Supporting Information

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Binaural Loudness

The phenomenon of directional binaural loudness is visualized in Fig. S1. The figure shows the change in the binaural loudness from the frontal area to one side of the head over a range of azimuth and elevation angles at high frequencies (800–10,000 Hz). The highest mean increase occurs at lateral angles between 60 and 80 degrees at elevations above the lateral plane. However, the shape of the loudness increase is smoother at smaller lateral angles, approximately at 45 degrees to the side. Furthermore, the flatness (i.e., difference between the spectral minimum and maximum between 800 and 10,000 Hz) is indicated by the thickness of the bars. Thus, a thinner plotted bar at a certain angle can be related to a more colored sound in the respective direction in comparison with the direct sound from the frontal region. In general, the binaural loudness at the middle and high frequencies is most emphasized for sounds arriving from lateral directions.

Experiment

The binaural dynamic responsiveness experiment used the unoccupied acoustic measurements from the ten European concert halls listed in Table S1. Binaural impulse responses h were measured with a dummy head (Head and Torso Simulator; Brüel and Kjaer) at five equally spaced positions down an off-center line beginning from 7 m from the stage. The receiving positions denoted by R1…R5 are shown in floor plans in Fig. S2. The source was the calibrated loudspeaker orchestra (1).

In practice, measurements with the loudspeaker orchestra enable us to distribute individual instruments to their typical positions on the stage. Thus, different source spectra can be assigned to different loudspeakers s. Therefore, Eq. **3** in the main article assumes the form

$$Y^{\{d\}}_{\mathrm{Left}}(\omega) = \sum_{s}^{S} \left(X^{\{d\}}_{s}(\omega) \cdot H_{s,\mathrm{Left}}(\omega) \right). \qquad \textbf{[S1]}$$

The per-channel source spectra $X^{\{d\}}_s$ were estimated from the anechoic orchestra instrument samples (2) with the following procedure. The spectrum for individual notes in each dynamics $\{d\}$ was obtained by analyzing the recorded note with the short-time Fourier transform (STFT) using an analysis window length and step size of 8,192 and 512 samples, respectively. The average spectrum of STFT frames containing most energy were chosen to represent the note spectrum. The source spectra $X^{\{d\}}_s$ were then formed by averaging the note spectra of the instruments at each source in proportions typical to a full symphony orchestra. The string-instrument spectra were also detuned using the method by Pätynen et al. (3) for simulating the natural spectral spreading in the section sound. The overall range of fundamental frequencies spanned the frequency band of 55–1,760 Hz (a1–a6). The spectra were analyzed from the instruments' principal radiation directions, similarly to the orchestra recordings used in the loudspeaker orchestra concept (1).

Examples of the source spectrum calculation are shown in Fig. S3. Fig. S3*A* demonstrates how the spectrum for one source is made up of individual note spectra (dashed lines). Fig. S3*B* then displays how the total spectrum of the orchestra is composed of individual source spectra $X^{\{d\}}_s$ (dashed line) and the resulting sum of full-orchestra spectrum in one dynamics.

The spectrum for the left ear (Eq. **S1**) in one receiver position for two dynamics and the subsequently calculated binaural excitation are visualized in Fig. S3*C*. Binaural excitation $B^{\{d\}}$ was calculated with the same method using impulse responses from the five receiving positions in 10 concert halls (see Table S1 and Fig. S2). The overall binaural sound level was adjusted to a realistic level because the anechoic orchestra measurements and room impulse responses were recorded at an arbitrary, yet constant, gain. The balance between instruments is kept constant from the anechoic measurements.

SI Results

Although the comparison with a full orchestra piano and fortissimo treats different instrument groups equally, dramatic variations in dynamics rarely occur with full orchestra. A more typical case would be that, in softer dynamics, only certain instrument sections are in voice, and other instruments then join in during strong dynamics. Comparison with mismatched instruments in piano and fortissimo would yield erroneous results. Instead, differences in the binaural dynamic responsiveness are calculated separately with string, woodwind, and brass instrument groups. Sources representing string instruments are located in the front half of the orchestra. Four sources in a rectangular formation in the middle represent the woodwinds, and the back row and two sources at the far left represent the brass section. Results with separate instrument groups are shown in Fig. S4, with the average of positions R3–R5. The results indicate that, at higher frequencies, the brass instruments contribute the most for the dynamic responsiveness. This effect is in agreement with the strong dynamic emphasis of high brass harmonics. Strings show a slight emphasis around 1 kHz, and woodwinds have some dynamic responsiveness between 1 and 4 kHz. Notably, the dynamic responsiveness for the full orchestra is not directly the sum or average of the instrument-group responsiveness. With full orchestra, interaction of the spectra of all instrument groups' spectra results in a nonlinear combined effect.

Comparisons with halls separately revealed the most prominent contrast between two individual halls with Wuppertal Stadthalle (WS in Fig. S2*a*) and Stuttgart Beethovensaal (SB in Fig. S2*b*). The respective curves are shown in Fig. S5. At the front positions R1–R3, the Wuppertal hall begins to show higher responsiveness already at 1.5 kHz. Toward the middle and rear seating areas, the effect shifts to slightly higher frequencies. In general, the comparison results indicate that the binaural dynamic responsiveness is notably higher than in Stuttgart, thus expanding the orchestra dynamics of the room at high frequencies.

The results for all individual halls in Fig. S6*a* demonstrate the overall trend of higher binaural dynamic responsiveness (BDR) in rectangular halls. At the low and middle frequencies, there is no noticeable difference between hall geometries, but, toward high frequencies, the BDR increase with rectangular halls becomes prominent.

Rectangular rooms typically provide stronger early lateral reflections than alternative geometries. The standardized objective measure of lateral energy fraction (LEF) indicates the proportion of sound energy arriving from lateral angles in the overall early sound. Because higher BDR is hypothesized to result from stronger lateral reflections, LEF is considered to be the most closely related parameter to the dynamic responsiveness. LEF is defined as the relation between energy in the early and direct sound (0–80 ms) with an omnidirectional microphone, and early sound (5–80 ms) from the sides using a figure-of-eight microphone pattern. Fig. S6*b* shows the measured octave-band values for LEF similarly as BDR is shown in Fig. S6*a*. Rectangular halls have higher values of LEF throughout the octave bands.

However, the increased dynamic responsiveness emerges only at higher frequencies, where the spectral effect in the orchestra dynamics is largest (Fig. 1).

Table S2 shows the results from an analysis with correlation coefficients between LEF and BDR in octave bands. At the 2- to 8-kHz octave bands, the correlation is prominent.

SI Discussion

The most notable BDR differences between two concert halls were found between Wuppertal Stadthalle and Stuttgart Beethovensaal. Their floor plans (Fig. S2) would imply that the possibility of lateral reflection varies greatly. The development of the measured room impulse response is demonstrated with the spatiotemporal analysis (4). Fig. S7 shows the spatial-energy distributions in the lateral and median planes in two forward-integrated time windows. By visual comparison, the difference between Wuppertal and Stuttgart halls is evident. In both halls, the direct sound is virtually equally strong. Early lateral energy in Wuppertal is characteristic of narrow halls with parallel side walls (Fig. S7*a*). At the example position, the early reflection after the direct sounds cumulates from azimuth angles of ~45 degrees. As shown in Fig. S1, such reflections enhance evenly the high frequencies, if present in the source signal. In Stuttgart hall, the overall level of early surrounding energy is lower than in Wuppertal (see Fig. S7*c*). The ceiling reflection in Wuppertal Stadthalle is moderate (Fig. S7*b*) whereas the Stuttgart hall has particularly strong first- and second-order ceiling and floor reflections (Fig. S7*d*). Together, such reflections concentrate the reflection pattern to the median plane. In addition, the analysis indicates that balcony fronts and undersides in Wuppertal provide prominent reflections from elevated angles. Relating these observations to Fig. S1, the median plane reflections do not contribute to a similar high-frequency emphasis as the lateral reflections from angles seen with Wuppertal Stadthalle.

It should be noted that, in comparison of BDR in concert halls, a high dynamic responsiveness is not necessarily an indisputable sign of a better or worse acoustic quality. Because the measure aims to reflect only the change in the auditory direct-to-early relation, it leaves entirely without consideration the overall levels of direct and early energy. Therefore, a sufficient value for G continues to be very important. Of nonrectangular halls, Munich Gasteig, for instance, exhibits a moderately high BDR with respect to other compared halls. However, the amount of both early and total energy in Gasteig is low to begin with, mainly due to the vast volume (Table S1). With informal listening in situ and auralizations as well, the hall was considered generally too quiet and nonenveloping.

The experiments in this paper have been conducted only in the spectral domain, applying the respective properties of source signals, room impulse responses, and binaural hearing. In addition to the presented results of varying auditory excitation with changing dynamics, auditory processing includes time-variant temporal masking. This effect has not been included in this analysis. Results by Schubert (5) suggest that the absolute threshold of perceptibility for early reflections varies depending on the signal although, in his experiments, only the reproduction level was varied instead of the spectral shape of the signal. An increase in the sound level decreased the threshold of lateral reflection perceptibility. Consequently, in higher dynamics, more early reflections would become audible, thus contributing more to the loudness as well as spatial impression. The effect of dynamic spectral changes could further emphasize the effect. Blauert and Lindemann (6) found that high-frequency components in lateral reflections specifically increase the degree of spaciousness and preference. One major challenge in conducting objectively time-variant masking experiments using orchestra excitation is that the transients of the instrument sounds should be included. However, the sound attack varies along instruments, dynamics, and notes. Therefore, using a time-variant auditory excitation model adds several more dimensions to the analysis.

1. Pätynen J (2011) A virtual symphony orchestra for studies on concert hall acoustics. PhD thesis (Aalto University School of Science, Aalto, Finland).
2. Pätynen J, Lokki T (2010) Directivities of symphony orchestra instruments. *Acta Acust United Ac* 96:138–167.
3. Pätynen J, Tervo S, Lokki T (2011) Simulation of the violin section sound based on the analysis of orchestra performance. *IEEE Workshop on Applications of Signal Processing to Audio and Acoustics* (IEEE, Piscataway, NJ), pp 173–176.
4. Pätynen J, Tervo S, Lokki T (2013) Analysis of concert hall acoustics via visualizations of time-frequency and spatiotemporal responses. *J Acoust Soc Am* 133(2):842–857.
5. Schubert P (1966) Untersuchunger ber die wahrnehmbarkeit von einzelrckwrfen bei musik. *Tech Mitt Rundfunk Fernsehtechnik* 10:124–127.
6. Blauert J, Lindemann W (1986) Auditory spaciousness: Some further psychoacoustic analyses. *J Acoust Soc Am* 80(2):533–542.

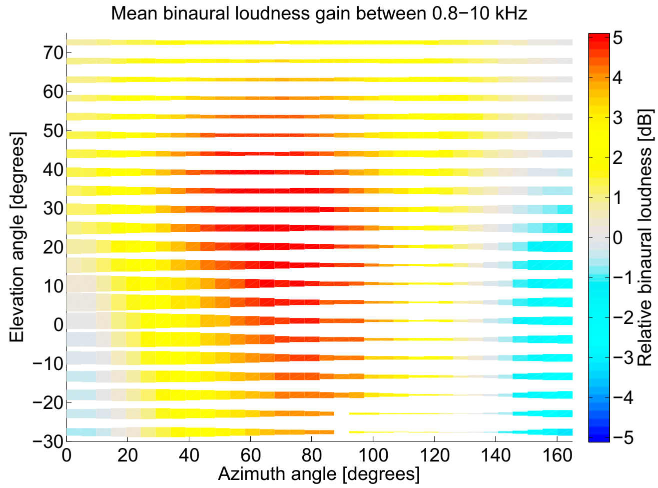
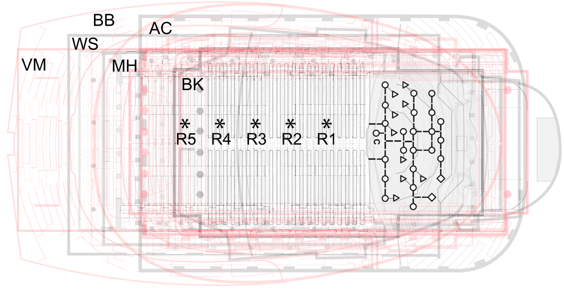
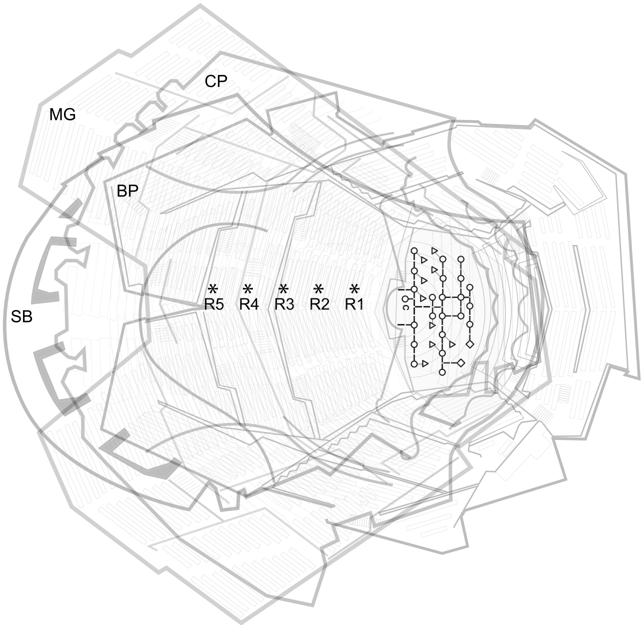


Fig. S1. Analysis on the binaural loudness from regions on one side of the head at the frequency band of 0.8–10 kHz. The results show the characteristics of the binaural loudness magnitude responses averaged over a region of ±15 degrees in azimuth and elevation angles centered at the nominal angle in relation to the mean response at the frontal region (±10 degrees azimuth/0–30 degrees elevation). The thickness of the bars in each angle displays the difference between the minimum and maximum of the mean response curve (Fig. 3) within the analyzed band. Thickest and thinnest bars denote a variation range of 0.7 and 16 dB, respectively.



(a) Rectangular halls including Brussels Palais des Beaux-arts



(b) Non-rectangular halls

Fig. S2. Overlaid floor plans of studied concert halls aligned in scale with the loudspeaker orchestra layout and the receiver positions R1–R5. (*a*) AC, Amsterdam Concertgebouw; BB, Brussels Palais des Beaux-arts; BK, Berlin Konzerthaus; MH, Munich Herkulessaal; VM, Vienna Musikverein; and WS, Wuppertal Stadthalle. (*b*) BP, Berlin Philharmonie; CP, Cologne Philharmonie; MG, Munich Gasteig; and SB, Stuttgart Beethovensaal. Although the Brussels Palais des Beaux-arts hall (BB) is not a rectangular room as such, it was included in the respective group.

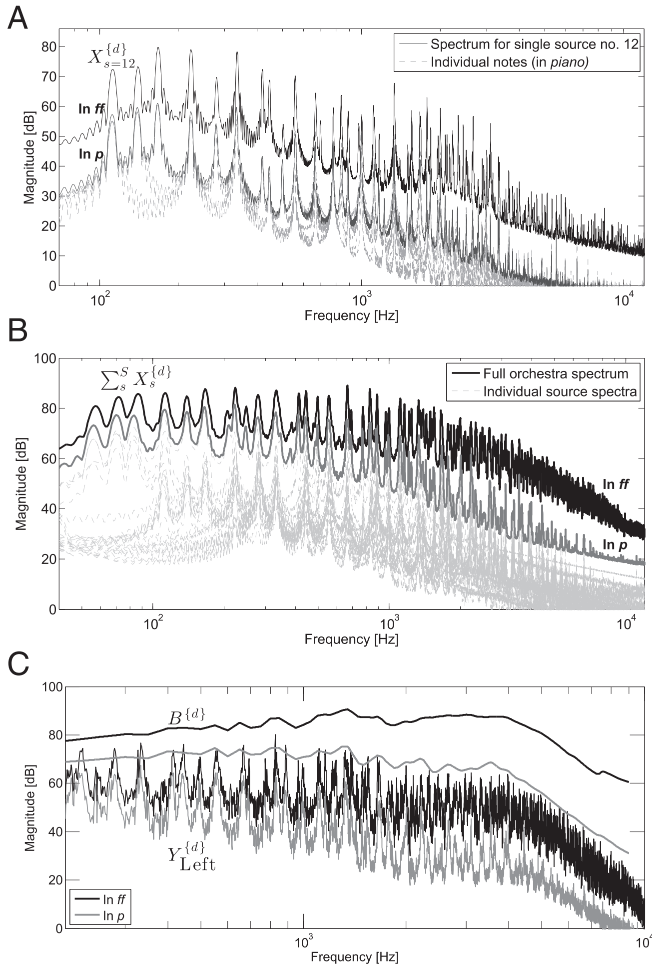


Fig. S3. Examples from estimation of signal-magnitude spectra and binaural excitation. (*A*) Anechoic spectrum in two dynamics (*p* and *ff*; solid lines) for one source representing three cellos. Individual analyzed notes in piano contributing to the total spectrum are illustrated with dashed lines. (*B*) Anechoic full orchestra spectrum in two dynamics (solid lines) combined from all sources. Individual analyzed sources in piano contributing to the orchestra spectrum are illustrated with dashed lines. (*C*) Spectrum of the full orchestra at the left ear with two dynamics in one receiving position (peaky curves). Binaural excitation $B^{\{d\}}$ with left and right ears in the same position using Eq. **5** are shown with smooth curves.

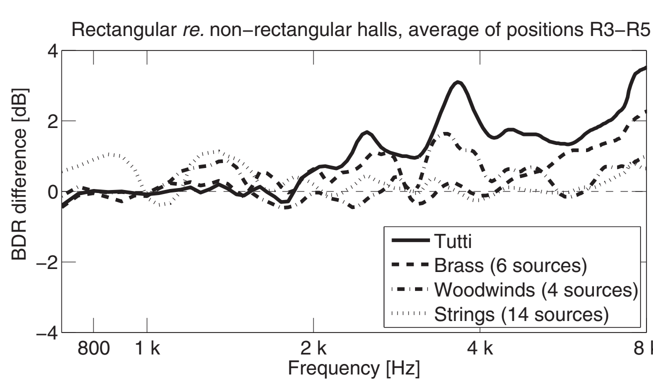


Fig. S4. Binaural dynamic responsiveness calculated separately for sources representing strings, woodwind, and brass instrument groups, and full orchestra at varying distances between rectangular and nonrectangular halls. The curves show the difference in the binaural excitation between direct sound (0–5 ms) and early sound (5–100 ms).

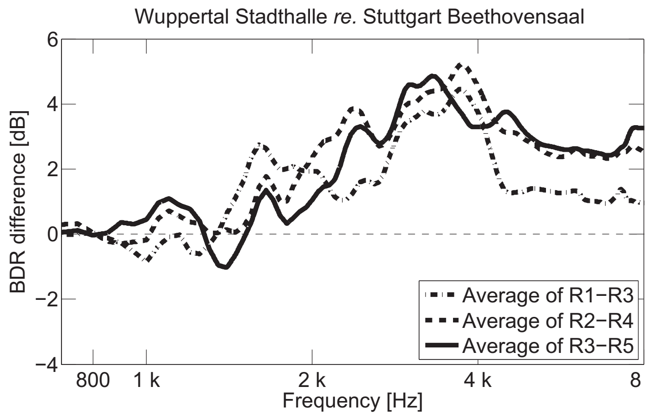
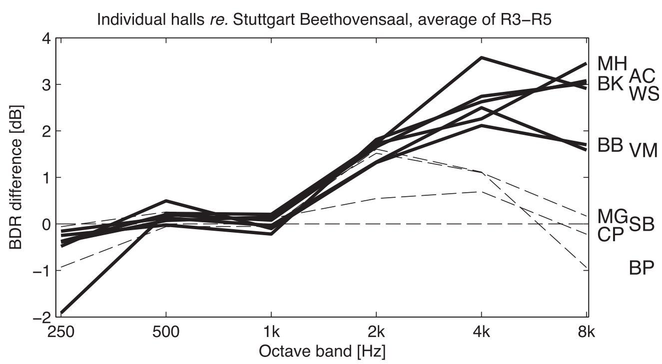
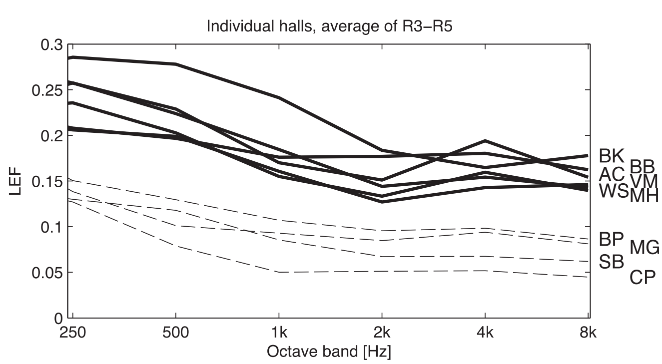


Fig. S5. Difference in the binaural dynamic responsiveness with full orchestra in Wuppertal and Stuttgart concert halls.

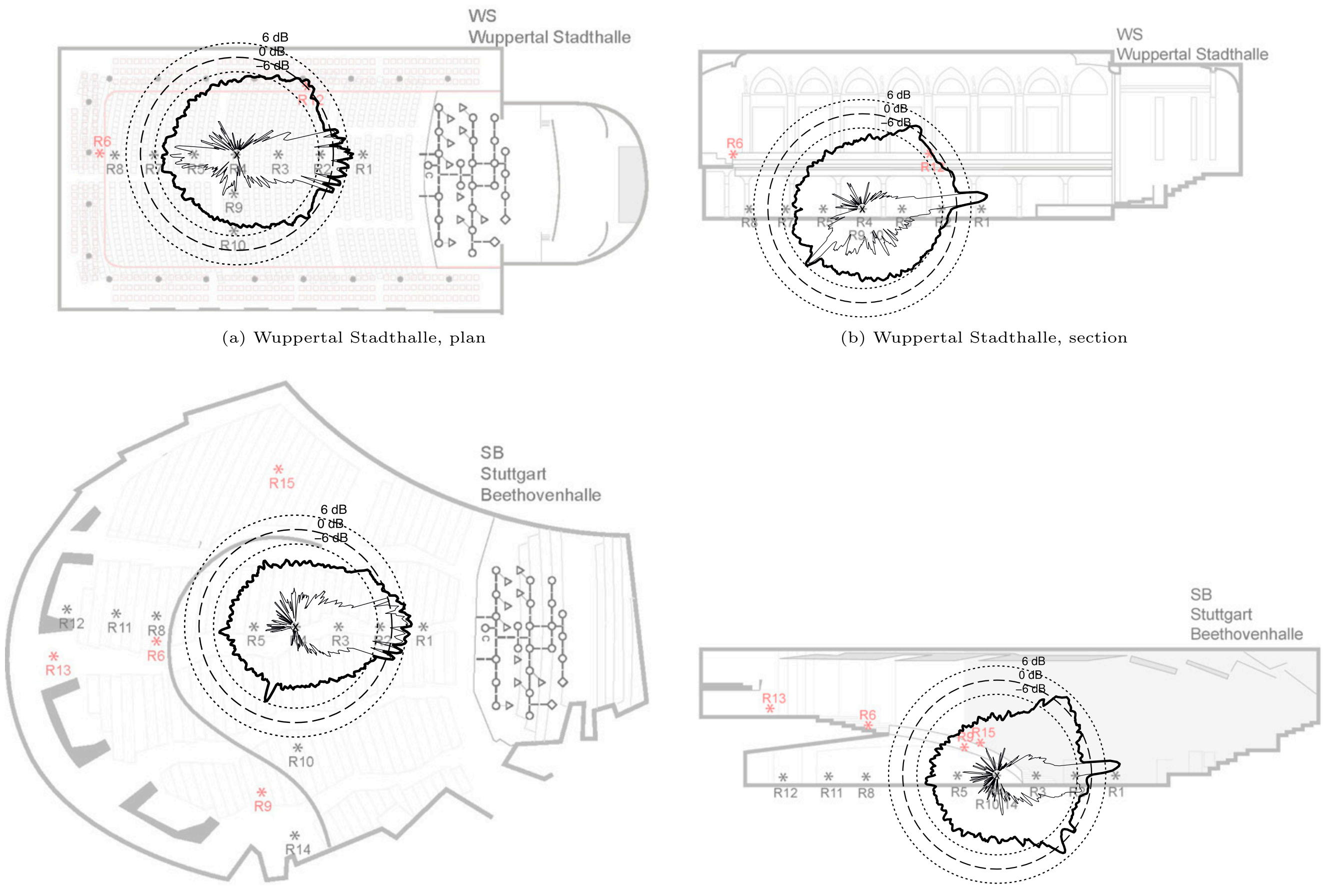


(a) BDR



(b) LEF

Fig. S6. Comparison of BDR and LEF from individual concert halls in octave bands. Values for the curves are averaged from positions R3–R5 (Fig. 4). Curves in thick and dashed line types represent the halls with rectangular (including BB) and nonrectangular halls, respectively. The reference level for BDR values in *a* is SB.



(a) Wuppertal Stadthalle, plan

(b) Wuppertal Stadthalle, section

(c) Stuttgart Beethovensaal, plan

(d) Stuttgart Beethovensaal, section

Fig. S7. Spatiotemporal analysis (4) from two compared halls in plan and sections. Receiver position is at 19 m from the front line of the loudspeaker orchestra. The innermost radial plot shows the cumulative energy distribution between 0 and 5 ms beginning from the initial direct sound averaged from all source channels at the stage. The outer curve shows the respective spatial energy distribution between 0 and 100 ms (Fig. 2).

Table S1. List of European concert halls included in the binaural dynamic responsiveness experiment

Abbrev.	Hall	Shape	V	N	*G*	EDT
VM	Vienna Musikverein	Rect.	15,000	1,680	4.1	3.1
WS	Wuppertal Stadthalle	Rect.	17,000	1,500	3.6	2.6
AC	Amsterdam Concertgebouw	Rect.	18,780	2,040	2.8	2.4
MH	Munich Herkulessaal	Rect.	13,590	1,300	2.9	2.1
BK	Berlin Konzerthaus	Rect.	15,000	1,575	2.7	2.1
BB	Brussels Palais des Beaux-arts	Curved	12,520	2,150	3.6	1.6
MG	Munich Gasteig	Fan	29,700	2,400	1.2	2.1
CP	Cologne Philharmonie	Fan	*19,000	2,000	1.9	1.6
BP	Berlin Philharmonie	Vineyard	21,000	2,220	2.1	1.9
SB	Stuttgart Beethovensaal	Fan	16,000	2000	1.8	2.0

V, N, *G*, and EDT denote volume in m^3, number of seats, average strength in dB, and average early decay time in seconds, respectively. Measured values for *G* and EDT are averages from 500- and 1,000-Hz octave bands. *, estimated.

Table S2. Correlation coefficients *r* between BDR of the Stuttgart Beethovensaal and absolute lateral energy fraction in respective measuring positions

Octave band, Hz	250	500	1,000	2,000	4,000	8,000
r	−0.25	0.00	0.10	0.42	0.66	0.76

Each correlation coefficient is calculated from 30 pairs (10 halls × 3 distance averages) of LEF and BDR values.