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Publisher's version / Version de l'éditeur:

Inter-Noise 2011: 4 September 2011, Osaka, Japan [Proceedings], pp. 1-7, 2011-09-04

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NRCC-54534

A version of this document is published in / Une version de ce document se trouve dans:

Inter-Noise 2011, Osaka, Japan, September 4-7, 2011, pp. 7

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Objective and Subjective Assessment of Lightweight Wood-Framed Floor Assemblies in Response to Footstep and Low-Frequency Impact Sounds

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ABSTRACT

The acoustical performance of lightweight wood-framed floor assemblies has been assessed, in response to various impact sounds. For each of a series of full-scale floor-ceiling assemblies, standard impact measurements were made with the sources defined in JIS A 1418 including the tapping machine (light impact source), the rubber ball (heavy impact source), and the so-called “bang machine” tire (heavy impact source). The impact measurements were used to calculate standardized metrics and non-standardized variants. Also, for each assembly, sound recordings were made of the sounds generated by the ball drops and by adult walkers without shoes. These recordings were played back in a controlled laboratory room to listening test participants, who rated the reproduced sounds in terms of “annoyance”. Preliminary results from floors without coverings indicate that listeners ranked the floor assemblies slightly differently for the walkers than for the ball drops. In addition, some of the standardized sources and metrics were less appropriate than others for rating subjective response. The rankings based on use of the heavy tire (“bang machine”), in particular, were not best correlated with subjective rankings.

Keywords: Floor, Impact, Subjective Rating

1. INTRODUCTION

In this paper, preliminary results are presented for the objective and subjective ratings of the impact sound insulation provided by light-weight wood-framed floor ceiling assemblies. Some related results from this preliminary investigation have been presented in Ref. [1], but in this paper, additional results specific to the heavy impact sources are discussed.

The objective ratings are determined from measurements using impact sources described in JIS A 1418 [2]: the tapping machine (light impact source), the rubber ball (heavy impact source), and the so-called “bang machine” tire (heavy impact source).

The subjective ratings are based on judgments of relative “annoyance” by 12 listening test participants, in response to two types of impact sound: the footfalls of adult walkers (without shoes), and the sound resulting from dropping the rubber impact ball. The latter has been suggested to be similar to children running or jumping [3].

2. RECORDINGS AND PHYSICAL MEASUREMENTS

The floor-ceiling assemblies were constructed at the National Research Council in Ottawa, Canada, in the facility used for investigation of direct sound transmission, in which flanking sound transmission is greatly suppressed. This facility consists of two reverberation rooms, one above the other, each with a volume of about 175 m³. There is a 3.8 by 4.7 m opening between the two rooms, for the specimen. The impact sources are in the upper room, and the measurement microphones are in the lower room.

2.1 Floor-Ceiling Assemblies

In total, 19 floor-ceiling assemblies were tested. All were wood-framed, and represented a wide range of construction details in terms of: toppings, subfloor layers, framing (joists and blocking), ceiling attachment method, and ceiling layers. None of the floors had coverings (such as carpet, laminate flooring, vinyl, etc.). Table 1 lists the specimens and gives a brief coded description of each. The labels “NRC-xx” are simply to identify the specimens. The descriptive short codes in the right-hand column are explained in the bottom rows of the table. This set of floors includes a wide

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range of performance, in terms of sound insulation, from excellent to very poor.

Table 1 – Specimen descriptions

NRC-08CT	REF004100_RESL9_PLY28_SCWJ235(455)_GFB100_RC13(455)_G21_G16		
NRC-06	2PLY16_WJ254(455)_CWJ140(455)_GFB100_RC13(455)_G21_G16		
NRC-07A	PLY16_SCWJ235(455)_GFB100_RC13(455)_G21_G16		
NRC-02T	REF01268_PLY16_SCWJ235(455)_BLKING235(455)_GFB100_WFUR19(455)_RC13(455)_G21_G16		
NRC-01	2PLY16_WJ235(455)_BLKING235(455)_GFB100_WFUR19(455)_RC13(455)_G21_G16		
NRC-05T	REF01268_PLY16_SCWJ235(455)_GFB100_RC13(455)_G21_G16		
NRC-08A	PLY28_SCWJ235(455)_GFB100_RC13(455)_G21_G16		
NRC-04	2PLY16_SCWJ235(455)_GFB100_WFUR19(455)_RC13(455)_G21_G16		
NRC-02	2PLY16(455)_SCWJ235(455)_BLKING235(455)_GFB100_WFUR19(455)_RC13(455)_G21_G16		
NRC-03	2PLY16_WJ235(227)_GFB100_WFUR19(455)_RC13(455)_G21_G16		
NRC-05	2PLY16_SCWJ235(455)_GFB100_RC13(455)_G21_G16		
NRC-16	PLY16_WJ235(455)_GFB100_RC13(455)_G13		
NRC-20	OSB19_WI302(406)_GFB150_RC13(406)_2G16		
NRC-22	PLY16_WJ235(455)_CWJ140(455)_GFB100_RC13(455)_G13		
NRC-18	PLY16_WJ254(455)_CWJ140(455)_GFB100_2G13		
NRC-15AT	REF01268_PLY16_WJ235(455)_GFB100_2G13		
NRC-21	PLY16_WJ235(455)_CWJ140(455)_GFB100_G13		
NRC-15	PLY16_WJ235(455)_GFB100_2G13		
NRC-14	PLY16_WJ235(455)_GFB100_G13		
Codes above read left-to-right describe the specimen from top to bottom. Element codes are:			
PLY	Plywood	REF004100	100 mm Concrete Topping
OSB	Oriented Strand Board	REF01268	68 mm Mortar Topping
GFB	Glass Fibre Batts	RESL	Resilient Underlay
WJ	Wooden Floor Joists	CWJ	Wooden Ceiling Joists
SCWJ	Scabbed Wooden Floor Joists	BLKING	Wooden Blocking
RC	Resilient Channels	WFUR	Wooden Furring Strips
G	Gypsum Board		
Numbers preceding the element codes indicate multiple layers: e.g., “2PLY” means 2 layers of plywood			
Numbers following the element code indicate thickness in mm: e.g., “G21” means 21 mm thick gypsum board			
Numbers in parentheses indicate spacing in mm: e.g., “WJ235(455)” means 235 mm wood joists, spaced 455 mm on centre			

2.2 Objective Measurements and Metrics

Measurements of impact sound were made in accordance with JIS A 1418 and ISO 10140-3 [4], using all three sources (impact ball, tire machine, standard tapping machine), for all 19 assemblies.

The physical metrics calculated from the impact ball and the tire machine included $L_{i,Fmax,r}$ (in accordance with JIS A 1419 [5]), $L_{i,Fmax,Aw}$ (in accordance with KS F 2863 [6]), and $L_{iFavg,Fmax(63-1k\ Hz)}$, recently proposed in Ref. [7]. For the standard tapping machine, the physical metrics included $L_{i,r,L}$ (in accordance with JIS A 1419), and $L_{n,w}$, $L_{n,w}+C_{1,50-2500}$, and $L_{n,w}+C_{1,100-2500}$ (in accordance with ISO 717 [8]).

The relationships between the metrics are summarized in Table 2, which shows the “R-squared” (square of correlation coefficient) between pairs of metrics. Note that there are very high correlations between $L_{i,Fmax,r}$ and $L_{i,Fmax,Aw}$ measured with both the ball (A and B) and the tire (D and E). The correlation of $L_{iFavg,Fmax(63-1k\ Hz)}$ (C and F) with these standardized metrics is somewhat lower, particularly for the tire (F). Note also that the correlations of $L_{iFavg,Fmax(63-1k\ Hz)}$ measured with the impact ball (C) with $L_{n,w}+C_{1,100-2500}$ (H) and $L_{n,w}+C_{1,50-2500}$ (I) measured with the standard tapping machine are very high ($R^2 = 0.97$).

Table 2 – R^2 (square of correlation coefficient) between pairs of metrics.

(Letter codes A–I refer to objective metrics at left.)

A	B	C	D	E	F	G	H	I
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A	$L_{i,Fmax,r}$ (ball)	1	0.97	0.90	0.90	0.94	0.79	0.79	0.82	0.91
B	$L_{i,Fmax,Aw}$ (ball)		1	0.96	0.86	0.91	0.90	0.85	0.90	0.96
C	$L_{iFavg,Fmax(63-1kHz)}$ (ball)			1	0.75	0.81	0.91	0.92	0.97	0.97
D	$L_{i,Fmax,r}$ (tire)				1	0.98	0.71	0.56	0.63	0.77
E	$L_{i,Fmax,Aw}$ (tire)					1	0.77	0.63	0.70	0.84
F	$L_{iFavg,Fmax(63-1kHz)}$ (tire)						1	0.80	0.89	0.92
G	$L_{i,r,L}$							1	0.96	0.91
H	$L_{n,w}+C_{I,100-2500}$								1	0.95
I	$L_{n,w}+C_{I,50-2500}$									1

2.3 Recordings for Listening Tests

For the listening tests, two sets of recordings were generated: adult walkers not wearing shoes, who walked in an approximately circular pattern around the centre of the specimen, and a single drop of the rubber impact ball, dropped from a height of 10 cm, in the centre of the assembly. (Recordings and listening tests for the impact ball dropped from heights of 50 cm and 100 cm were also conducted, and some results are presented in Ref. [1].) A low-noise microphone was located directly under the centre of the assembly, 115 cm from the ceiling. Absorptive foam was brought into the lower room to control reverberation, so that the recordings sounded more typical of dwelling spaces.

3. LISTENING TEST

3.1 Facility

The laboratory room used for playback and subjective evaluation measures 9.2 by 4.7 m, with a height of 3.6 m, and is constructed of concrete block. The interior walls of the room were lined with 10 cm-thick foam, and a “T-bar” ceiling with 25 mm-thick glass fibre ceiling tiles was installed. The floor was covered with carpet.

A single 46-cm subwoofer (JBL Professional 4641) and a pair of full range loudspeakers (Paradigm Compact Monitor) hung from the concrete ceiling of the room, above the suspended ceiling. The ceiling tiles in front of the loudspeakers were removed and replaced with a thin fabric sheet. A crossover with a cutoff frequency of 100 Hz was used to send the low frequency components to the subwoofer, and the higher frequency components to the full range loudspeakers.

The electroacoustic playback system was tuned by first equalizing (± 1 dB) over the frequency range from 30 to 5000 Hz, when measured at the listener position using steady state noise. The transient response of the loudspeakers was then further compensated via equalization derived by analysis of playback and comparison with the original recorded ball drops.

3.2 Presentation and Subject Response

For the listening tests of ball drops, one ball drop per test specimen was used (dropped at the centre of the floor). There were 18 test samples to rate – one for each assembly except NRC-16 (no usable recordings were gathered).

For the listening tests of walkers, recordings for each of three walkers per test assembly were included. These recordings were obtained for all 19 test assemblies. There were therefore $3 \times 19 = 57$ test samples to rate, each 4 s in duration.

The test samples from ball drops and walking were not presented during the same test. The test participant first heard and rated all the samples from the 10 cm ball drop before moving on to a separate test containing the walking sounds. For the ball drops, each sample was presented 5 times (i.e., throughout the duration of the test, the participant was asked to rate the same sound 5 different times). Each test therefore included $5 \times 18 = 90$ test items to score. For the walkers, the 57 walking samples were presented 3 times each (for a total test length of 171 test items). In all cases, the order of presentation within a test was randomized.

The test participants heard the sounds presented in pairs, and were then asked to rate the second

sound relative to the first, which within a given test, was always the same reference. The instructions and scale are shown in Fig. 1. The reference sound for the tests was the test recording made from assembly NRC-05 (the corresponding ball drop, or for the case of the walkers, one of the three included samples). This was selected since it was estimated based on objective measures that the performance of assembly NRC-05 would be near the middle of the group when ranked. The subject was instructed that if the second sound was equally annoying to the first (reference) sound, to respond numerically by scoring the second sound a “5”. This testing method allows the subject to rate a floor as “better” or “worse” than the reference by scoring lower or higher than 5, and to quantify how much “better” or “worse” by using the scale from 1-5 and from 5-9.

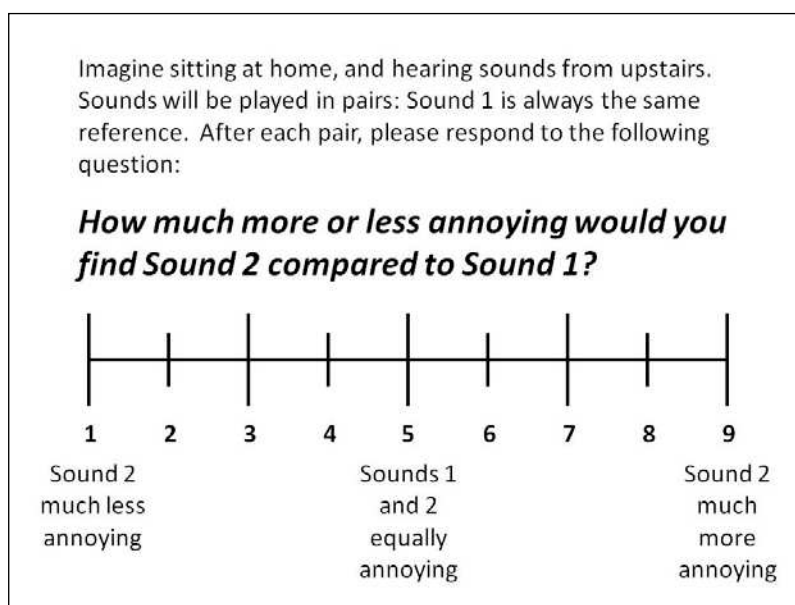


Fig. 1: Instructions and scale for listening test.

4. LISTENING TEST RESULTS

A summary of the listening test results is shown in Fig. 2. Each of the two bar plots shows the average annoyance rating given for the test samples corresponding to the assembly listed to the left of the bars. Each of the two bar graphs is for one impact source – ball drop from 10 cm or walker, indicated at the top. The assemblies are listed from top to bottom on each plot in order of increasing annoyance score (i.e., the “best” floor assembly is listed at the top, the “worst” at the bottom). The red brackets indicate that the difference in scores for the indicated pair of bars is not significant at the $p < 0.05$ level. The absence of a red bracket indicates that the difference is significant at the $p < 0.05$ level. The results shown are from the same 12 subjects for each of the two tests.

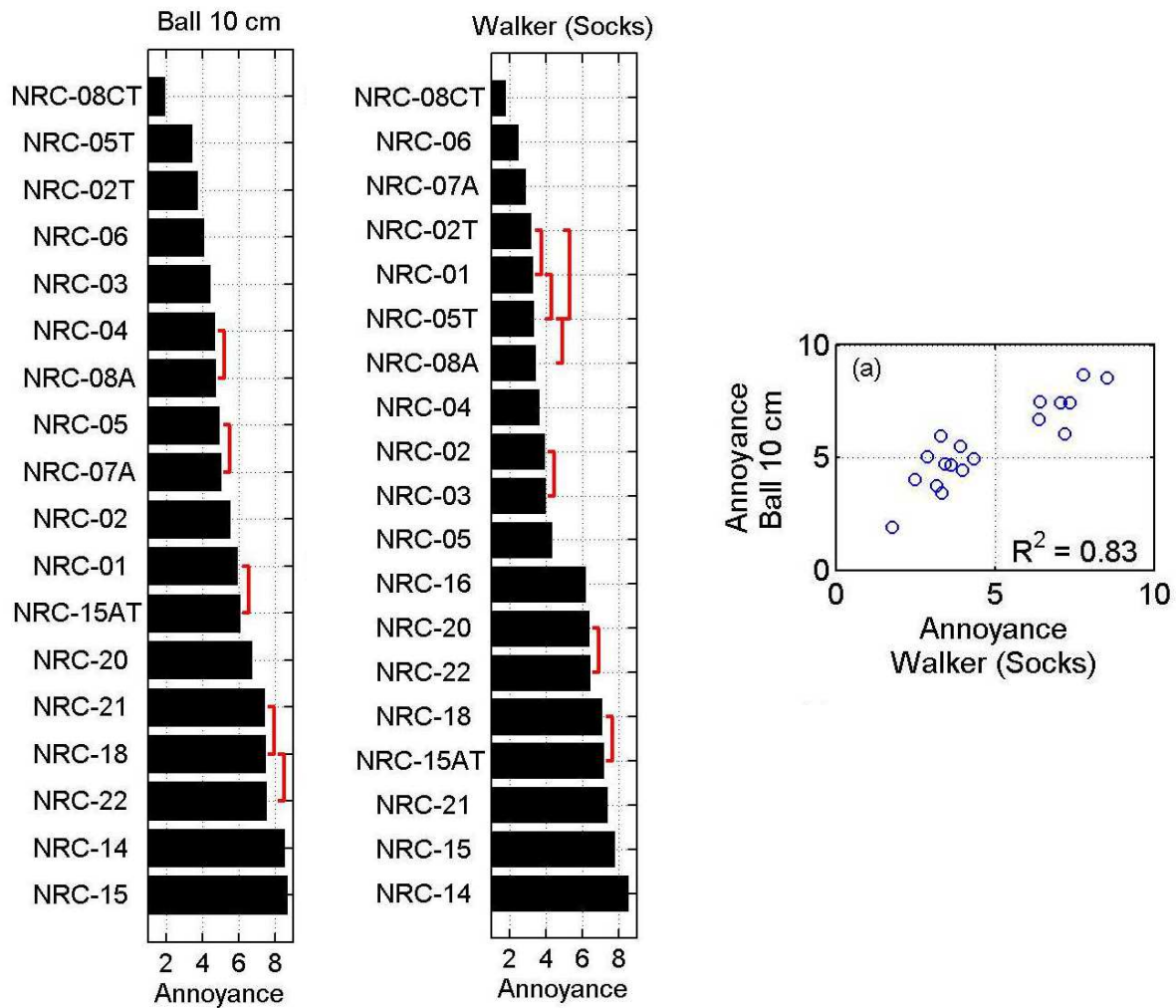


Fig. 2: Listening test results from 12 subjects. Bar length indicates mean annoyance rating for each assembly, which are listed at left of each plot. Assemblies are sorted by score from least annoying at top to most annoying at bottom. A red bracket between a pair of bars indicates that the difference is not statistically significant at the $p < 0.05$ level. Absence of a red bracket means the difference is significant at the $p < 0.05$ level. Plot at right shows relationship between the two judgements.

The ranking order of assemblies based on walkers is somewhat different than that based on the ball drops. Note specifically assembly NRC-07A, which was judged 3rd-best for walking, but 9th-best for the ball drops. This is perhaps not surprising since the floors are intentionally being excited differently. Furthermore, it is expected to observe more variance in the walker data since there is a variance due to different walkers in the test. Shown at the right of Fig. 2 is a plot of subjective ranking by ball drops versus subjective ranking by walking. The R-squared was 0.83.

5. CORRELATION WITH OBJECTIVE METRICS

Figure 3 shows the relationships between the subjective ratings of annoyance, determined from the listening tests, and the objective measures of sound insulation, determined from the physical measurements. The results include both the subjective rankings of the walkers ('o') and of the ball drops from a height of 10 cm ('x'). The R^2 of each relationship is listed on each plot.

Notice from panels (a)–(c) that the correlations with the metrics derived from use of the tire machine are the lowest, particularly for $L_{i,Fmax,r}$ and $L_{i,Fmax,Aw}$. The $L_{iFavg,Fmax(63-1k\text{ Hz})}$ measure correlates well with annoyance judgments of the ball drop sound for both the tire and the ball. The plots in panels (d)–(f) suggest that the metrics derived from use of the impact ball are well correlated

with subjective response to the ball drops, and to a lesser extent, the walking sounds. The plots in panels (g)–(i) indicate that measures determined from use of the standard tapping machine are in fact quite highly correlated with subjective ranking for both types of sounds, particularly for the variants including the spectrum adaptation terms.

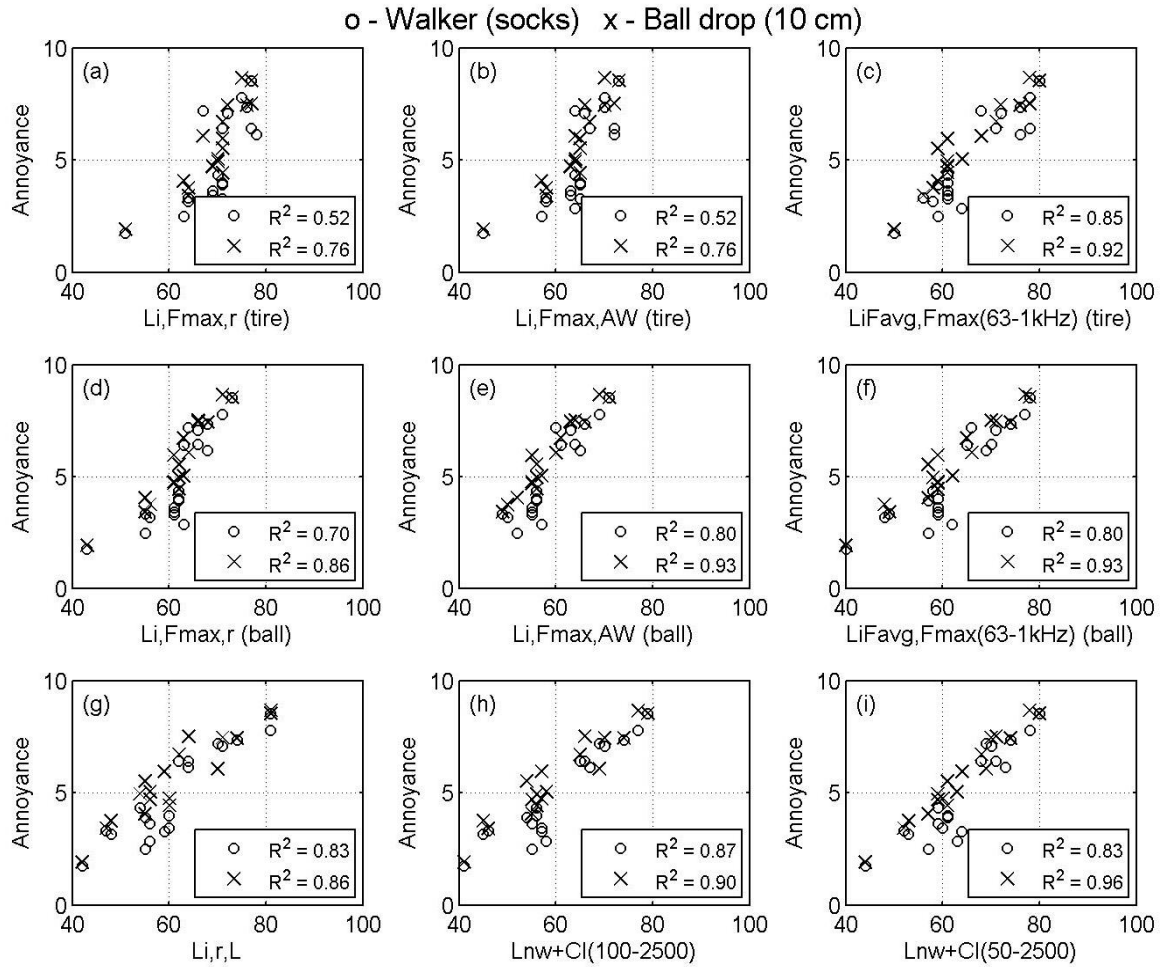


Fig. 3 Subjective annoyance score versus objective measures of sound insulation: the ‘o’ symbols for walkers without shoes, and the ‘x’ symbols for the ball drop from 10 cm.

6. CONCLUSIONS

Based solely on the results of Fig. 3, it appears that the ratings $L_{i,Fmax,r}$ and $L_{i,Fmax,AW}$, determined by use of the tire machine, are not the best options. The results obtained with the impact ball are more highly correlated with subjective judgments. $L_{iFavg,Fmax(63-1k\text{ Hz})}$ correlates well with annoyance judgments of the ball drop sounds for both the tire and the ball. It is particularly noteworthy that using the standard tapping machine and metrics that include the spectrum adaptation term C_1 , give the highest correlations for both types of impact sounds. This supports similar conclusions offered in Ref. [9], which included only objective analyses, but of a wider range of assemblies, and included walkers wearing shoes.

Further investigations that include more listening tests, and floor assemblies having coverings, are ongoing.

ACKNOWLEDGEMENTS

The support of the Council of Forest Industries through the Canada Wood and Forestry Innovation Initiative Programs is gratefully acknowledged.

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