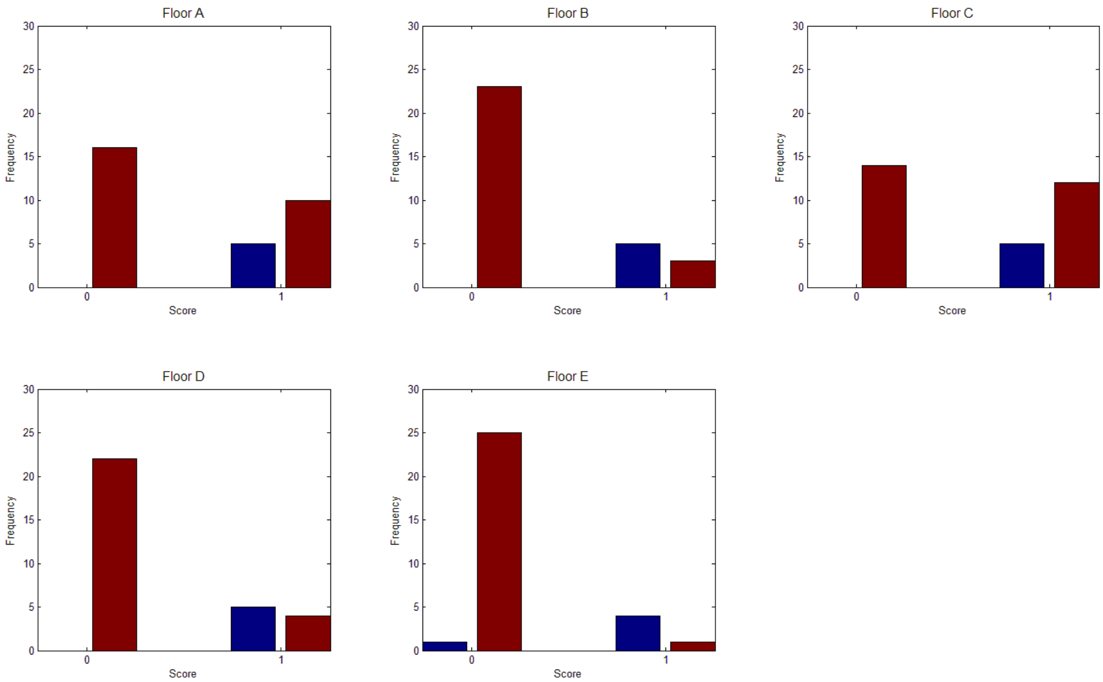


Figure 38. Vibration acceptability histograms for each floor. In brown: subgroup 1; in blue: subgroup 2.

One can observe that:

i) For subgroup 1, no floor is judged as acceptable by a majority of subjects. Floor C is considered as the most acceptable.

ii) For subgroup 2, almost all the subjects find all the floors acceptable.
NB: The size of subgroup 2 (i.e. 5) is small, so one has to be cautious about the trends brought out.

Vibration acceptability (walking subtest)

Figure 39 shows histograms for each floor.

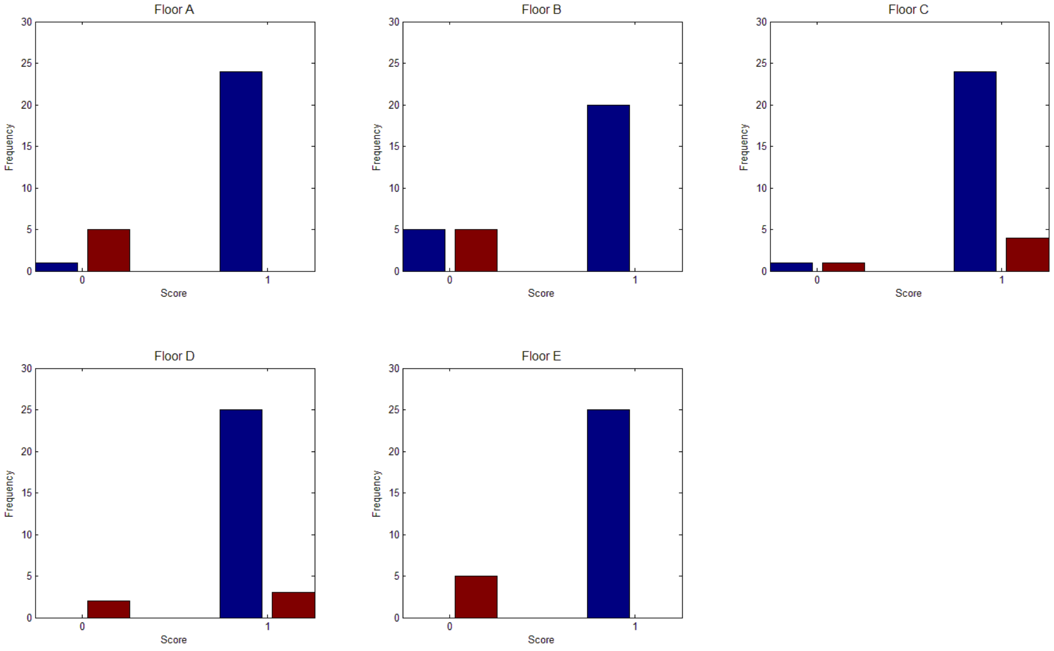


Figure 39. Vibration acceptability histograms for each floor. In brown: subgroup 1; in blue: subgroup 2.

One can observe that:

i) For subgroup 1, some floors are judged as not acceptable by all the subjects (A, B and E); for the other floors (C and D), the subjects are divided.
NB: The size of subgroup 1 (i.e. 5) is small, so one has to be cautious about the trends brought out.

ii) For subgroup 2, almost all the subjects find all the floors acceptable.

Summary

From this discussion, one can retain that:

i) For the numerical attributes, after clustering the data into subgroups, the inter-individual differences within the subgroups are lower, though sometimes still important, depending on the floor.

ii) For the numerical attributes, it seems that subgroups were mainly formed according to the range of the scale used by the subjects to utter their judgments: overall, i.e. for each numerical attribute of interest within each subtest of interest, one subgroup tended to use lower scores whereas the other tended to use higher scores.

iii) For the numerical attributes, except for vibration annoyance within seated subtest, there are slight differences in judgment about floors between the subgroups: the floors that obtain the highest or the lowest median score (when there are ones) are not exactly the same for both subgroups.

iv) For the numerical attributes, with respect to the non-clustered data, the trends are – overall – not so different for the clustered data: i) the vibrations of floor C still appear among the least annoying; its performance regarding springiness still appears among the best; ii) the vibrations of floor B still appear among the most annoying; its performance regarding springiness still appears among the worst;

v) For vibration acceptability, for each subtest, there is one subgroup whose size is small. Thus, the trends brought out have to be considered with caution. In this case, it may be not necessary to *c*luster the data into subgroups regarding the following steps of analysis.

4.2.4.3 Step 3: First assessment of the effects of the floor and subtest condition on the subjective responses

Objectives

The third step eventually aimed at more quantitatively assessing the effects of the floor and the subtest condition, seated or walking (wherever appropriate), on the subjective responses. This step can be seen as an extension of step 1. Several questions were addressed:

i. What is the importance of these effects?
ii. With respects to springiness, which floor(s) can be considered as the best? The worst?
iii. Regarding vibration and noise annoyance, what floors are the most / least annoying when considering vibrations.
iv. Regarding vibration acceptability, what floors are the most / least acceptable when considering vibrations?

To answer these questions, bayesian ANalyses Of VAriance (ANOVA) using multilevel models were carried out.

Procedure

Theoretical aspects of ANOVA

To facilitate the comprehension of what follows, the reader will find in Appendix C a reminder of theoretical aspects concerning classical and Bayesian statistical inferences.

Generalities about ANOVA

The use of ANOVA is very widespread in the field of experimental psychology. Fundamentally, ANOVA can be viewed as a summary of additive data decomposition, i.e. the total variation in data is partitioned into components, with as many components as plausible sources of variation (these sources of variation can be factors underlying the experimental design, or interactions between these factors, or residual errors). Within the additive model, to each source of variation *m* corresponds a batch $\beta^{(m)}$ of coefficients[3] $\beta_j^{(m)}$ ($j = 1, ..., J_m$), i.e. $\beta^{(m)} = (\beta_1^{\ m}, ..., \beta_{J_m}^{\ m})$, such that it can be written as follows (Gelman A. a., 2007):

$$Y_i = \sum_{m=0}^{M} \beta_{j_i^m}^{(m)}$$

where Y_i are data points ($i = 1, ..., n$), j_i^m indexes the appropriate coefficient *j* in batch *m* corresponding to data point *i*. Note that i) batch 0 includes only one coefficient $\beta_1^{(0)}$ that is the grand mean, and ii) the coefficients $\beta_j^{(M)}$ correspond to the residual errors of the model.

[3] According to ANOVA terminology, coefficients can be also called *effects*, more particularly i) *main effects* whenever source of variation *m* is a factor, or ii) *interaction terms* whenever source of variation *m* is an interaction between factors.

Classical ANOVA

In classical ANOVA, least squares estimates $\beta^{(m)}$ of sub-vectors $\beta^{(m)}$ are determined[4]. Then, for each source of variation *m*, the following statistics are computed:

- The sum of squares (SS), defined as $_{i=1}^{n}(\beta_{j_i^m}^{m})^2$;
- The mean square (*MS*), defined as the sum of squares divided by the degrees of freedom (*dof*).

In the end, mean squares are used for null hypothesis testing. The null hypothesis states the absence of effect of the factorial source of variation (i.e a factor or an interaction between factors) under consideration. If a given factorial source of variation gives rise to zero variance component, “then its mean square will, on average, equal the mean square of [residual errors] in the model” (Gelman A. a., 2007). The ratios of mean squares are called the F-statistics; these are assumed to be distributed like Fischer-Snedecor variables. The usual goal of classical ANOVA is to test whether F-statistics are significantly greater than 1 or not (Gelman A. a., 2007). Actually, the statistical test provides a *p*-value, which is the probability to observe, the null hypothesis being true, a value of F-statistic as extreme as the one obtained, because of chance only.

ANOVA using multilevel models

Rather than testing, ANOVA using multilevel models focuses on the estimation of the importance of different batches of coefficients, i.e. the importance of effects due to different factorial sources of variation[5]. In particular, its main aim is to estimate the standard deviation of the batches of coefficients (taken as a measure of this importance). Thus, if this standard deviation is estimated to be small, the effects of the source of variation are considered to be minor. This approach is justified by the fact that the effects of factorial sources of variation are seldom null in the strict sense. Moreover, another aim is to estimate – like classical ANOVA – the coefficients $\beta_j^{(m)}$ themselves[6].

Within a multilevel formulation, each batch of coefficients $\beta_j^{(m)}$ is modeled as a sample from a normal distribution with mean 0 and *superpopulation standard deviation* σ_m (Gelman A. a., 2007):

$\beta_j^{(m)} \sim N\ 0, \sigma_m^2$, for $j = 1, \ldots, J_m$, for each batch m = 1, …, *M*.

The superpopulation standard deviations σ_m’s can be taken as measures of the importance of effects due to different factorial sources of variation; but, when dealing with small samples, one can preferably compute the standard deviation s_m of each batch of coefficients (also called *finite-population standard deviation*), defined as (Gelman A. a., 2007):

$$s_m = \sqrt{\frac{1}{J_m-1}\ {}_{j=1}^{J_m}(\beta_j^{\ m} - \beta^{(m)})^2} \qquad \text{(where } \beta^{(m)} = \frac{{}_{j=1}^{J_m}\beta_j^{(m)}}{J_m}\text{)}$$

Uncertainty in s_m’s is usually lower.

ANOVA using multilevel models lends itself to Bayesian inference. Inference about parameters of interest is made using their Bayesian posterior distributions (see Appendix D). One can use non-informative prior distributions for the model *hyperparameters* (i.e. σ_m^2’s). Afterwards, the posterior

---

[4] The coefficients $\beta_j^{(m)}$ are computed from the sample means.

[5] And not on the existence (or not) of effects due to different factorial sources of variation such as in classical ANOVA.

[6] With the difference that the uncertainty in estimation of the coefficients $\beta_j^{(m)}$ is here assessed through Bayesian credibility intervals (Gelman 2004).

distributions of the model parameters can be computed using analytical formulae or Markov Chain Monte Carlo simulations (Gelman 2004, Gelman 2007).

Multilevel models used in the analysis

The responses of all the subjects are considered here. Indeed, at the end of step 2, we could observe that the trends were – overall – not so different for the clustered data with respect to the non-clustered data.

Model specification

Regarding springiness, vibration annoyance and vibration acceptability, two factors were controlled within our experimental design: floor *F* (with 5 levels: level 1 = floor A, level 2 = floor B, …, level 5 = floor E) and condition *C* (with 2 levels: level 1 = seated and level 2 = walking). We shall select a model that makes it possible to assess the effects due to both experimental factors and to the interaction between them, namely (*FC*). Moreover, owing to the test procedure adopted, ANOVAs shall all be “repeated measures” ones (the different samples of scores come from the evaluation of a corpus of stimuli by a same group of subjects). This means that the ANOVA design includes a factor “subjects” *S* (with 31 levels: level 1 = subject 1, level 2 = subject 2, …, level 31 = subject 31), as well as interactions between *S* and experimental factors *F* and *C*, that is (*SF*) and (*SC*).

In order to model springiness and vibration annoyance data (numerical data), we shall use a cross-classified multilevel model that can be written as follows:

$$Y_i = \mu + \alpha_{j[i]} + \beta_{k[i]} + \gamma_{l[i]} + (\alpha\beta)_{j\ i\ ,k[i]} + (\alpha\gamma)_{j\ i\ ,l[i]} + (\beta\gamma)_{k\ i\ ,l[i]} + \epsilon_i$$

With

$\alpha_j \sim N(0, \sigma_\alpha^2)$, for $j = 1, \ldots, J$

$\beta_k \sim N(0, \sigma_\beta^2)$, for $k = 1, \ldots, K$

$\gamma_l \sim N(0, \sigma_\gamma^2)$, for $l = 1, \ldots, L$

$(\alpha\beta)_{j,k} \sim N(0, \sigma_{(\alpha\beta)}^2)$, for $j = 1, \ldots, J$ and $k = 1, \ldots, K$

$(\alpha\gamma)_{j,l} \sim N(0, \sigma_{(\alpha\gamma)}^2)$, for $j = 1, \ldots, J$ and $l = 1, \ldots, L$

$(\beta\gamma)_{k,l} \sim N(0, \sigma_{(\beta\gamma)}^2)$, for $k = 1, \ldots, K$ and $l = 1, \ldots, L$

$\epsilon_i \sim N(0, \sigma_\epsilon^2)$, for $i = 1, \ldots, n$

where μ is the grand mean, α_j are the main effects of factor *S* (with J = 31 levels), $\square_k$ are the main effects of factor *F* (with K = 5 levels), γ_l are the main effects of factor *C* (with L = 2 levels), $(\alpha\beta)_{j,k}$ are the interaction terms for the first-order interaction between factors *S* and *F*, $(\alpha\gamma)_{j,l}$ are the interaction terms for the first-order interaction between factors *S* and *C*, $(\beta\gamma)_{k,l}$ are the interaction terms for the first order interaction between factors *F* and *C*, ϵ_i are the residual errors[7] and Y_i are the raw springiness or vibration annoyance scores (with a total number $n = J \times K \times L$).

Moreover, σ_α^2, σ_β^2, σ_γ^2, $\sigma_{(\alpha\beta)}^2$, $\sigma_{(\alpha\gamma)}^2$, $\sigma_{(\beta\gamma)}^2$ are the superpopulation standard deviations of the normal distributions of coefficients α_j, β_k, γ_l, $(\alpha\beta)_{j,k}$, $(\alpha\gamma)_{j,l}$ and $(\beta\gamma)_{k,l}$ respectively; σ_ϵ^2 is the superpopulation standard deviation of the normal distribution of residuals errors ϵ_i.

For modeling vibration acceptability data (binary data), we shall also use a cross-classified multilevel model. Note that, when dealing with binary data, what is modeled is the probability p_i that the outcome Y_i is equal to 1 (here 1 = “acceptable”). The model can be written as follows:

[7] Note that, in this case, with one observation *i* per cell (*j*, *k*, *l*), the residual errors are equivalent to the interaction terms for the second-order interaction between factors *S*, *F* and *C*, i.e. (*SFC*).

$$logit(p_i) = \mu + \alpha_{j[i]} + \beta_{k[i]} + \gamma_{l[i]} + (\alpha\beta)_{j\ i\ ,k[i]} + (\alpha\gamma)_{j\ i\ ,l[i]} + (\beta\gamma)_{k\ i\ ,l[i]} + \epsilon_i$$

With

$\alpha_j \sim N(0, \sigma_\alpha^2)$, for $j = 1, \ldots, J$

$\beta_k \sim N(0, \sigma_\beta^2)$, for $k = 1, \ldots, K$

$\gamma_l \sim N(0, \sigma_\gamma^2)$, for $l = 1, \ldots, L$

$(\alpha\beta)_{j,k} \sim N(0, \sigma_{(\alpha\beta)}^2)$, for $j = 1, \ldots, J$ and $k = 1, \ldots, K$

$(\alpha\gamma)_{j,l} \sim N(0, \sigma_{(\alpha\gamma)}^2)$, for $j = 1, \ldots, J$ and $l = 1, \ldots, L$

$(\beta\gamma)_{k,l} \sim N(0, \sigma_{(\beta\gamma)}^2)$, for $k = 1, \ldots, K$ and $l = 1, \ldots, L$

where $logit\ p_i\ = \log(p_i\ \ (1 - p_i))$. The residual errors ϵ_i here follow a logistic distribution.

Regarding noise annoyance, only one factor was controlled within our experimental design: floor *F* (with 5 levels: level 1 = floor A, level 2 = floor B, …, level 5 = floor E). Owing to the test procedure adopted, ANOVA shall also be a "repeated measures" one (see above). For modeling noise annoyance data (numerical data), we thus use the following model:

$$Y_i = \mu + \alpha_{j[i]} + \beta_{k[i]} + \epsilon_i$$

With

$\alpha_j \sim N(0, \sigma_\alpha^2)$, for $j = 1, \ldots, J$

$\beta_k \sim N(0, \sigma_\beta^2)$, for $k = 1, \ldots, K$

$\epsilon_i \sim N(0, \sigma_\epsilon^2)$, for $i = 1, \ldots, n$

where μ is the grand mean, α_j are the main effects of factor *S* (with $J = 31$ levels), β_k are the main effects of factor *F* (with $K = 5$ levels), ϵ_i are the residual errors[8] and Y_i are the raw noise annoyance scores (with a total number $n = J \times K$).

Moreover, σ_α^2 and σ_β^2 are the superpopulation standard deviations of the normal distributions of coefficients α_j and β_k respectively; σ_ϵ^2 is the superpopulation standard deviation of the normal distribution of residuals errors ϵ_i.

Computations

Uniform distributions are used as non-informative prior distributions for the model hyperparameters (i.e. the superpopulation standard deviations).

The posterior distributions of the model parameters are computed using Markov Chain Monte Carlo simulations with 5000 iterations. These computations are performed using Software Winbugs©. All the models implemented in Winbugs© are shown in Appendix E.

For each model parameter, a median value (i.e. a point estimate) and a 95% credibility interval are determined from its posterior distribution.

Analysis

To assess the importance of the effects of the floor and condition (wherever appropriate) − and of the other sources of variation as well − on the subjective responses (i.e. our first objective, see section 2.3.1), for each attribute, we shall compare the finite-population standard deviations computed for all the batches of coefficients (see paragraph "Theoretical aspects of ANOVA", subparagraph "ANOVA using multilevel models"). These comparisons can be carried out graphically.

[8] Note that, in this case, with one observation *i* per cell (*j*, *k*), the residual errors are equivalent to the interaction terms for the first-order interaction between factors *S* and *F*, i.e. (*SF*).

To answer questions such as “Regarding springiness, which floor(s) can be considered as the best and the worst?”, “Regarding vibration annoyance and noise annoyance, what are the floors whose vibrations are the most / least annoying?”, “Regarding vibration acceptability, what are the floors whose vibrations are the most / least acceptable?” (i.e. our second objective, see section 2.3.1), we shall compare, for each attribute, the coefficients of the five floors. In particular, for each pair of floors *k* and *m*, we check whether 95% or more of the simulations show $\beta_k > \beta_m$. If so, we can claim with 95% confidence that floor *k* outperforms floor *m* (Gelman 2011). From these comparisons, we can constitute groups of floors for which the subjective responses are not statistically different.

Results

Springiness

Figure 40 shows the finite-population standard deviations computed for all the sources of variation, i.e. factors *S*, *F* and *C*, first-order interactions (*SF*), (*SC*) and (*FC*) and residual errors (i.e. second-order interaction (*SFC*)).

One can observe that:

i) Overall, the 95% credibility intervals are large, i.e. the uncertainty in estimation of the finite-population standard deviations is high.

ii) The median finite-population standard deviation for factor *F* is small, i.e. the effect of the floor on the subjective responses may be weak.

iii) The median finite-population standard deviation for factor *C* is greater (in comparison with that for factor *F*) but the 95% credibility interval is very large. The effect of the condition on the subjective responses may be not negligible.

iv) The median finite-population standard deviations for interactions (*SF*) and (*SC*) are large, i.e. there are large inter-individual differences regarding the marking of the floors and the assessment of the conditions.

v) The median finite-population standard deviation for interaction (*FC*) is close to zero. The interaction between factors *F* and *C* has a negligible effect on the subjective responses.

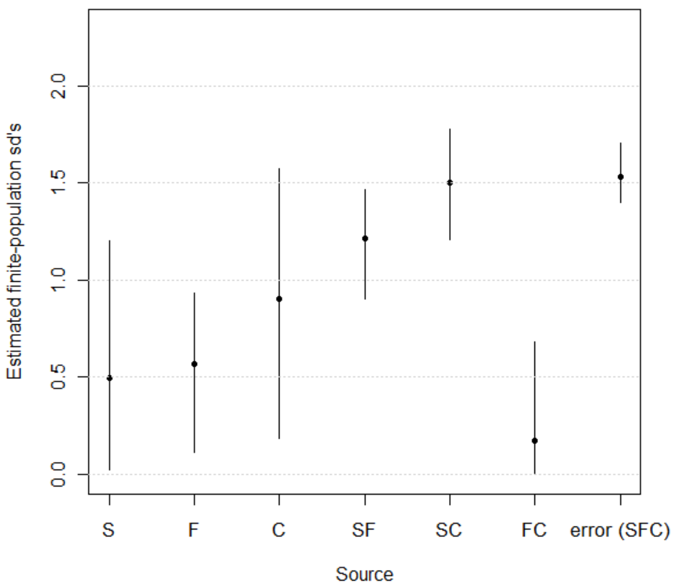


Figure 40. Springiness - Estimated finite-population standard deviations. •: median value; |: 95% credibility interval.

Figure 41 shows the estimated coefficients (i.e. main effects) of the floors.

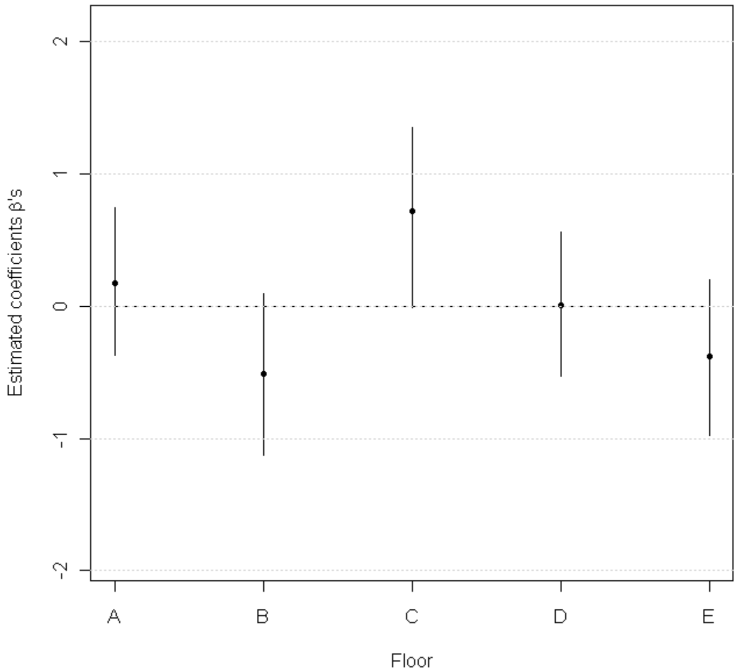


Figure 41. Springiness – Estimated coefficients (i.e. main effects) of the floors. •: median value; |: 95% credibility interval.

Table 12 shows the groups of floors for which the subjective responses are not statistically different (see section 4.2.4.3, paragraph "Multilevel models for the analysis", sub-paragraph "Analysis"). The floors are sorted out according to their median coefficient, in ascending order.

Table 12. Springiness - Groups of floors.

Floor	Group 1	Group 2
B	****	
E	****	
D	****	****
A	****	****
C		****

One can observe that performance regarding springiness of floor C is considered the best, significantly better than that of floors E and B, the worst.

Figure 42 shows the estimated coefficients (i.e. main effects) of the conditions. According to the test described in section 4.2.4.3, paragraph "Multilevel models for our analysis", sub-paragraph "Analysis", the coefficients are statistically different from each other. This confirms that the condition really has an effect on subjective responses. Notably, with respect to the seated condition, the performance of the floors regarding springiness is considered better for the walking condition.

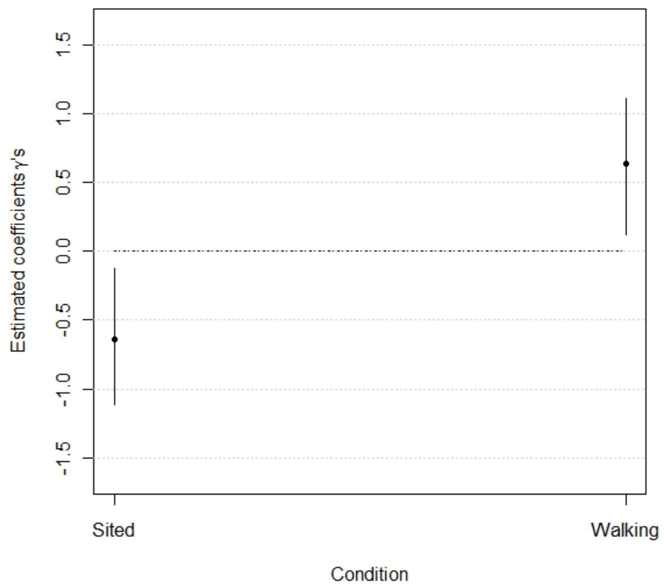


Figure 42. Springiness – Estimated coefficients (i.e. main effects) of the conditions. •: median value; |: 95% credibility interval.

Vibration annoyance

Figure 43 shows the finite-population standard deviations computed for all the sources of variation, i.e. factors *S*, *F* and *C*, first-order interactions (*SF*), (*SC*) and (*FC*) and residual errors (i.e. second-order interaction (*SFC*)).

One can observe that:

i) Overall, in comparison with what was obtained for springiness, the 95% credibility intervals are narrower, i.e. the uncertainty in estimation of the finite-population standard deviations is lower.

ii) The median finite-population standard deviation for factor *F* is small, i.e. the effect of the floor on subjective responses seems weak.

iii) The median finite-population standard deviation for factor *C* is great. That is, the effect of the condition on subjective responses is rather important.

iv) The median finite-population standard deviation for interaction (*SF*) is small, i.e. there are small inter-individual differences regarding the marking of the floors. In comparison, the median finite-population standard deviation for interaction (*SC*) is greater, i.e. there are larger inter-individual differences regarding the assessment of the conditions.

v) The median finite-population standard deviation for interaction (*FC*) is small, but significantly different from 0. That is, the interaction between factors *F* and *C* has a small effect on the subjective responses.

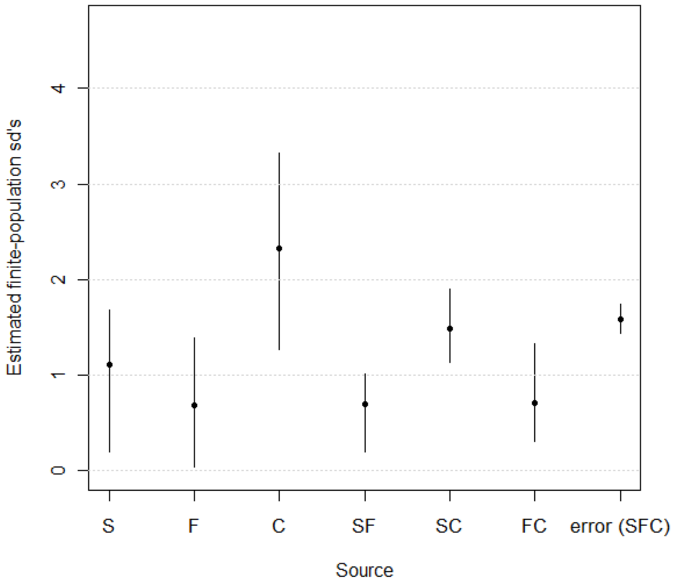


Figure 43. Vibration annoyance - Estimated finite-population standard deviations. •: median value; |: 95% credibility interval.

As the interaction (*FC*) is present, one shall not directly interpret the main effects of factors *F* and *C*; this interpretation can be misleading (Howell, 2009). Indeed, the presence of interaction (*FC*) notably means that the *simple effects*[9] of factor *F* are not identical at both levels of factor *C*. This can be seen through Figure 44, which shows the estimated scores of the floors for both conditions. The fact that both lines are not parallel reveals the presence of interaction (*FC*).

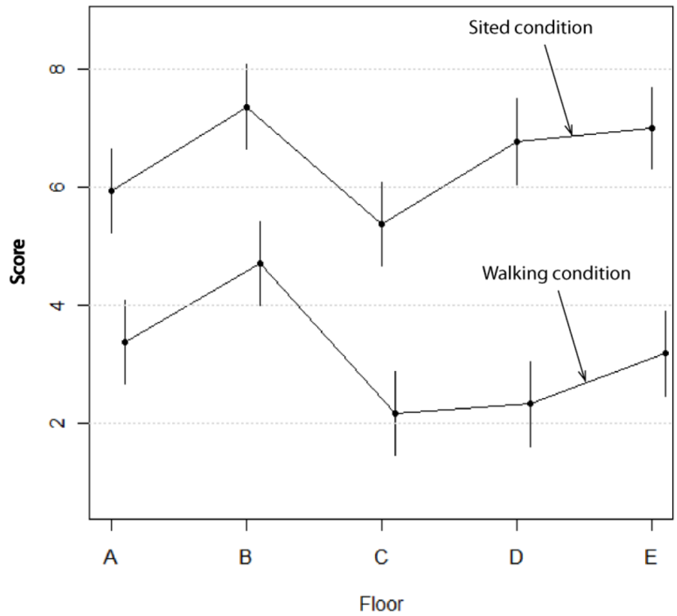


Figure 44. Vibration annoyance – Estimated scores of the floors for both conditions. •: median value; |: 95% credibility interval.

[9] The *simple effect* of a factor is the effect of this factor at one of its levels, at a given level of the other factor.

One can notice that:

i) Whatever the floor, median scores are higher for the seated condition with respect to the walking condition, i.e. the vibrations of the five floors are considered more annoying for the seated condition.

ii) The largest difference between both conditions lies in the median score of floor D: for the seated condition, its median score is close to that of floor B; for the walking condition, its median score is close to that of floor C.

Table 13 and *Table **14*** show the groups of floors for which the subjective responses are not statistically different, for the seated and walking conditions respectively. The floors are sorted out according to their median score, in ascending order.

Table 13. Vibration annoyance - Groups of floors (seated condition).

Floor	**Group 1**	**Group 2**
C	****	
A	****	
D		****
E		****
B		****

Table 14. Vibration annoyance - Groups of floors (walking condition).

Floor	**Group 1**	**Group 2**	**Group 3**
C	****		
D	****		
E		****	
A		****	
B			****

One can notice that:

i) For the seated condition, the vibrations of floors C and A are significantly less annoying than those of floors D, E and B.

ii) For the walking condition, the vibrations of floor C, the least annoying, are significantly less annoying than those of A and D, and significantly much less annoying than those of floor B, the most annoying.

Vibration acceptability

Figure 45 shows the finite-population standard deviations computed for all the sources of variation, i.e. factors *S*, *F* and *C* and first-order interactions (*SF*), (*SC*) and (*FC*).

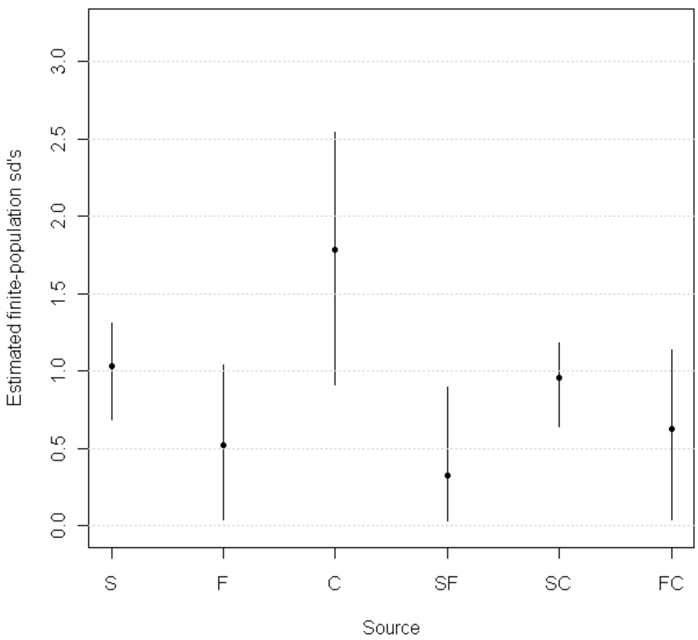


Figure 45. Vibration acceptability - Estimated finite-population standard deviations. •: median value; |: 95% credibility interval.

One can observe that:

i) The median finite-population standard deviation for factor *F* is small, i.e. the effect of the floor on subjective responses is rather weak.

ii) The median finite-population standard deviation for factor *C* is great. That is, the effect of the condition on subjective responses is rather important

iii) The median finite-population standard deviation for interaction (*SF*) is small, i.e. there are small inter-individual differences regarding the marking of the floors. In comparison, the median finite-population standard deviation for interaction (*SC*) is greater, i.e. there are larger inter-individual differences regarding the assessment of the conditions.

iv) The median finite-population standard deviation for interaction (*FC*) is small. That is, the interaction between factors *F* and *C* has a small effect on the subjective responses.

Once again, as the interaction (*FC*) is present, one shall not directly interpret the main effects of factors *F* and *C*. Figure 24 shows the estimated logit scores of the floors for both conditions.

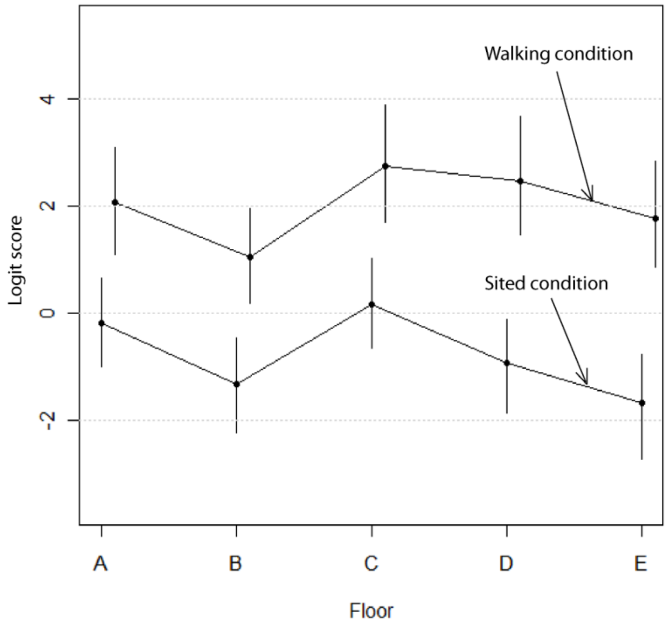


Figure 46. Vibration acceptability – Estimated logit scores of the floors for both conditions. •: median value; |: 95% credibility interval.

One can notice that median logit scores are higher, whatever the floor, for the walking condition with respect to the seated condition, i.e. the vibrations of the five floors are considered more acceptable for the walking condition.

Table 15 and Table 16 show the groups of floors for which the subjective responses are not statistically different, for the seated and walking conditions respectively. The floors are sorted out according to their median logit score, in ascending order.

Table 15. Vibration acceptability - Groups of floors (seated condition).

Floor	Group 1	Group 2	Group 3
E	****		
B	****		
D	****	****	
A		****	****
C			****

Table 16. Vibration acceptability - Groups of floors (walking condition).

Floor	Group 1	Group 2
E	****	
B	****	****
D		****
A		****
C		****

One can observe that:

i) For the seated condition, the vibrations of floor C are considered the most acceptable, significantly more acceptable than those of floor E and B, the least acceptable.

ii) For the walking condition, the vibrations of floor D, A and C are considered the most acceptable, significantly more acceptable than those of floor E, the least acceptable.

Noise annoyance

Figure 47 shows the finite-population standard deviations computed for all the sources of variation, i.e. factors *S* and *F* and residual errors (i.e. first-order interaction (*SF*)).

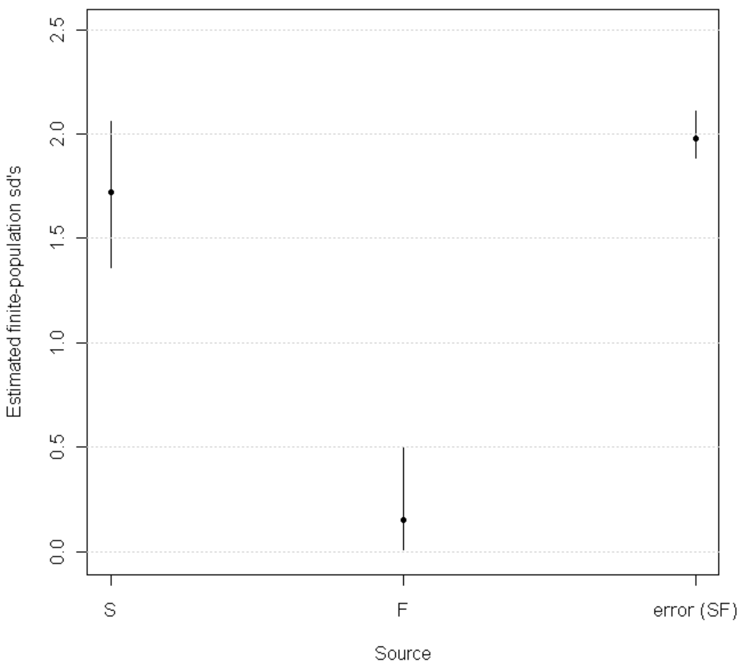


Figure 47. Noise annoyance - Estimated finite-population standard deviations. •: median value; |: 95% credibility interval.

Mainly, one can observe that the median finite-population standard deviation for factor *F* is close to 0, i.e. factor *F* may have a negligible effect on the subjective responses.

Figure 48 shows the estimated coefficients (i.e. main effects) of the floors.

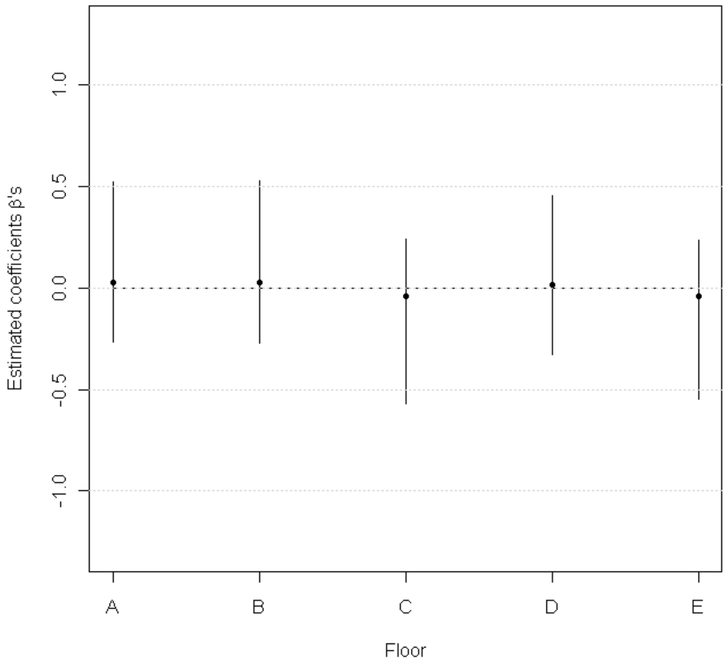


Figure 48. Noise annoyance – Estimated coefficients (i.e. main effects) of the floors. •: median value; |: 95% credibility interval.

Table 17 shows the groups of floors for which the subjective responses are not statistically different. The floors are sorted out according to their median coefficient, in ascending order.

Table 17. Noise annoyance - Groups of floors.

Floor	Group 1
E	****
C	****
D	****
A	****
B	****

There is only one group gathering together all the floors. This confirms that the effect of the floor on subjective responses is really negligible, i.e. the five floors are not statistically different in terms of noise annoyance.

Summary of results from step 3

The findings can be summarized as follows:

i) Regarding springiness, vibration annoyance and vibration acceptability, there is a substantial effect of factor *C* on the subjective responses. That is, whatever the floor, its performance regarding springiness is considered better when people are walking themselves on it; its vibrations are considered less annoying / more acceptable when people are walking themselves on it.

ii) Regarding noise annoyance, factor *F* has a negligible effect on subjective responses, i.e. the floors were not discriminated in terms of noise annoyance.

iii) Regarding vibration annoyance and vibration acceptability, the interaction between factor *F* and *C* has a small effect on the subjective responses, i.e. the simple effects of factor *F* on the subjective responses are not identical for both conditions. This interaction can be seen through small differences between both conditions in the hierarchy of the floors.

iv) Regarding springiness, for both conditions, factor *F* has an effect on the subjective responses; one could observe several significant differences between floors. Performance regarding springiness of floor C is considered the best, significantly better than that of floors E and B, the worst.

v) Regarding vibration annoyance, for both conditions, factor *F* has an effect on the subjective responses; one could observe several significant differences between floors. For the seated condition, the vibrations of floors C and A are significantly less annoying than those of floors D, E and B. For the walking condition, the vibrations of floor C, the least annoying, are significantly less annoying than those of A and D, and significantly much less annoying than those of floor B, the most annoying.

vi) Regarding vibration acceptability, for both conditions, factor *F* has an effect on the subjective responses; one could observe several significant differences between floors. For the seated condition, the vibrations of floor C are considered the most acceptable, those of floor E and B, the least acceptable. For the walking condition, the vibrations of floor D, A and C are considered the most acceptable, those of floor E, the least acceptable.

To sum up further, whatever the condition, it appears that:

- The vibrations of floor C are the least annoying and the most acceptable whereas the vibrations of floors B and E are the most annoying and the least acceptable.

- Performance regarding springiness of floor C is the best whereas that of floors B and E is the worst.

4.3 Summary of results

Both in Växjö and Lund, the psycho-vibratory tests show that, for each floor, within each subtest, there are large differences between the judgments uttered by the test participants. Still, there are detectable differences between the floors in terms of performance regarding springiness, vibration annoyance and vibration acceptability. The subtest condition, seated or walking, has a great effect on the subjective responses. The vibrations are considered less annoying / more acceptable when people are walking themselves on the floors.

Regarding noise annoyance from impact sound, the differences in subjective response between the floors are negligible, i.e. the floors are not discriminated in terms of noise annoyance.

Regarding vibration annoyance and vibration acceptability, the results from Lund show that the vibrations of floor 3 are considered the most acceptable / least annoying and the vibrations of floors 2 and 5 the least acceptable / most annoying. In Växjö, the test participants favored floor 1, it had the most positive response on all questions regarding vibrations, springiness and noise. On the contrary, floor 2 had the most negative response. The findings of the physical testing of the floors seem to support these results, but the relationships between the results from the physical testing and the subjective responses need to be analyzed in more details and will be presented in a separate report. The aim is to find a vibratory indicator for each of the attributes, i.e. springiness, vibration annoyance and vibration acceptability, that would make it possible to predict at best the subjective responses.

These results should be read with caution as the size of the floors has a great impact on the vibration performance parameters and on the way the test participants experience them. This means that the floor structures are not comparable in such a way that it is possible to rank them as better or worse when completely installed in a building.

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Physical and psycho-vibratory testing of wooden floors

This report contains results of physical and psycho-vibratory testing of five wooden floors. The findings of the physical testing of the floors seem to support the psycho-vibratory results, but the relationships need to be analyzed in more details and will be presented in a separate report

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