Reexamination of the favorable physical parameters and overall acoustical quality of concert halls measured in a 3D synthesized sound field

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1 INTRODUCTION

To date, listening surveys at actual concerts or laboratory tests have been conducted to investigate the relationship between the acoustical quality of a hall and physical parameters [1–5]. This study [6,7] is classified almost in the same category as the previous papers. However, it is differentiated from those in the method of sound presentation to the listeners. For example, it is arguable that the interviews and questionnaires at actual concerts rely on the long-term memory of the subjects, and what criteria the judgments are based on needs to be clarified. In addition, the conductor might have managed to adjust the performance style even for the same music, depending on the acoustic conditions at the performance venue.

Conversely, in laboratory experiments, the type and/or the length of musical pieces used was limited, and the presented sound's reality had issues in realism due to the technical restraint in reproduction. However, with recent advancements in Ambisonics, spatial sound reproduction with significantly improved fidelity compared to conventional methods is achievable. This also addresses the memory retention issue more favorably. For these reasons, this report examined the acoustical quality of concert halls using multichannel recording and Ambisonics reproduction.

In the following sections, we report subjective judgment results concerning reverberance, clarity, loudness, spatial impression (ASW, apparent source width), and overall acoustical quality of concert halls for orchestral music as test stimuli.

2 EXPERIMENTAL SETUP

2.1 Anechoic Recording of an Orchestra

To create the test signals, each orchestral instrument was individually recorded by a member of the Tokyo Philharmonic Orchestra in the anechoic chamber at the Takenaka Research & Development Institute. The total number of players was 32. For the first violin, three concertmasters and one associate principal (*Vorspieler*) participated. For the other instruments, the principal players participated. Fifteen 1/2–inch microphones were arranged in the upper hemisphere around the performer (radius = 3 m) for multichannel recording. The output signal of the microphone used in this experiment was in front of the instrument, but for the French horn, the output toward the bell opening behind the player was used. This recording procedure was basically the same as that stated in the literature [8,9]. In order to match the sound pressure level of a performance as much as possible during the recording, the musicians were asked to play while remembering their experience at the actual concerts to avoid excessive consciousness.

The number of performers was determined through preliminary experiments. Among others, the first violin had an important role in the selected four excerpts. Therefore, it was desirable to ensure the performance precision as well as the chorus effect [10] as much as possible to make the reproduced sound quality approach that of a large orchestra. In addition, if the same violin sound was reproduced from multiple loudspeakers, then coloration occurred due to a comb filter effect. In this paper, it was confirmed that satisfactory sound quality of the first violin section could be realized by a combination of four players: eight sound sources total for the upper and lower *divisi*. For woodwind and brass, the second and third players needed to ensure harmony with the first player by consistent pitch and articulation.

2.2 Musical Excerpts

From classical, romantic, and modern categories, the following pieces were chosen for the sake of diversity in dynamic range, register, and tempo; dramatic orchestration; and general popularity.

- Symphony No. 41 in C major, K. 551 by W.A. Mozart, 4th movement *Allegro molto*, bar 272 to 423 (end), duration: 138 s
- *March of the Swiss Soldier*s from Guillaume Tell Overture, by G. Rossini, *Allegro vivace*, bar 226–387, duration: 130 s
- Symphony No. 9 in D minor by A. Bruckner, 1st movement *Moderato*, bar 518 – 567 (end), duration: 102 s
- *Infernal Dance* from Ballet Suite (1945) *The Firebird* by I. Stravinsky *Vivo*, bar 1 – 98, duration: 107 s

2.3 Loudspeaker Orchestra

An instrument layout the Tokyo Philharmonic Orchestra selects at regular concerts is shown in Fig. 1, on which loudspeaker positions are overlaid. The string section is the type for 16 first violins. For the string sections, corresponding loudspeakers were distributed so that the distance between adjacent loudspeakers was shorter than the minimum audible angle [11] as seen from receiving points. For wind instruments, one loudspeaker corresponded to one instrument. The loudspeaker playback levels were calibrated to reciprocate 16, 14, 12, 10, and 8 players for the first violin, the second violin, the viola, the cello, and the double bass, respectively. The loudspeakers were 43 Bowers & Wilkins 685s (Worthing, England) and two Electro-Voice ZX5-90s (Burnsville, the U.S.). The former had a frequency range of 52 - 22,000 Hz (±3 dB), which was close to the lower range of double bass, while the latter had an equivalent frequency range with higher output sound level suitable for percussion playback. The reproduced sound level from each loudspeaker was calibrated so that the sound pressure level at the 3 m distance from the loudspeaker center was equal to that produced by each musician at the anechoic recording (Fig. 2).

In orchestral performance, the players themselves act as sound absorbers so that the bulk of radiated sound from instruments toward the stage floor is absorbed. The preliminary experiments with a bare floor confirmed that the reproduced sound of the loudspeaker orchestra became slightly harsh and caused a sense of discomfort in the sound quality.

Sound absorptivity of the urethane foam with a thickness 50 mm laid on the stage floor is compared

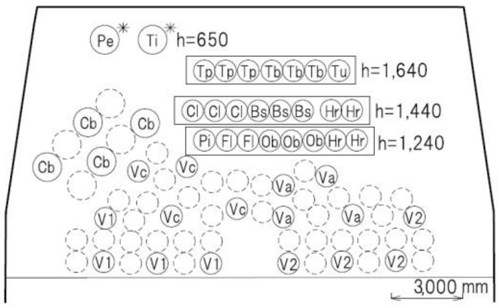

Fig. 1 Arrangement of the loudspeakers on the stage for Stravinsky's *Firebird*.

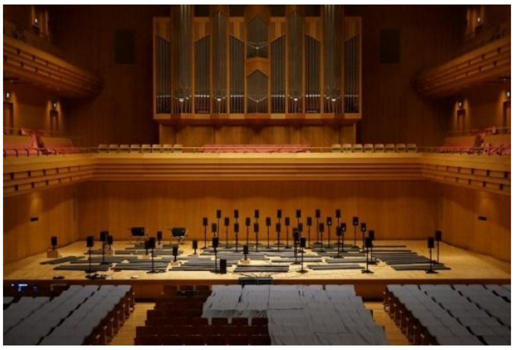

Fig. 2 The loudspeaker orchestra in Hall E seen from a recording position.

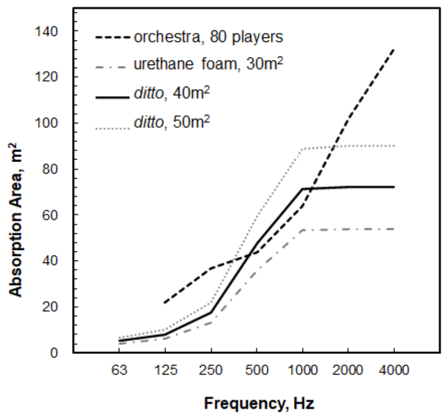

Fig. 3 Sound absorption area of urethane foam (t = 50 mm) measured in a reverberation chamber. Urethane foam units of 2.05 m × 0.265 m were laid with an interval of about 0.3 to 0.5 m on the floor.

in Fig. 3. For an area of 40 m^2, this urethane foam approximates the absorption area of 80 orchestra players at 1000 Hz and below [1]. Then the auditory discomfort without the urethane foam is improved to a large degree. Objective data in Table 1 include the absorption by the urethane foam. When simulating an orchestra with loudspeakers, moderate sound absorption over the stage floor can be a method to improve the auditory impression.

2.4 Recording in the halls

The loudspeaker orchestra playback experiment was conducted in five unoccupied concert halls for orchestra music. Table 1 outlines the dimensions and acoustic data of the concert halls, in which the latter was measured using a dodecahedral loudspeaker placed at position S0 (Fig. 4) and with a 1/2-inch microphone and a real head. As Hall A was built with a removable orchestra reflector, the recording was undertaken under two conditions, i.e., with and without the reflectors. In Hall D, a cloth [12] was spread over the seating area to simulate audience absorption (Hall E). In this recording, RT_M ranged from 1.1 to 2.5 s for the five halls, which covered the actual domain of existing symphony halls [1].

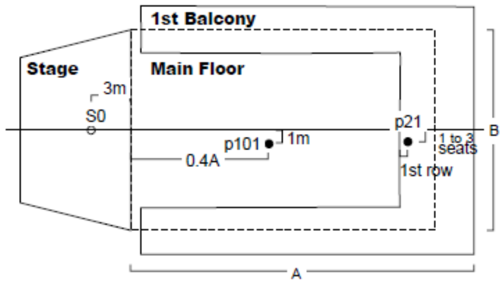

Fig. 4. The letters *A* and *B* relate to the hall's dimensions and determine the receivers' locations.

The loudspeaker orchestra was recorded with a spherical 32-ch microphone, em32 Eigenmike (mh acoustics LLC, S.F., U.S.A). Two receiving points were chosen for each of the halls, if available. Their locations were 1 m off center of the main floor p101 and, if available, close to the center of the front row at the first balcony p21 (Fig. 4). The center height of a spherical microphone was set at 1.1 m. Each of the four musical excerpts was recorded at ten receiving positions in Table 1.

Table 1 Objective measurements of concert halls. "p101" and "p21" are main floor and balcony seats, respectively (Fig. 4).

Hall	Receiver	Plan shape	N	V (m^3)	RT_L	RT_M	BR	EDT_L	EDT_M	$C_{80,3}$	G_L	G_M	$IACC_{E3}$
A	p101	Fan+rectangle	1,932	9,200	1.26	1.22	1.03	1.29	1.25	3.3	5.1	5.3	0.63
Awo	p101				1.25	1.05	1.20	1.60	1.14	5.9	1.5	3.1	0.69
B	p101	Fan+rectangle	1,945	16,290	1.78	1.55	1.15	2.09	1.79	3.3	3.5	5.4	0.61
	p21				1.71	1.56	1.10	1.92	1.67	0.0	2.3	3.3	0.52
C	p101	Surround	2,008	28,000	2.17	2.12	1.02	1.75	1.66	0.9	7.2	7.3	0.57
	p21				2.29	2.19	1.05	2.08	1.54	0.2	2.8	4.2	0.64
D	p101	Shoebox	1,636	15,300	2.09	2.41	0.87	1.80	2.13	-1.2	9.2	9.3	0.33
	p21				2.18	2.51	0.87	1.70	2.27	-3.2	6.6	6.6	0.30
E	p101	Shoebox	1,636	15,300	2.15	2.05	1.05	1.70	1.68	1.3	5.4	6.3	0.27
	p21				1.96	2.07	0.95	1.84	1.90	-0.7	3.8	3.6	0.30

2.5 Acoustic test in the semi-anechoic chamber

The test sound was presented to the listeners in a 4th-order Ambisonics sound field. The sound pressure level at the listener's head was calibrated to be the same as that at each of the recording positions in the halls: L_{Aeq} = 66.4−72.4 dB, 70.9−77.5 dB, 75.5−81.5 dB, and 70.0−75.6 dB, and L_{A5} (upper 5% level) = 70.3−76.3 dB, 75.7−81.5 dB, 80.3−86.4 dB, and 76.0-81.7 dB for Mozart, Rossini, Bruckner, and Stravinsky, respectively. Here, L_{Aeq} (A-weighted equivalent sound level) is a measure of the same accuracy as Zwicker's method for the loudness of temporally varying sounds [13].

The favorable physical parameters studied here were intended for experienced listeners of classical music in various concert venues, rather than for general audiences. Further, they needed to be absolute values, not relative values. The participants were 21 musical experts. Prior to the subjective test, the listeners were given a 30-minute explanation of the relevant knowledge of room acoustics and the purpose of the research to minimize any discrepancies in the terminology used by the acoustician and the musician. At the beginning of the test signal, the listeners were presented with the most reverberant and dry test signals as a reference without mentioning the name of the sound fields to make them understand the sound field's dynamic range. Also, the listeners were instructed not to shift or rotate their heads as much as possible because the sound image could vary due to such a slight change in an Ambisonics sound field.

The listeners answered questions on reverberance, clarity, sound strength, spaciousness, and overall acoustical quality. Reverberance was rated by five levels: "too short or deficient," "somewhat short," "just right or optimum," "somewhat long," and "too long or excessive." Then, the subjects were told that they could rate according to the impression of whether the continuous tones were muddy or separated and that of the stop chord.

Clarity was rated by three levels: the musical detail was "unclear," "passably clear," and "clear" without distinguishing temporal and spatial clarities, i. e., discernibility of tones played in succession, and separation of different motives (voices) performed simultaneously for the first ten subjects. On the other hand, the later 11 subjects were asked to judge the spatial aspect in clarity by five levels: "unclear," "passably unclear," "neither," "passably clear," and "clear." Perceived sound strength was rated by five levels: "too soft," "somewhat soft," "optimum," "somewhat loud," and "too loud." Spaciousness (ASW) was rated by five levels: "narrow," "somewhat narrow," "neither narrow nor expansive," "somewhat expansive," and "strongly expansive." Overall acoustical quality was rated by five levels: "poor," "somewhat poor," "neither poor nor good, passable," "somewhat good," and "good."

3 RESULT

3.1 Reverberance

Assuming an equidistant scale for the criteria in the questionnaire, the average value of the judgments by all subjects was calculated. The five levels of reverberance corresponded to the numerical values 0, 1, 2, 3, and 4 from "too short" to "too long," and reverberance was plotted against the reverberation time RT_M and the early decay time EDT_M in Figs. 5 and 6. The correlation coefficients for the four music excerpts are r = 0.83－0.95 for RT_M and r = 0.89－0.94 for EDT_M, respectively. Both parameters highly corresponded to reverberance. Assuming that a value of 2±0.5 on the vertical axis is optimum, the favorable reverberation time and early decay time for each excerpt (from the intersection of the regression lines) are shown in Table 2. The resultant RT_M and EDT_M that simultaneously satisfy four music excerpts are 1.7－2.2 s and 1.5－2.0 s, respectively. In this experiment, RT_M and EDT_M are equally good parameters regarding the correlation coefficient.

Table 2 Favorable ranges of RT_M and EDT_M obtained from the regression lines in Figs. 5 and 6.

	RT_M (s)	EDT_M (s)
Mozart	1.5 – 2.2	1.4 – 2.0
Rossini	1.6 – 2.3	1.5 – 2.0
Bruckner	1.6 – 2.5	1.5 – 2.2
Stravinsky	1.7 – 2.2	1.5 – 2.0

3.1.1 Loudness of music

As shown in Figs. 5 and 6, RT_M and EDT_M already show a high regression with the reverberance. This means that the possible difference in the reproduced sound level up to 6 dBA (see Sec. 2.5), equivalent to that in the strength factor G_M, has little influence on the reverberance. There was a report [14] that both reverberation time and loudness contributed to the perception of reverberation, and the 5 dB difference was significant. They evaluated steady-state noise and its decay process as the

Table 3 Analysis of multiple regression of reverberance on loudness and reverberation time.

Variables	RT_M, L_{Aeq}	EDT_M, L_{Aeq}	RT_M	EDT_M
Multiple correlation coeff.	0.87	0.90	0.88	0.90
Adjusted coeff. of determination	0.75	0.81	0.76	0.81
F value	< 0.001	< 0.001	< 0.001	< 0.001
t value of RT_M / EDT_M	10.64	12.54	11.04	12.82
t value of L_{Aeq}	0.248	-0.909	–	–

test signal, using the A-weighted equivalent sound pressure level of the steady-state portion as loudness. We examined the loudness (L_{Aeq}) of the entire presented music as a surrogate of steady-state noise. As previously mentioned, the loudness of time-varying sound corresponds well to the equivalent noise level L_{Aeq}. Multiple regression analysis with the reverberance was performed using L_{Aeq} for all presented signals (10 sound fields × 4 excerpts) and RT_M (or EDT_M) as variables.

Table 3 shows the following: (1) Reverberance can be explained by RT_M or EDT_M as a single variable. (2) The contribution of L_{Aeq} to reverberance is not statistically significant at a 95% or lower probability level (the *t*-values are below 2). (3) This analysis is statistically significant at a less than *F* = 0.1% significance level. It should be emphasized that music is not in a steady state, and the reverberance is not determined only by the stop chord.

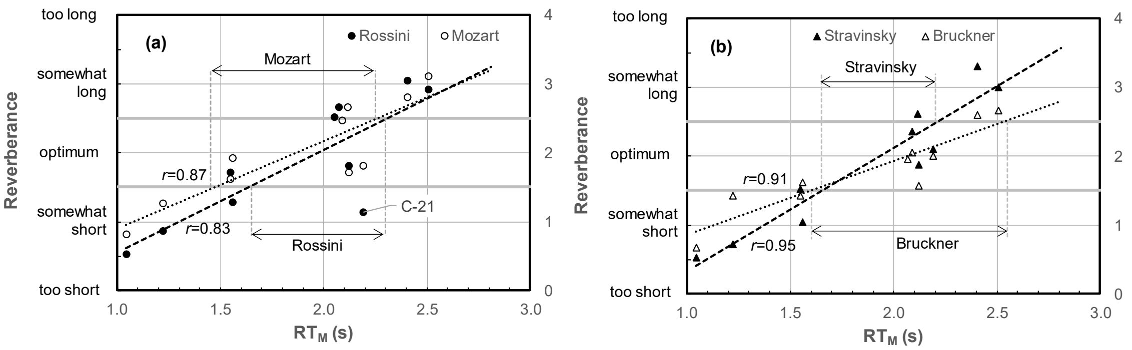

Fig. 5 Judgments of reverberance plotted against RT_M for four music excerpts. Horizontal arrows show the favorable ranges. The subscript "M" represents the octave band average for 500 and 1000 Hz.

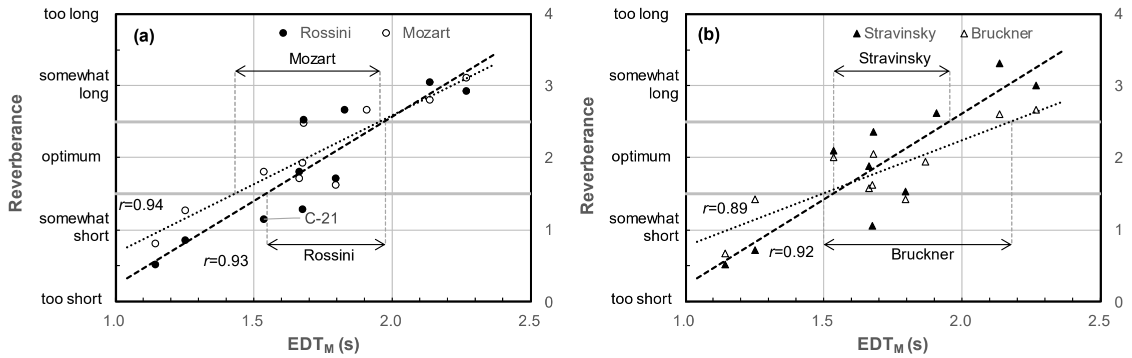

Fig. 6 The same as in Fig. 5 except for the horizontal axis EDT_M.

3.1.2 Reverberance and tempo

When plotting the median RT_M and EDT_M values in Table 2 for the four excerpts against the average duration of a quarter note (hereinafter called tempo), these median values have a strong link to tempo, where the correlation coefficients with musical tempo are r = 0.94 with a p-value of 0.06 for RT_M and r = 0.95 with a p-value of 0.05 for EDT_M. This result indicates that the optimum reverberation time depends not on the chronological category of the music, but on its tempo.

Figure 7 represents a favorable region of RT_M as a function of tempo, where the extrapolations of regression lines corresponding to the upper and lower values of favorable RT_M in Table 2 are depicted. As the tempo in this experiment is from *Presto* to *Allegro*, the favorable RT_M is given by 1.7–2.2 s, judging from the shaded area. If this extrapolation can be permitted, one can discuss the favorable RT_M corresponding to music with a slower tempo.

In Fig. 7, when RT_M is 2 s (horizontal broken line), the permissible slowest tempo approaches around 0.9 s, and the reverberance is judged to be optimum from *Presto* to *Andante.* Meanwhile, for RT_M lower than 1.7 s (horizontal dotted line), reverberance is not satisfactory in the movements slower than *Allegro*. Of course, if the conductors' experience and intimate knowledge of the hall are sufficient, the lack of reverberation is compensated in actual performance. They would require endless bow arms of the players and direct them to attack and sustain notes to make the music “sing.” On the other hand, when RT_M is longer than 2.25 s, reverberance becomes excessive in *Presto*. Accordingly, one can obtain RT_M = 2.0–2.2 s as the favorable reverberation time that covers from *Presto* to *Andante* (hatched area). This range is slightly longer than the recommendation, 1.8–2.1 s, for a symphonic repertoire with over 1,400 seats, as proposed by Beranek [1]. One of the possible reasons for this difference might be caused by the fact that the loudspeaker orchestra cannot simulate a conductor’s feedback to the orchestra and the precise directivity of musical instruments, and a difference in the era investigated.

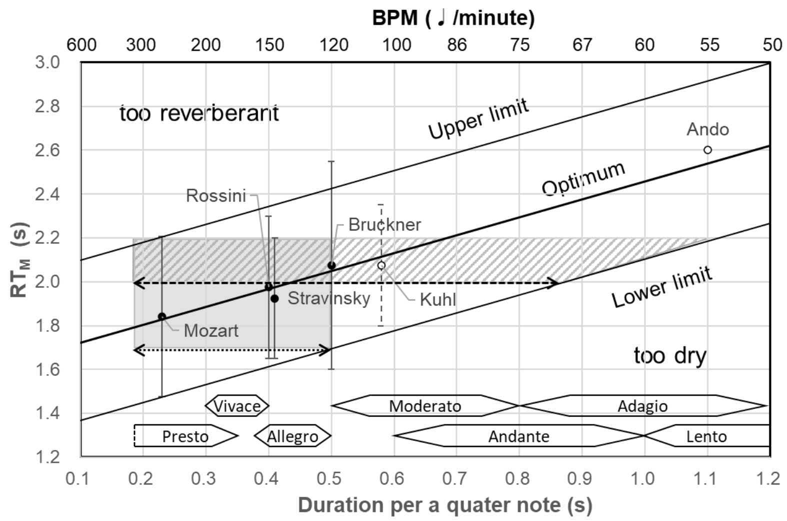

Fig. 7 Region of favorable RT_M vs. tempo. The lower and upper limits of RT_M are the extrapolation of the tolerable range in Table 2.

3.2 Clarity

In this experiment, the first ten subjects judged temporal and spatial aspects in clarity of the test signals en masse (hereinafter referred to as overall clarity). The latter 11 subjects judged clarity, concentrating only on its spatial aspect, that is, the degree to which different notes or voices that sound simultaneously were heard separately (spatial clarity). This change was due to the subjects’ comments that it was sometimes difficult to evaluate both aspects collectively for some excerpts.

As a result, $C_{80,3}$ and EDT_M were obtained as parameters that contribute to overall and spatial clarity, as in Figs. 8 and 9. The correlation of $C_{80,3}$ and EDT_M with the overall clarity were r = 0.25–0.62, r = -0.41–-0.66, and with the spatial clarity were r = 0.63–0.75, r = -0.56–-0.72, respectively (Table 4). Excepting $C_{80,3}$ for Rossini (r = 0.25) and EDT for Bruckner (r = -0.41), both objective parameters related moderately to overall clarity and had a slightly higher correlation with spatial clarity. Based on a questionnaire survey conducted in the UK,

Table 4 Correlations with overall clarity (upper two blocks) and spatial clarity (lower two blocks) in $C_{80,3}$ and EDT_M.

		Degree of freedom	Correlation coefficient	p value	Standard error
$C_{80,3}$	Mozart		0.62	0.05	0.043
	Rossini		0.25	0.49	0.043
	Bruckner		0.62	0.06	0.031
	Stravinsky		0.55	0.10	0.044
EDT_M	Mozart		-0.66	0.04	0.295
	Rossini		-0.46	0.19	0.297
	Bruckner		-0.41	0.24	0.295
	Stravinsky	9	-0.58	0.08	0.304
$C_{80,3}$	Mozart		0.63	0.05	0.066
	Rossini		0.75	0.01	0.048
	Bruckner		0.65	0.04	0.035
	Stravinsky		0.66	0.04	0.062
EDT_M	Mozart		-0.56	0.09	0.499
	Rossini		-0.72	0.02	0.374
	Bruckner		-0.63	0.05	0.254
	Stravinsky		-0.66	0.04	0.441

Barron [2] stated that the only parameter correlated with clarity was RT_M with r = -0.55. This value is of the same order as shown in Table 4.

Provided that "passably clear" in Fig. 8 and the median between "neither" and "passably clear" in Fig. 9, which corresponded to numerical numbers 1 and 2.5 in the vertical axis, respectively, were the undesirable boundaries in detecting the musical detail, one obtained Table 5 by fitting each of the regression lines.

Table 5 Favorable lower limit of $C_{80,3}$ and upper limit of EDT_M determined from the regression lines in Figs. 8–9. The square bracket means the corresponding regression line is not reliable enough (|r| < 0.4).

	Overall clarity		Spatial clarity	
	$C_{80,3}$ (dB)	EDT_M (s)	$C_{80,3}$ (dB)	EDT_M (s)
Mozart	1.6	1.6	-1.0	1.4
Rossini	[-5.2]	2.1	-5.2	2.1
Bruckner	-5.3	[3.0]	-9.8	2.3
Stravinsky	-2.6	2.1	-4.0	1.9

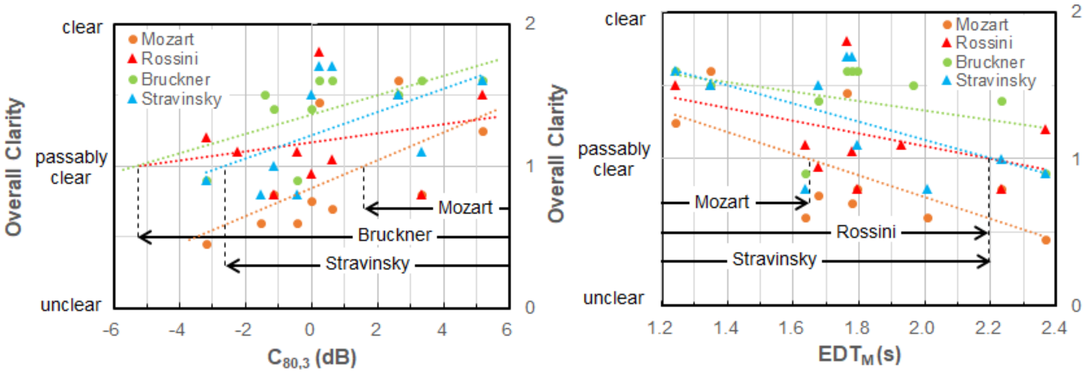

Fig. 8 The judgments of overall clarity plotted against $C_{80,3}$ (left) and EDT_M (right) for the four music excerpts. Three levels of clarity, from "unclear" to "clear," correspond to numerical values from 0 to 2. Regression lines are plotted by a dotted line for Mozart in orange, Rossini in red, Bruckner in green, and Stravinsky in blue. The favorable ranges are shown by horizontal arrows.

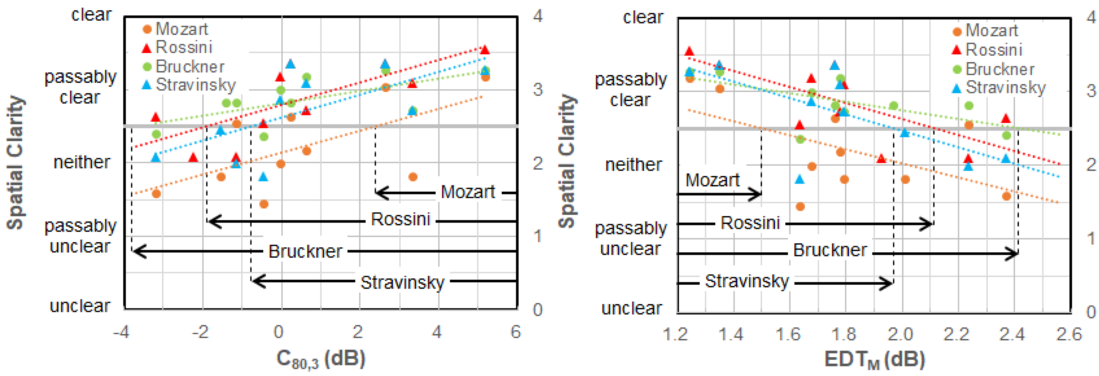

Fig. 9 The same as in Fig. 8 except for the vertical axis being spatial clarity.

This experimental result indicates that $C_{80,3}$ and EDT_M were not fully independent of each other from the correlation coefficient r = -0.83 (Table 6), and when referring to the partial correlation coefficients between each of these and subjective clarity in Table 7, one could not argue the superiority of one over the other. This experiment suggested that both parameters were necessary, at least in evaluating clarity. In addition, multiple regression analyses using EDT_M and $C_{80,3}$ as variables did not work better

Table 6 Correlation matrix between physical parameters. Bold type means r > 0.8.

	RT_M	EDT_M	BR	$C_{80,3}$	G_L	G_M	BQI
RT_M	1.00						
EDT_M	**0.87**	1.00					
BR	**-0.83**	**-0.84**	1.00				
$C_{80,3}$	**-0.88**	**-0.83**	**0.86**	1.00			
G_L	0.57	0.55	-0.65	-0.37	1.00		
G_M	0.53	0.52	-0.52	-0.25	**0.96**	1.00	
BQI	0.69	0.77	-0.73	-0.76	0.39	0.29	1.00

substantially: the multiple correlation coefficients were r = 0.48–0.59 and r = 0.67–0.78 for overall and spatial clarity, respectively.

For solo performance, reverberance and clarity were highly likely to be equivalent subjective attributes of each other [15] because temporal clarity was inextricably linked to the running reverberance of successive musical notes. However, for orchestra music, spatial clarity that is connected to the separation of each orchestra voice must also be included, which is the reason for the reduced correlation between reverberance and clarity. Reverberance and clarity should be evaluated separately for orchestral music.

Table 7 Partial correlation coefficients among clarity judgment, EDT_M, and $C_{80,3}$, controlling for the effects of another parameter.

		$C_{80,3}$	EDT_M		$C_{80,3}$	EDT_M
Mozart		0.17	-0.33		0.34	-0.09
Rossini		-0.23	-0.45		0.41	-0.28
Bruckner	Overall clarity	0.55	0.24	Spatial clarity	0.30	-0.21
Stravinsly		0.13	-0.28		0.26	-0.27
4 excerpts		0.11	-0.21		0.25	-0.17

3.3 Perceived Sound Strength

Figure 10 plots the average judgments of perceived sound strength versus G_M for each excerpt. The regression lines (dotted lines) were almost identical regardless of the musical piece. For the four excerpts, the degree of correlation between sound strength and G_M was equivalent to that with G_L (octave band average at 125 and 250 Hz) as shown in Table 8. Next, we tested the significance of differences among four groups (excerpts). Then, the effect sizes, Cohen's q, indicated that the effect of differences between correlation coefficients between for each excerpt and that for all 40 data was small. Accordingly, we provisionally used the regression line for all 40 data points (solid line in Fig. 10) in the following discussion. A similar result was found for G_L.

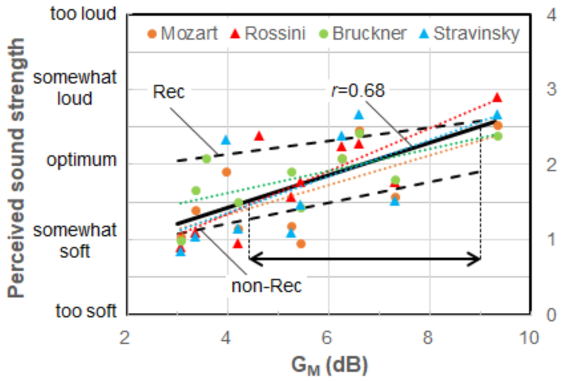

Fig. 10 The judgments of sound strength vs.G_M. Five levels of sound strength, from "soft" to "loud," correspond to numerical values from 0 to 4. Regression lines for each of the four excerpts and for all 40 data points are plotted by a dotted line and a solid line, respectively. The favorable range of G_M is shown by a horizontal arrow. The broken lines are regression lines of rectangular and non-rectangular halls.

Assuming that a value of 2 ± 0.5 on the vertical axis was optimum, the favorable ranges for G_M and G_L from the intersection of the regression lines were 4.4 to 9.0 dB and 3.3 to 8.9 dB, respectively. Since these two parameters were not independent (r = 0.96) as shown in Table 6, either one should be used as the representative value.

The regression lines for halls with rectangular (Halls D and E) and nonrectangular (Halls A, B, and C) plan shapes are plotted in Fig. 10. One can observe that these halls are clearly classified by the plan shapes with rectangular halls falling into one higher category than nonrectangular ones. All rectangular halls are judged "optimum" (with a vertical value of 2) or higher. Since the G_M of rectangular halls under an occupied condition takes values of 3 to 4 dB or higher [1,16], this result indicates that lack of sound strength (loudness) does not occur in rectangular halls.

In contrast, about 50% of nonrectangular halls fall into the category of less than a vertical value of 1.5, "somewhat soft." The regression line for nonrectangular halls ($y = 0.22x + 0.56$) means raising the judgment score by one, an increase of 1/0.22 ≈ 4.5 dB (which converts to 1/0.18 = 5.6 dB in G_L) on average. Accordingly, for nonrectangular halls, some instructions, such as the conductor asking the performers to increase the sound volume or augmenting the number of performers, would be necessary to compensate for the lack of sound strength.

In Table 8, the correlation coefficient between RT_M and perceived sound strength was in a similar order to that of G_M. Here, the partial correlation coefficients for G_M and RT_M for perceived sound strength were 0.43 and 0.52, respectively. This means that both parameters' contributions were almost the same. In Table 8, Rossini highly correlated with G_L and G_M, Bruckner with G_L, and Mozart and Stravinsky with RT_M. The judgments of sound strength were divided into two cases: one depending on G and the other on RT_M. Compared to previous research, this study covers a variety of musical expressions and a broader range of RT_M. Some factors associated with the perception of reverberant sound, such as the running reverberance and spectral differences in stop chords, might have influenced sound strength.

3.4 Spaciousness, ASW

In Fig. 11, a vertical value of 2.5, (the midpoint between "somewhat expansive" and "neither") or lower indicates that desirable spaciousness cannot be expected. Therefore, the lower limit for favorable BQI = 1 - $IACC_{E3}$ (see definition of $IACC_{E3}$, p.616 in [1]) is 0.6, determined from the intersection with the solid line. Beranek [1] recommended a hall-averaged BQI of 0.65-0.71. This value corresponds to a vertical value of 3, "somewhat expansive."

In this experiment, ASW also showed a high correlation with G_L (Table 8). As with BQI, the differences in the regression lines for the four excerpts were insignificant (Fig. 12). Focusing on the regression line for all data points, the recommended lower limit value for G_L becomes 6.5 dB. Based on the above results, the multiple regression equation for ASW using BQI and G_L is as follows (coefficient of determination R^2 = 0.869):

$$ASW=3.4\times BQI+0.12\times G_L-0.19 \qquad (1)$$

At this point, the regression line between the measured values and the values calculated by Eq. (1) is y=x+0.0003. When both physical quantities are known, ASW can be well explained by BQI and G_L, independent of the type of music.

Table 8 Correlations with sound strength (upper three blocks) in G_L, G_M, and RT_M and with ASW (lower two blocks) in BQI and G_L, and effect sizes, Cohen's q, of the difference in the correlation. Bold (r>0.8).

		Deg. of freedom	Correlation coeff. r	p value	Standard error	Effect size
G_M	Mozart	9	0.67	0.04	0.078	0.01
	Rossini		**0.81**	< 0.01	0.072	0.13
	Bruckner		0.65	0.04	0.060	0.02
	Stravinsky		0.66	0.04	0.097	0.02
	4 excerpts	39	0.68	< 0.01	0.037	
G_L	Mozart	9	0.70	0.02	0.058	0.02
	Rossini		**0.81**	< 0.01	0.057	0.10
	Bruckner		**0.80**	< 0.01	0.039	0.08
	Stravinsky		0.64	0.05	0.078	0.06
	4 excerpts	39	0.72	< 0.01	0.028	
RT_M	Mozart	9	0.78	< 0.01	0.256	0.06
	Rossini		0.64	0.05	0.365	0.06
	Bruckner		0.74	0.01	0.211	0.02
	Stravinsky		**0.80**	< 0.01	0.305	0.08
	4 excerpts	39	0.72	< 0.01	0.138	
BQI	Mozart	9	**0.91**	< 0.01	0.665	0.07
	Rossini		**0.88**	< 0.01	0.743	0.00
	Bruckner		**0.85**	< 0.01	0.815	0.05
	Stravinsky		**0.95**	< 0.01	0.688	0.20
	4 excerpts	39	**0.88**	< 0.01	0.380	
G_L	Mozart	9	0.72	0.02	0.070	0.01
	Rossini		0.75	0.01	0.073	0.02
	Bruckner		**0.84**	< 0.01	0.057	0.13
	Stravinsky		0.68	0.03	0.101	0.04
	4 excerpts	39	0.73	< 0.01	0.036	

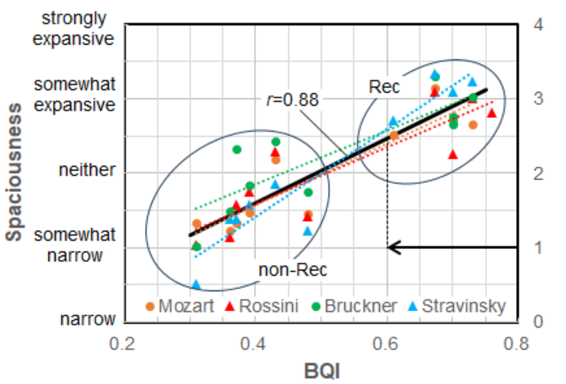

Fig. 11 The judgments of ASW vs. BQI. Five levels of ASW, from "narrow" to "strongly expansive," correspond to numerical values from 0 to 4. Regression lines for each of the four excerpts and for all 40 data points are plotted by a dotted line and a solid line, respectively. The correlation coefficient for the latter is given. The favorable range of BQI is shown by a horizontal arrow.

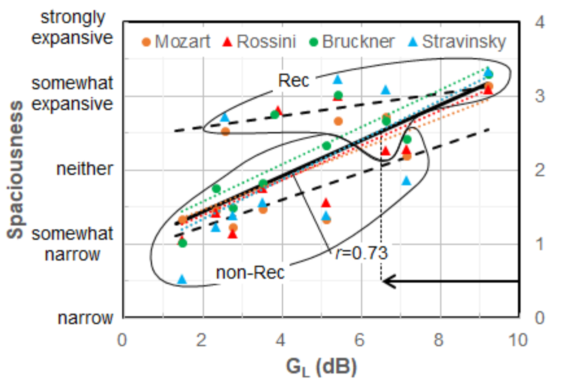

Fig. 12 The same as in Fig. 11 except for the horizontal axis G_L. Regression lines for rectangular and nonrectangular halls are plotted by dashed lines. The favorable range of G_L is shown by a horizontal arrow. Rec: r=0.56, non-Rec: r =0.78.

In Figs. 11 and 12, for rectangular halls, the judgments are high within a narrow range as BQI is high, which are consistently between 2.5 and 3.5 on the vertical axis. This result is because the relative contribution of G_L is smaller than BQI as shown in Eq. (1). On the other hand, the ranges of G_L are similar for rectangular and nonrectangular halls, but the judgment is low for the latter, meaning that G_L significantly contributes to ASW in Eq. (1). Therefore, increasing G_L is desirable to achieve better spatial impressions for nonrectangular halls.

3.5 Overall acoustical quality, OAQ

In the questionnaire, the endpoints of the bipolar scale for OAQ were “poor” and “good.” In contrast, the endpoints for reverberance (Fig. 5) were “too short” and “too long,” and for sound strength, they were “too soft” and “too loud” with the optimal values located in the center of the bipolar scale. To replace the range of this scale with inappropriate and optimal, the judgment values “0, 1, 2, 3, 4” were rewritten as “0, 1, 2, 1, 0,” where “0” corresponded to inappropriate and “2” corresponded to optimum. With this conversion, one could set up a linear combination representation of OAQ with the subjective attributes. Figure 13 shows an example of a plot of RT_M vs. the converted reverberance judgment, where the data are regressed with a quadratic polynomial. In the following, attributes and parameters that refer to this post conversion are denoted by an asterisk.

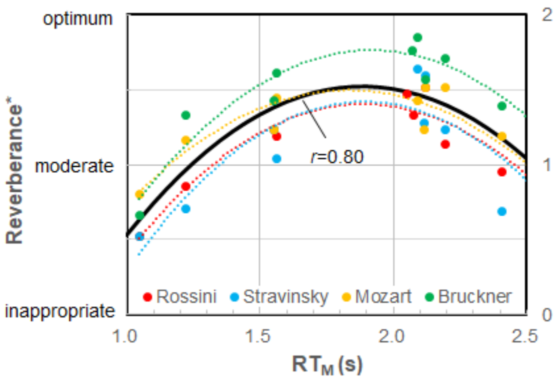

Fig. 13 Converted reverberance, Reverberance* vs. RT_M. Regression curves for each of the four excerpts and for all 40 data points are plotted by a dotted line and a solid line, respectively. The correlation coefficient of the latter is shown in the figure, and those for Mozart, Rossini, Bruckner, and Stravinsky are 0.88, 0.94, 0.94, and 0.85.

Table 9 shows the statistics for the multiple regression equations that attempt to express OAQ. As seen in the second row, without overall clarity and sound strength, OAQ can be explained by the three attributes: reverberance, spatial clarity, and ASW. Furthermore, along with ASW, OAQ can be well represented by reverberance or clarity as a two-variable model (see bottom two lines).

Table 9 Statistics for each attribute in multivariate regression analysis of OAQ with subjective attributes as variables. The asterisk Reverberance* and Sound strength* refer to the postconversion.

Variable: Subjective attribute					Multiple corr. coef.	Adjusted coef. of determi-nation
Rever-berance*	Total clarity	Spatial clarity	Sound strength*	ASW		
< 0.01	0.37	0.09	0.68	**< 0.01**	0.97	0.93
< 0.01		**< 0.01**		**< 0.01**	0.97	0.93
< 0.01				**< 0.01**	0.95	0.89
		< 0.01		**< 0.01**	0.93	0.87

Referring to the partial correlation coefficients between the four attributes and OAQ in Table 10, ASW contributed the most to OAQ, followed by spatial clarity and reverberance, which contributed equally. Note that overall clarity and spatial clarity were highly correlated (r = 0.82), so only the latter was included. Although the musical excerpts in this experiment contained a broad dynamic range, the contribution of sound strength to OAQ was smaller than the other three.

Table 10 Partial correlations between subjective attributes and OAQ, controlling for the effects of the other attributes.

	Rever-berance*	Spatial clarity	Sound strength*	ASW
Partial r	0.51	0.56	0.07	0.89
p-value	<0.01	<0.01	0.68	<0.01

Table 11 Partial correlations between physical parameters and OAQ, controlling for the effects of the other parameters.

	RT_M*	$C_{80,3}$	G_L	BQI
Partial r	0.43	0.23	0.55	0.67
p-value	<0.01	0.17	<0.01	<0.01

Table 11 shows the partial correlation coefficients between the physical quantities most highly correlated with each subjective attribute in Table 10 and OAQ. BQI has the highest contribution to OAQ, similar to the previous paper [1]. Although G_L has the second highest value, this is because G_L contributes to ASW, as shown in Sec. 3.4. Next, RT_M* has a high value. Here, RT_M* is a normalized value of RT_M divided by the quadratic polynomial regression equation ($y = -1.27x^2 + 4.8x - 3$) for all 40 data points shown in Fig. 13. This manipulation results in a linear relationship between the converted reverberance and RT_M* ($r = 0.80$, $p < 0.001$). On the other hand, the contribution of $C_{80,3}$ is weak. One reason for this is that $C_{80,3}$ is not necessarily an adequate measure of clarity. EDT_M* instead of RT_M* yields similar results as those in Table 11.

Figure 14 shows the plot of OAQ versus BQIs for the four excerpts. ANCOVA indicated that the significant level at which the difference between the four groups (excerpts) was not significant was p = 1.8%. Applying a regression line for all 40 data points provisionally, OAQ and BQI exhibited a high correlation coefficient ($r = 0.80$). In this figure, only eight out of 40 data points (20%) fell outside the range of the regression line ± 0.5.

For the multivariable regression equation of OAQ based on the aforementioned physical quantities, a regression equation using the following three variables yielded a correlation ($r = 0.87$, Fig. 15) as high as that of an equation with a greater number of variables:

$$OAQ = 0.55\ RT^{*}_{M} + 0.11\ G_L + 2.46\ BQI - 0.26 \qquad (2)$$

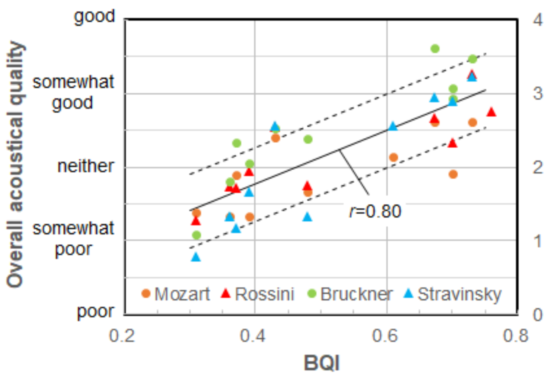

Fig. 14 The judgments of OAQ vs. BQI. The solid line is a regression line for all 40 points, with dashed lines showing this line ± 0.5.

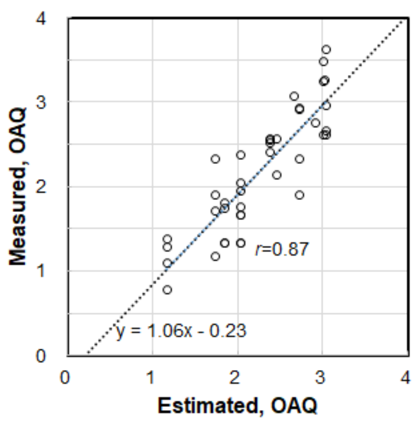

Fig. 15 Estimated OAQ vs. Measured OAQ.

4 CONCLUSION

(1) The musical tempo determines the favorable reverberation time in concert halls for orchestral music. The optimum reverberance for the music from *Presto* to *Allegro* is achieved when RT_M = 1.7－2.0 s, and by extrapolation, that from *Presto* to *Andante* is expected at 2.0–2.2 s.
(2) Both RT_M and EDT_M are suitable parameters that highly correlate with the sensation of reverberance. This reconfirms that RT_M, which can be easily estimated from architectural drawings, is a reliable objective parameter during the basic design phase of concert halls.
(3) $C_{80,3}$ and G are not single physical quantities that explain clarity and sound strength perception, respectively. It appears likely that unknown physical parameters are necessary to complement these two attributes.
(4) ASW is determined accurately by BQI and G_L. This result supplements previous reports in laboratory experiments.
(5) The primary subjective attributes determining the OAQ are reverberance, clarity, and ASW. OAQ can be accurately estimated using the physical parameters RT_M, G_L, and BQI.

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