Acoustical Survey of 25 European Concert Halls

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Abstract

To collect the acoustical data of European concert halls, an acoustical journey of acoustical measurements in European concert halls was performed in the years 2000-2007. The data were analysed to reveal differences, similarities and averages of the common acoustical parameters. Furthermore, the measurements were correlated with subjective judgments of concert acoustics, stage acoustics and recording acoustics. The correlation results of these different aspects could be confirmed: for concert and recording acoustics [1], no uniform sound ideal seems to exist, but different groups of similarly judging subjects, the size of which is influenced by the chosen stimulus, whereas for podium acoustics a trend can be found highly intelligible and well strength-supported stage acoustics to be preferred by the musicians.

Motivation and target of the research

The motivation for this survey was the objective, if in concert halls tendencies exist of ideal or optimum audience [2] or stage acoustics or if several disjunctive tastes exist [3]. To answer this, in 2000 a survey of European concert hall acoustics was started continuing until the present.

City	Hall	Date	Seats	V /m^3	Spec. V / m^3
Nijmegen	De Vereeniging []	Jun.00	1.200	12.000	10
Haarlem	Concertgebouw* []	Jun.00	1.200	8.000	07
Berlin	Jesus-Chr.-Church []	Jun.00	≈300	7.900	26
Berlin	Konzerthaus* []	July00	1.575	15.000	10
Leipzig	Gewandhaus	July00	1.900	21.000	11
Düsseldorf	Tonhalle*	July00	2.100	15.000	07
London	Royal Albert Hall*	Aug.00	5.089	86.650	17
Köln	Aula Universität	Mrt.01	1.000	7.700	08
Köln	WDR Sendesaal []	Mrt.01	700	6.800	09
Hamburg	Musikhalle []	Mrt.01	1.993	11.700	06
Amsterdam	Concertgebouw []	Aug.01	2.037	18.780	09
Wien	Musikvereinssaal []	Aug.01	1.598	15.000	09
Basel	Stadtcasino []	Aug.01	1.448	10.500	07
Duisburg	Mercatorhalle*	Aug.01	1.800	12.500	07
Praha	Dvořák Hall []	Aug.02	1.104	10.000	09
Zürich	Tonhalle []	Aug.02	1.546	11.400	07
München	Herkulessaal []	Aug.02	1.321	13.950	11
Hilversum	Studio MCO5 []	Nov.02	≈200	16.000	80
Bochum	University Audimax	Feb.03	1.995	45.000	23
Kissingen	Regentensaal []	July03	936	≈8.000	09
Wiesbaden	Kurhaus []	July03	1.310	12.000	09
London	Royal Albert Hall +	Aug.03	5.089	86.650	17
Rotterdam	De Doelen	Nov.03	2.242	24.070	11
London	R. Festival Hall*	Nov.03	2.901	21.950	08
Düsseldorf	Tonhalle +	Apr.06	1.850	16.500	09
München	Philh. am Gasteig	Nov.07	2.380	29.000	12
*: *Situation before renovation*		**Min**	**200**	**6.800**	**06**
+: *Situation after renovation*		**Avg.**	**1.801**	**20.887**	**13**
[]: *Shoe-box type shaped hall*		**Max**	**5.089**	**86.650**	**80**

Table 1: Measured halls of the survey until now

Survey of European Concert Halls

Between 2000 and 2007, in the course of a Ph.D. thesis, comparative acoustical measurements have been performed in 25 European concert halls, following the example of Gade [4]. Especially the Concertgebouw Amsterdam and of course the Golden hall of the Musikverein Vienna, see fig.1, were measured, known as the best concert halls of the world. The choice of the halls does not claim completeness; it was attempted to include as many different historical or established halls in middle Europe; however, some very interesting (Philharmonic Hall Berlin, Liederhalle Stuttgart, the „Glocke“ Bremen) could not be measured until now. The Dvořák Hall Prague, the Gewandhaus Leipzig and the Jesus-Christ-Church Berlin-Dahlem were included for their famous recording sound. Table 1 shows the halls, dates of measurement and size of the halls as well as the specific volumes (volume per seat), averages end extreme values.

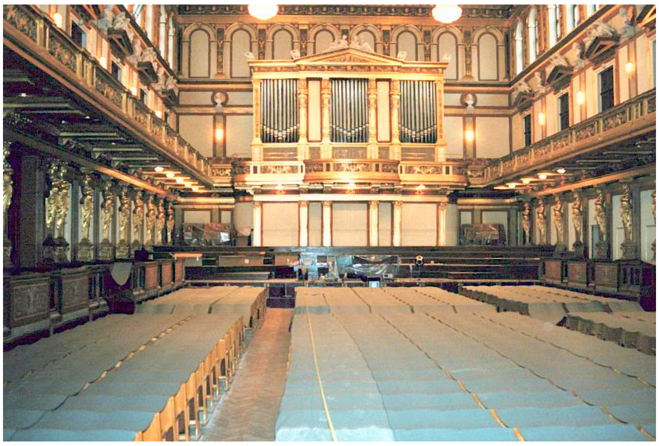

Figure 1: Typical measurement situation Musikverein Vienna 2001

Room acoustical Measurements

All room acoustical measurements were performed at comparable source- and microphone positions with almost identical equipment and settings for all halls unseated and for 14 halls also mostly covered with audience simulation (stage unseated): the audience was simulated by application of stripes from a special polyester cloth spread over the seats, featuring an absorption comparable to chairs seated with average audience. In all halls room impulse response measurements were performed using a PC-based Maximal Length Sequence measuring system (MLS of degree 17B, Fs=44.1 kHz, resolution 16 Bit). The MLS-measurements provided monaural and binaural impulse response sets. The reverberation times additionally were measured using noise bursts and balloon bursts. Furthermore, the decrease of sound level with increasing distance to the sound source was measured for the most halls separately.

Evaluation of the objective parameters

By help of a specially written computer script, the acoustical parameters T_{30} (reverberation time), EDT (Early Decay Time), T_{Centre}, C_{80} (Clarity), D_{50} (Deutlichkeit) were evaluated for the octave bands with mid-frequency 63 to 8000 Hz. Here, the results are averaged over the octave bands with mid-frequencies 500 to 2000 Hz. Additionally, STI (Speech Transmission Index) and AL_{cons} (Articulation Loss of Consonants, see equation (1), Peutz 1988 [5]) were calculated. STI and AL_{cons} were calculated from the omni-directional impulse response (Q_{source} = 1) instead of the for speech intelligibility measurements commonly used directional source with a directivity factor of Q= 2,5 of a human voice.

$$AL_{cons} = 3 + 100 \cdot 10^{\left\{\left[0{,}1\cdot(L_{Rev} - L_{Dir}) + \lg\left(T_{1,3kHz}\cdot 0{,}009\right)\right]\cdot\left[\frac{L_{Send} - L_{Noise} + 10}{35}\right]\right\}} \quad [\%] \quad (1)$$

Evaluated Parameters

Reverberation times

The resulting values for the reverberation times of the halls were averaged over all measurement paths > r_h. Table 2 shows the resulting reverberation times for the halls measured while covered most of the audience with audience simulation, but unseated stage, sorted in increasing order.

Hall / Octave band /Hz	125	250	500	1000	2000	4000	500-2k	125-4k
Royal Festival Hall (03)	1,4	1,4	1,5	1,6	1,6	1,4	**1,5**	**1,5**
Bad Kissingen []	1,1	1,4	1,7	1,7	1,9	1,4	**1,7**	**1,5**
Aula Universität zu Köln	1,5	1,7	1,7	1,6	1,6	1,5	**1,7**	**1,6**
Tonalle Düsseldorf (2006)	1,9	1,9	1,8	1,9	1,9	1,5	**1,9**	**1,8**
Kurhaus Wiesbaden []	2,0	2,0	2,1	2,0	1,9	2,0	**2,0**	**2,0**
Herkulessaal []	2,1	2,0	2,1	2,1	2,1	1,7	**2,1**	**2,0**
De Doelen Rotterdam	2,0	2,0	2,3	2,3	2,2	1,8	**2,3**	**2,1**
Philharmonie am Gasteig	2,3	2,1	2,1	2,1	2,1	2,0	**2,1**	**2,1**
Stadtcasino Basel []	2,5	2,6	2,1	2,1	2,0	1,7	**2,1**	**2,2**
Mercatorhalle (2001)	1,9	2,2	2,4	2,3	2,3	1,8	**2,3**	**2,2**
Concertgebouw A'dam []	2,8	2,4	2,3	2,4	2,2	1,8	**2,3**	**2,3**
Musikverein Wien []	2,6	2,6	2,5	2,5	2,3	1,9	**2,4**	**2,4**
Rudolfinum Prag []	2,2	2,4	2,7	2,9	2,8	2,3	**2,8**	**2,5**
Tonhalle Zürich []	3,2	3,2	2,8	2,5	2,2	1,8	**2,5**	**2,6**
Minimum	**1,1**	**1,4**	**1,5**	**1,6**	**1,6**	**1,4**	**1,5**	**1,5**
Average	**2,3**	**2,3**	**2,2**	**2,2**	**2,1**	**1,8**	**2,2**	**2,1**
Maximum	**4,2**	**3,6**	**3,2**	**2,9**	**2,8**	**2,3**	**2,8**	**3,0**

Table 2: Measured reverberation times covered most of the audience with audience simulation, but unseated stage

In figure 2, the reverberation time averages, maxima and minima are shown with and without audience simulation. The famous halls exhibit, that their reverberation times mostly covered with audience simulation, but unseated stage tends to be a little higher than the average of all *un*seated halls. In comparison, in literature lower values are given due to the fact, most measurements of seated halls are carried out with full occupation and orchestra on stage, the additional absorption in the halls resulting in lower reverberation times than measured here. The situation measured here may be regarded best as average seated soloist recital concert state.

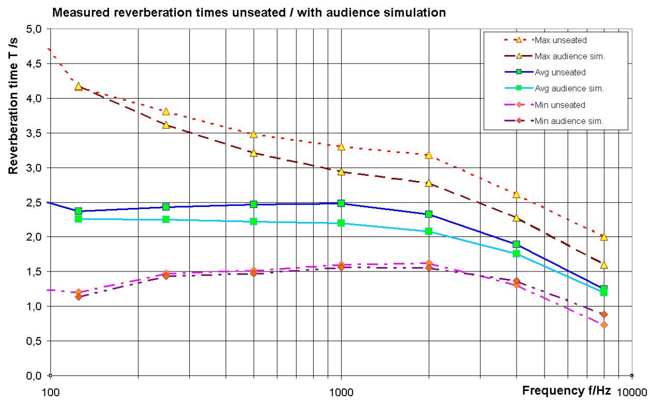

Figure 2: Reverberation times averages, maxima and minima with and without average audience simulation, unseated stage

Other parameters

The other measurement parameters evaluated from the room impulse responses were, if applicable, averaged over the 3 octave bands 500 Hz to 2 kHz (C_{80}, D_{50}, T_{center}) and finally the stage path results (w/o the 1 m position) and all hall path results were averaged separately yielding two parameter values for every hall state. For the halls measured with audience simulation, table 3 shows some results, sorted by increasing clarity. Obviously, the most famous historical shoe-box-type halls are found at the lower end of this scale.

Hall / Octave band /Hz	C_{80} /dB	T_{center} /ms	AL_{cons} /% hall	AL_{cons} /% stage
Royal Festival Hall (2003)	3,1	82	7,7	5,8
Philharmonie am Gasteig	1,6	131	12,2	8,0
Aula Universität zu Köln	0,5	124	10,2	7,6
Kurhaus Wiesbaden []	0,2	117	9,0	8,6
Tonhalle Düsseldorf (2006)	-0,6	119	9,1	6,8
Bad Kissingen []	-0,6	124	9,7	8,0
Stadtcasino Basel []	-1,0	141	12,2	8,8
De Doelen Rotterdam	-1,2	144	12,4	8,8
Herkulessaal []	-1,5	153	12,6	10,9
Concertgebouw A'dam []	-1,6	158	12,3	9,8
Mercatorhalle (2001)	-1,8	152	15,0	12,6
Tonhalle Zürich []	-2,0	168	13,5	9,2
Musikverein Wien []	-2,3	177	14,5	10,0
Rudolfinum Prag []	-2,9	188	16,5	11,4
Minimum	**-2,9**	**82**	**7,7**	**5,8**
Average	**-0,7**	**141**	**11,9**	**9,0**
Maximum	**3,1**	**187**	**16,5**	**12,6**

Table 3: Measured parameters C_{80}, T_c, AL_{cons} (most of hall with audience simulation, unseated stage); AL_{cons} stage (unseated halls)

As result of the objective measurements in famous halls may be stated, that with average audience simulation and unseated stage, they exhibit averaged clarity values from -1 to -3 dB, averaged centre times from 140 to 180 ms and averaged AL_{cons}-values from 12 to 16 %. These values are remarkable because they are not too bad even for speech (and Q=2,5) and significantly less than it could be expected.

The range of AL_{cons}-values on stage with unseated halls is 6 to 13%, even significantly less than in the audience areas.

Subjective quality judgements

Parallel to the survey subjective quality judgement tests were performed for audience acoustics [6] and stage acoustics [7].

Audience acoustics

The method to obtain subjective judgements on audience acoustics were preference tests with many subjects (N > 100) by blind pair comparison tests. Therefore, a selection of five halls (A, B, C, D, E) was chosen their binaural impulse responses of unseated state convolved with anechoic music stimuli (< 15 s). This concentration allowed to give the test-persons a pre-defined randomly found order of 15 (including three identical) pairs in test II (23 pairs AE, EE, AB, DA, EB, BE, …including 3 identical ones in both tests), for which the subjects were asked to decide, whether the first or the second stimulus in the current pair was the most favourable to them. The tests were distributed on CD-R with printed questionnaires. In test 5 an excerpt from the "Ruslan and Ludmilla" ouverture by M. Glinka was used (recorded in 1987, Osaka Philharmonic Orchestra on a non-reverberant furnished stage) was used as non-reverberant recording, in test 6 this was altered to examine the influence of the music stimulus to an excerpt from "Les Toreadors" of G. Bizets "Carmen"-suite, recorded in June 2005 in the anechoic chamber of the institute of technical acoustics with the student orchestra of the RWTH Aachen. A more or less uniform group of 100 test-listeners (members of orchestras and choires as well as individuals) contributed to both of the listening tests. The evaluation of both tests was performed in the following manner: For both tests, re-arranging the test-persons and order of questions was used to identify obviously existing groups of listeners, having judged the questions similarly. It turns out, that the judgement patterns are mostly not of random nature: in both tests they reveal at least three separate, characteristic judgement groups, which can be regarded as different taste groups. This confirm to a certain degree the findings in [4]. From the answers in the similarly answering groups, a preference order of the halls was generated for every consistent group. In test 5, the largest groups III (44%) and II (27%) gave almost opposed answers. A third, smaller group, I (8%) showed another answering pattern, whereas the last group, IV (23%) answered rather inconsistent, so that it was not possible to extract a valid preference order.

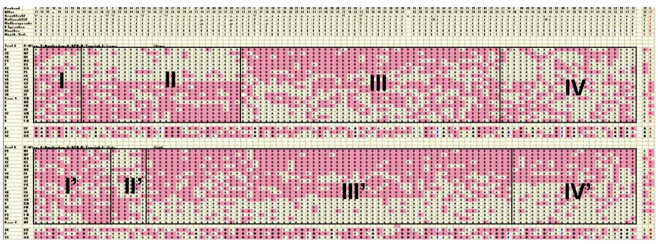

Figure 3: Sorted results of subjective tests 5 (above) and 6 (below)

In test 6, again there are at least three different groups of similarly judging test persons visible (I' to IV'), but to a certain degree, the membership of some individuals changes the group with the altered stimulus: figure 3 shows the results of both tests for all test persons (columns) and pair comparisons (lines), sorted to identify the groups. The influence of the stimulus on the judgement is present, but the stimuli chosen here did not change the global pattern of judgement.[8] In test 6, the groups III' (62%) and II' (7%) gave diametrically opposed answers. A third group, IV' (20%) showed another answering pattern, whereas the last group, I' (11%) answered rather inconsistent, so that it was not possible to extract a valid preference order. In the two tests evaluated here, three to four different groups of listeners can be identified and at least 3 different tastes. After identification of the similarly answering groups and the evaluation of the preference lists, a correlation of the results with acoustical paramaters was done, see table 3-4. The second largest group II in test 5 and group II' in test 6 rate the given stimuli pairs that way, that the order of preference correlates best with increasing values of ETD and T_{30}. For the largest groups (III in test 5, III' in test 6) the order of preference is identical in both tests and correlates best with decreasing values of AL_{cons} and EDT.

Preferred order	Hall	STI	EDT /s	T_{30} /s	C_{80} /dB
1	Concertgebouw	0,41	2,6	2,6	-3,6
2	Musikverein	0,46	3,1	3,1	-2,2
3	Tonhalle Z.	0,43	3,2	3,2	-4,3
4	Tonhalle D.	0,58	1,8	2,0	1,0
5	Festival Hall	0,51	1,5	1,5	0,2
Group I, 8%	Corr. Coeff.	**0,74**	**-0,72**	**-0,72**	**0,74**
Preferred order	**Hall**	**AL_{cons} /%**	**EDT /s**	**T_{30} /s**	**T_{center} /ms**
1	Tonhalle Z.	20,1	3,2	3,2	240
2	Musikverein	15,1	3,1	3,1	205
3	Concertgebouw	14,0	2,6	2,6	195
4	Tonhalle D.	6,9	1,8	2,0	100
5	Festival Hall	8,3	1,5	1,5	109
Group II, 27%	Corr. Coeff.	**-0,94**	**-0,97**	**-0,98**	**-0,94**
Preferred order	**Hall**	**AL_{cons} /%**	**EDT /s**	**D_{50} /%**	**T_{center} /ms**
1	Tonhalle D.	6,9	1,8	43	100
2	Concertgebouw	14,0	2,6	20	195
3	Festival Hall	8,3	1,5	28	109
4	Tonhalle Z.	20,1	3,2	12	240
5	Musikverein	15,1	3,1	23	205
Group III, 44%	Corr. Coeff.	**0,66**	**0,66**	**-0,66**	**0,65**

Table 3: Results tests 5, audience acoustics

Preferred order	Hall	AL_{cons} /%	EDT /s	T_{30} /s	T_{center} /ms
2	Tonhalle Z.	20,1	3,2	3,2	240
1	Musikverein	15,1	3,1	3,1	205
3	Concertgebouw	14,0	2,6	2,6	195
4	Tonhalle D.	6,9	1,8	2,0	100
5	Festival Hall	8,3	1,5	1,5	109
Group II', 7%	Corr. Coeff.	**-0,79**	**-0,95**	**-0,96**	**-0,85**
Preferred order	**Hall**	**AL_{cons} /%**	**EDT /s**	**T_{30} /s**	**T_{center} /ms**
1	Tonhalle D.	6,9	1,8	2,0	100
1	Concertgebouw	14,0	2,6	2,6	195
1	Festival Hall	8,3	1,5	1,5	109
3	Tonhalle Z.	20,1	3,2	3,2	240
2	Musikverein	15,1	3,1	3,1	205
Group III', 62%	Corr. Coeff.	**0,87**	**0,80**	**0,79**	**0,79**
Preferred order	**Hall**	**AL_{cons} /%**	**EDT /s**	**D_{50} /%**	**T_{center} /ms**
4	Tonhalle Z.	20,1	3,2	12	240
3	Musikverein	15,1	3,1	23	205
2	Concertgebouw	14,0	2,6	20	195
1	Tonhalle D.	6,9	1,8	43	100
2	Festival Hall	8,3	1,5	28	109
Group IV', 20%	Corr. Coeff.	**0,93**	**0,81**	**-0,88**	**0,87**

Table 4: Results tests 6, audience acoustics

In both tests there are two groups (IV, I') having made that contradictory judgements, that it was not possible to extract consistent preference orders – interestingly, the individuals are not the same in both tests.

Stage acoustics

For a quality judgement of stage acoustics, the method of questioning orchestras in residence was used by means of a questionnaire for the orchestras [7]. The orchestras were asked to agree on one answer on every question of the questionnaire concerning the different aspects of contact between the remote instrument groups across the stage. The consistency of these answers agreed over the whole orchestra was successfully proved for 2 orchestras by averaging the individual answers of the orchestra members. The quality judgements (five steps: very good to disastrous) were correlated with acoustical parameters measured on the corresponding measuring paths on the stages

The results of the correlation of the quality judgements with the objective parameters evaluated out of the impulse response paths on the podium S1-M2 (front to back), S1-M3 (diagonally) and S1-M4 (left to right) show certain interesting tendencies. As an example, the results for the contact diagonally across the podium, corresponding to measurement path S1-M3 are given in table 5.

City	Hall	T_{30} /s	EDT /s	C_{80} /dB	T_{center} /ms	AL_{cons} /%
Rotterdam	De Doelen	2.3	2.4	2.4	103	8.2
Zürich	Tonhalle (seated)	2.4	2.1	1.0	118	8.3
Hamburg	Musikhalle	1.9	1.9	0.4	120	8.4
Basel	Stadtcasino	2.3	2.1	-0.1	134	9.6
Amsterdam	Concertgebouw	2.7	2.4	-1.4	150	9.7
Zürich	Tonhalle (unseated)	3.2	2.9	0.4	150	9.8
München	Herkulessaal	2.2	2.1	0.0	135	11.8
Berlin	Konzerthaus (2001)	2.6	2.5	-1.6	170	16.5
Mittelwert	**Judged as good**	**2,1**	**2,1**	**1,3**	**112**	**7,9**
Mittelwert	Judged as not optimal	**2,7**	**2,5**	**0,5**	**136**	**10,5**

Table 5: Results for path S1 M3, stage acoustics; green: judged as good; red: judged as not optimal

Remarkably: The better the values for AL_{cons} the better the judgement of the orchestras tends to be for the contact on stage between remote instrument groups. Good stage acoustics seem to require values of AL_{cons} across the stage < 10%. It might be concluded, that orchestras judge stage acoustics as adequate, where acoustical communication is possible. Therefore the other instruments have to be heard and understood. Therefore, the indicator AL_{cons} seems to be a useful criterion for of stage acoustics. In a next step, a correlation will be done for the strength-parameter G, modified to measure the strength of the early reflections on the stage to G5-80, see equation (2) [9].

$$G_{5-80} = 10 \log \frac{\int_{5\,ms}^{80\,ms} p^2(t)\,dt}{\int p_{10}^2(t)\,dt} [dB] \quad \text{[dB]} \quad (2)$$

Résumé

To collect the acoustical data of European concert halls, an acoustical journey of acoustical measurements in European concert halls was performed in the years 2000-2007. The measured impulse responses were analysed to evaluate the common acoustical parameters and to reveal averages, similarities and differences. Furthermore, the measurements were correlated with subjective judgments of concert acoustics, stage acoustics and recording acoustics. The correlation results of these different aspects could be confirmed. The judgements of the 100 subjects per test show for concert and recording acoustics, the rating patterns are mostly not of random nature. Obviously no uniform sound ideal exists, but the subjects split up into (at least three) different large similarly judging groups. The size of and the membership of individuals to these groups is influenced by the chosen stimulus, whereas for podium acoustics a trend can be found highly intelligible and well supported stage acoustics to be preferred by the musicians.

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