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Effect of Stage Volume Ratio on Audience Acoustics in Concert Halls

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Received: 7 January 2020; Accepted: 11 February 2020; Published: 13 February 2020

Abstract: This report proposes the stage volume ratio (V_o/V) as an acoustic design factor for concert halls and presents an investigation of the dependence of the acoustic parameters of an auditorium on the stage volume through computer simulation. Firstly, the ratio of the stage volume to the total volume of a concert hall was defined as V_o/V through case studies of existing concert halls. It was verified using a simple model that the stage acoustic parameter ST_{Early} and audience acoustic parameters G and C80 decreased, whereas, the reverberation time and early decay time increased with increasing V_o/V. Secondly, a computer simulation was performed for nine existing concert halls, while changing V_o/V from −20% to 30%. The room acoustic parameters exhibited the same patterns as suggested by the simple model. V_o/V significantly affected the bass ratio and bass index. A comparison of the effects of V_o/V and the sound absorption coefficient in nine concert halls revealed that V_o/V contributed approximately 15% to the reverberation and affected the bass characteristics more substantially. Thus, V_o/V is a critical design factor when determining the warmth of the audience acoustics. The study results could be used as a basis for acoustic design in the future.

Keywords: stage volume ratio; acoustical parameters; audience acoustics; computer simulation

1. Introduction

Concert halls (such as Boston Symphony Hall, Vienna Großer Musikvereinssaal, etc.) that are considered good according to many people (architects, musicians, engineers, etc.) have existed for almost 100 years, and most recently built halls have been aging for at least 30–40 years. Recently, concert halls have been designed to be located in large cities, where they are required to accommodate a large number of users in terms of tourists and floating population. In this context, reckless expansion of the halls is taking place, and in particular, the stages are being expanded to accommodate performers, such as large orchestras. Additionally, redesigning or renovating an existing concert hall involves a significant capital investment [1], reduction of which necessitates the implementation of an optimized acoustic design by considering several design factors at an early design stage. Construction of concert halls that have indiscriminately large volumes cannot be accommodated at or near sustainable locations or commercial areas in urban centers. In such cases, therefore, the roles of an acoustician and architect become all the more important during initial design stages [2]. Stage elements of a concert hall consist of the stage area and stage floor elements, including the riser. In addition, there are various design elements, such as the stage enclosure, including the side wall, rear wall, and ceiling of the stage, as well as the reflector and canopy [3]. In a concert hall, the stage is one of the most important design elements that determine the acoustics of the stage and auditorium. To date, stage acoustics in concert halls has been researched from the perspective of musicians and the audience, and various methodologies have been proposed in terms of design and acoustics [4–7].

An initial report proposed objective measurement parameters before evaluating the conditions of the stage acoustics according to the stage design elements [8], and a proper direction for the stage design was presented based on the proposed parameters [9]. Gade [8] suggested the stage support (ST) parameter by considering the relative ratio of the reflected energy and emitted energy in terms of communication and the early ensemble level (EEL) as an indicator of the ensemble between the musicians on the stage on the laboratory scale. In a follow-up study [10], the possibility of utilizing these stage parameters in actual halls was investigated to validate the efficacy of the ST parameter. Besides the analysis of temporal information in terms of impulse response units, such as ST and EEL, a study concerning the importance of relative sound pressure difference during the performance of musicians has also been performed [11]. Based on these objective parameters, the changes in stage acoustics according to the occupancy of the performers on the stage were examined in follow-up studies [12–14]. Dammerud et al. [12] proposed a linear model for the attenuation of early reflection energy according to the existence or absence of a large orchestra without a stage enclosure. Wenmaekers et al. [13] confirmed that the existence of an orchestra serves to reduce the direct sound and early-reflected sound levels. Meanwhile, a much higher reduction was observed in the late-reflected sound level. Furthermore, Panton et al. [14] investigated the effect of a chamber orchestra with a stage enclosure on the early reflection using the boundary element method and found that the sound pressure decreased by up to 5 dB at 1 kHz. In short, most previous studies on stage acoustics have indicated that it is important for individual musicians to find the balance point for the ensemble, that is, the appropriate audibility levels of their own sound and the sound from other musicians [8–14].

In more advanced studies, stage acoustic designs based on the subjective assessment of performers on the stage, as well as objective indices were researched [15–17]. Barron [16] examined the effects of the stage configuration based on a survey of musicians in various halls. Chiang et al. [17] evaluated the preferred stage acoustics for solo and chamber music performances [18]. The preferred positions of musicians on the stage were also researched based on measurement data, and the results showed that positions at the front of the stage were preferred [19].

Scale models and computer simulations have been actively used as representative methods for evaluating the stage acoustics in concert halls. Jeon and Barron [20] used a 1:25 scale model and computer simulation to investigate the effects of musicians on the stage, ceiling height, and stage wall profile on the stage acoustics. Jeon et al. [21] examined the effects of the existence or absence of a pipe organ that occupies a large area of the rear wall on the stage on the auditorium sound field through computer simulation and measurements and presented proper design guidelines for the pipe organ surface. They also found that the difference between the two methods was less than the just noticeable difference (JND) [22]. Chiang and Shu [23] investigated the effects of the splaying angle of the perimeter; proportion, position, and direction of musicians; and the presence or absence of reflectors on the stage acoustics. They found that positioning the sound source behind the stage, while reducing the stage volume and width was effective for acquiring the initial energy and that the shape played a more important role than the volume for the late energy. Thus, it can be seen that stage acoustics can be satisfactorily researched by computer simulation.

Concert hall acoustics were also researched in terms of stage design. Knudsen and Harris [24] presented the design solutions for the long pass echo felt by musicians on the stage using design methods, such as tilting, diffusive, and absorbent treatments for the back wall of the auditorium. Beranek and Martin [25] and Ando [26] also examined the effects of the side reflector and stage side wall on the preferences of musicians and discovered that splaying the stage wall and ceiling could reinforce the late energy in the auditorium around the stage. Furthermore, Barron [3] proposed a design direction to achieve overhead reflection by installing a 6–8-m-high reflector for support in a large-area stage.

The above studies were conducted from the perspective of the musicians on the stage, but some studies have addressed stage acoustics from the perspective of the audience. Beranek and Martin [25] suggested that a maximum width and depth of 16 m and 11 m were appropriate for an orchestra stage from the perspective of the audience. Jeon et al. [7] examined the effects of musicians occupying the stage on the acoustics in the auditorium based on the reverberation time (RT) by performing a computer simulation. Meyer [27] found that the effect of the formation of excessive initial energy on the stage could be ameliorated by musicians playing at a lower sound level for the audience. Jang et al. [28] investigated the effects of the stage area and volume changes on the acoustic parameters related to the audience in a concert hall by conducting a simulation. However, despite these attempts, studies on the effects of stage elements on the auditorium (audience) acoustics in concert halls have been insufficient. In particular, the volume of a stage is a crucial factor because it includes the stage floor and surrounding walls, which are close to the direct sound. In addition, it affects the sound absorption and contributes greatly to the shape of the entire hall. However, studies on the effects of changes in the stage elements in a concert hall on the audience in the auditorium, rather than on the performances on the stage, such as an orchestra are insufficient. Dammerud [29] examined the correlations between the width (W), depth (D), H/W, and D/W of the stage and the results of the preferences of the performers, and he found that the overall impression of the performers showed a high correlation with the H/W ratio of the stage. Methodologically, he examined the effects of narrow and wide type stage enclosures via computer simulation. Although Dammerud conducted wide-ranging initial research, he focused on the performers on the stage and did not address the effects on the actual audience acoustics.

Therefore, the present study was focused on the stage volume among the various stage elements, new design elements were proposed for the stage volume in concert halls, and their effects on the audience acoustics were examined. To that end, the changes in the acoustic parameters in the auditorium were investigated by performing computer simulations according to various changes in the stage volume in nine existing concert hall models, including one simple model.

2. Experiment A: Stage Design Elements in Simple Model

2.1. Methods

2.1.1. Stage Design Elements

The design elements of a concert hall stage include shape factors, such as width, depth, height, area, and volume, as well as the sound absorption area. Concert halls have various stage shapes and volumes depending on the combination of these design elements. Among them, the stage volume of a concert hall can be considered in the early design stage. It can be divided into the stage volume (V_o) and the volume of the auditorium around the stage and the chorus seats (V_c). Table 1 lists the areas, volumes, and numbers of seats in 72 existing concert halls (31 shoebox-shaped halls, 13 fan-shaped halls, and 28 halls with other shapes) [30]. In this report, the stage volume ratio is presented as a new design element and is defined as the stage volume divided by the total volume of the concert hall. Depending on the definition of the stage volume, the stage volume ratios are divided into V_o/V and V_c/V, where V is the total volume of the concert hall. The volume of the concert hall ranged from 5800 m^3 to 30,800 m^3, the number of seats from 552 to 3524, and the stage area from 81 m^2 to 314 m^2, and the stage volume ratio was 8%–27% and 8%–64% for V_o/V and V_c/V, respectively.

Figure 1 shows the variations in stage volume according to the total volume and the stage floor area of the concert hall. Figure 1a reveals that V_o increases with increasing total volume. The multiple regression analysis also yielded a relatively high explanatory power with an R^2 value of 0.37, confirming statistical significance. This result is similar to the result for the variation in V_o according to the increase in the concert hall stage area, shown in Figure 1b. However, comparison of V_c, which denotes the area surrounding the stage, with V_o in Figure 1a reveals a weak positive correlation with the total hall volume, which appears to be because the change in volume is greatly affected by the shape of the hall and the auditorium layout. No clear tendency could be found for the variation of the stage volume with the stage area in Figure 1b either. Therefore, in this study, V_o/V was selected as the evaluation index for the stage volume ratio to examine the variations in the concert hall acoustics according to the variations in the stage volume, while minimizing the effects of other factors, such as the layout of the auditorium and chorus seats. In addition, the variations in the hall acoustics were examined, while changing the value of V_o/V. In other words, to define the stage volume ratio, which can be defined differently according to the shape of the concert hall, only V_o/V was set in the present study. This quantity is the ratio of the stage volume based on the pure stage floor area, excluding the auditorium surrounding the stage and the choir seats and has the remaining hall volume as the changing factor.

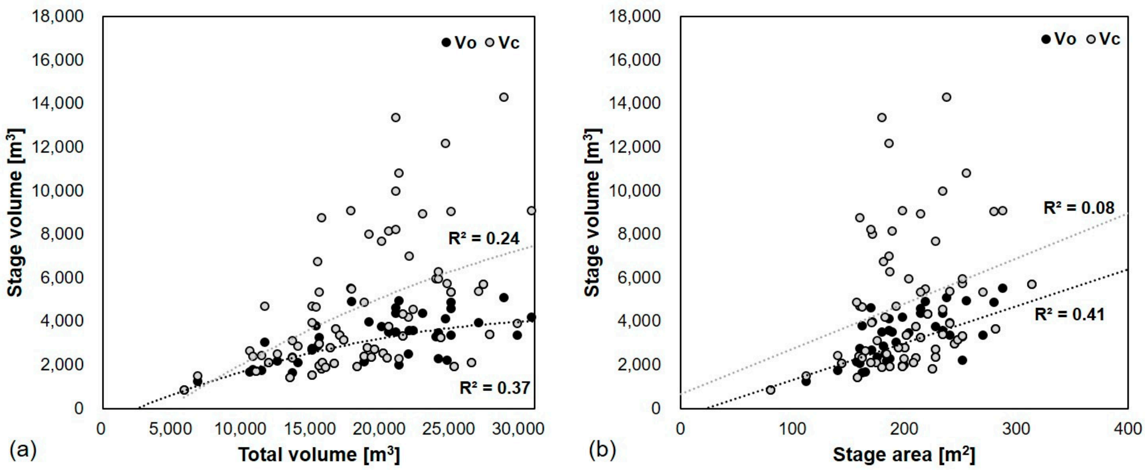


Figure 1. Variations in stage volumes of existing concert halls according to (**a**) total volume and (**b**) stage area [30].

Table 1. Variation of design elements according to the shape of the concert hall [30].

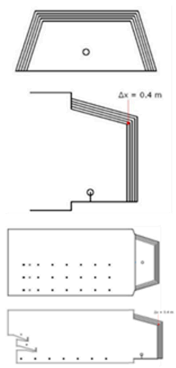
Elements (Number of Halls)		Shoebox (31)	Fan (13)	Other (28)
Total volume [m³]	V	5800–25,000	11,900–30,800	6800–28,800
	Mean	17,072	21,045	20,161
	SD	4251	6693	5307
Total area [m²]	S	468–2145	836–2317	642–1945
	Mean	1322	1652	1487
	SD	382	407	350
Stage area [m²]	S_o	81–288	158–314	112–270
	Mean	196	207	208
	SD	47	44	36
Stage volume [m³]	V_o	832–5529	1435–5685	1248–5100
	Mean	2917	2578	3270
	SD	1044	1204	1087
	V_c	832–9976	1432–9080	1504–13,345
	Mean	4429	3342	5620
	SD	2505	2226	3612
Stage volume ratio [%]	V_o/V	11–31	8–21	9–27
	Mean	17	13	16
	SD	5	4	4
	V_c/V	11–51	8–29	10–64
	Mean	26	15	27
	SD	12	7	15
Number of seats	N	552–2901	1286–3524	767–2903
	Mean	1959	2417	2122
	SD	625	621	548

2.1.2. Computer Simulation

To investigate the effects of the variations in the stage volume on the stage and audience acoustics in concert halls, a case study was conducted on the Boston Symphony Hall (V = 18,750 m^3, V_o = 2027 m^3, 2625 seats), which is a typical rectangular concert hall, using computer simulation [28]. The objective of this study was to examine the changes in the audience acoustics according to the stage volume ratio. We also investigated stage acoustics in Experiment A to determine whether the changes in stage acoustics were consistent with those in previous studies. To minimize the effects of the internal surface characteristics of the hall, it was modified to a simple model by simplifying the internal shape, as shown in Table 2. The hall models were divided into 13 cases by expanding the stage height, width, and depth in 0.4 m units simultaneously. The concert hall acoustics were evaluated, while changing V_o/V from 8.8% to 25.9% to include the general distribution of the shoebox halls in Table 1 (mean = 17, standard deviation = 5). The stage volume was increased from 1650 m^3 to 5982 m^3.

Odeon version 13 software was used for the computer simulation. A model of the Odeon library was used for the concert hall model. The default reference values were used for the internal finishing materials. In the library model, the sound absorption coefficient of the surface was applied based on the concert hall measurement data for the unoccupied state [31,32]. However, in the present study, the surface material was adjusted to make the data similar to the measurement data even in the occupied state of the auditorium; ISO 3382 was utilized as the measurement criterion of the acoustic parameters [33,34]. In the Odeon simulation, the transition order (i.e., change in the reflection order associated with a change from the early image source method to the late radiosity method) was set to the second order. To calculate the room acoustic parameters, the impulse response length was set to 3500 ms, and 5000 late rays were used to enable comparison with other models, although this value is slightly higher than the recommended value. The location of the sound source was fixed 3 m away from the stage end at the height of 1.5 m. Twenty-seven sound receiving points were used, which were positioned 1.2 m above the ground. In previous studies [7,13,35], the acoustics in the auditorium were changed according to the layout and positions of musicians on the stage. However, in the present study, the location of the sound source was fixed to examine the actual effects of the stage volume ratio on the audience acoustics, while excluding the effects of the musicians. The concert hall acoustics were divided into stage and audience acoustics. To examine the stage acoustics, we investigated ST_{Early}. The sound reception point was located 1.5 m above the ground and 1 m away from an omnidirectional sound source in accordance with ISO 3382–1, and the sound source was located at point 3 on the stage. Then, the average value of all measurements was calculated. The reverberation time (RT_{30}), early decay time (EDT), clarity (C_{80}), and strength (G) were analyzed for the audience acoustics. Values of RT_{30}, EDT and G were calculated as averages of those corresponding to 500- and 1000-Hz frequencies in accordance with ISO 3382-1. With reference to an extant study, the value of C_{80} was calculated as the average of corresponding values calculated at 500, 1000 and 2000 Hz [30]. Among them, ST_{Early} was analyzed to verify the linear relationship with the stage volume change, which was found in previous studies [10,22].

Table 2. Stage dimensions according to stage volume variation.

Case	S_o [m^2]	V_o [m^3]	V [m^3]	V_o/V [%]	Modification
1	130	1650	18,750	8.8	
2	145	1900	19,000	10.0	
3	160	2175	19,275	11.3	
4	175	2450	19,550	12.5	
5	190	2735	19,835	13.8	
6	208	3078	20,178	15.3	
7	225	3423	20,523	16.7	
8	241	3790	20,890	18.1	
9	257	4065	21,165	19.2	
10	285	4470	21,570	20.7	
11	299	5039	22,139	22.8	
12	324	5550	22,650	24.5	
13	345	5982	23,082	25.9	

2.2. Results and Discussion

Figure 2 shows the simulation results for the variations in the acoustic parameters of the stage and auditorium, according to V_o/V. Firstly, we review the stage acoustic parameter. ST_{Early} decreases by 6.1 dB on average, when V_o/V increases by 17% from 9% to 26%. As revealed in previous studies [10,22], this result suggests that ST_{Early} has a very strong negative linear correlation with the stage volume, because ST_{Early} is greatly affected by the initially reflected sound during 20–100 ms. Therefore, it can be inferred that the smaller the stage volume, the larger is the initial amount of energy that returns to the stage. For the Boston Symphony Hall, adjusting the stage volume ratio to less than 15% can help achieve the proper level of ST_{Early} (−14.4–−12 dB), as suggested by Beranek [30]. However, determining ST_{Early} based on the stage volume ratio may be useful objectively in this research, but additional investigation is required to validate its usefulness acoustically from the standpoint of musicians.

Next, we discuss the results of the acoustic parameters of the auditorium. The G values related to the loudness in the concert hall tended to decrease with increasing V_o/V, as shown in Figure 2b. RT and EDT increased proportionally with increasing stage volume ratio, as shown in Figure 2c. When V_o/V was higher than 20%, the EDT increased sharply, due to the coupling phenomenon, the stage and auditorium. C_{80}, which indicates the clarity of sound, decreased down to 1.27 dB as V_o/V increased, showing an overall decreasing tendency. However, when V_o/V was higher than 17%, the reduction rate became very small, showing almost no effect from V_o/V.

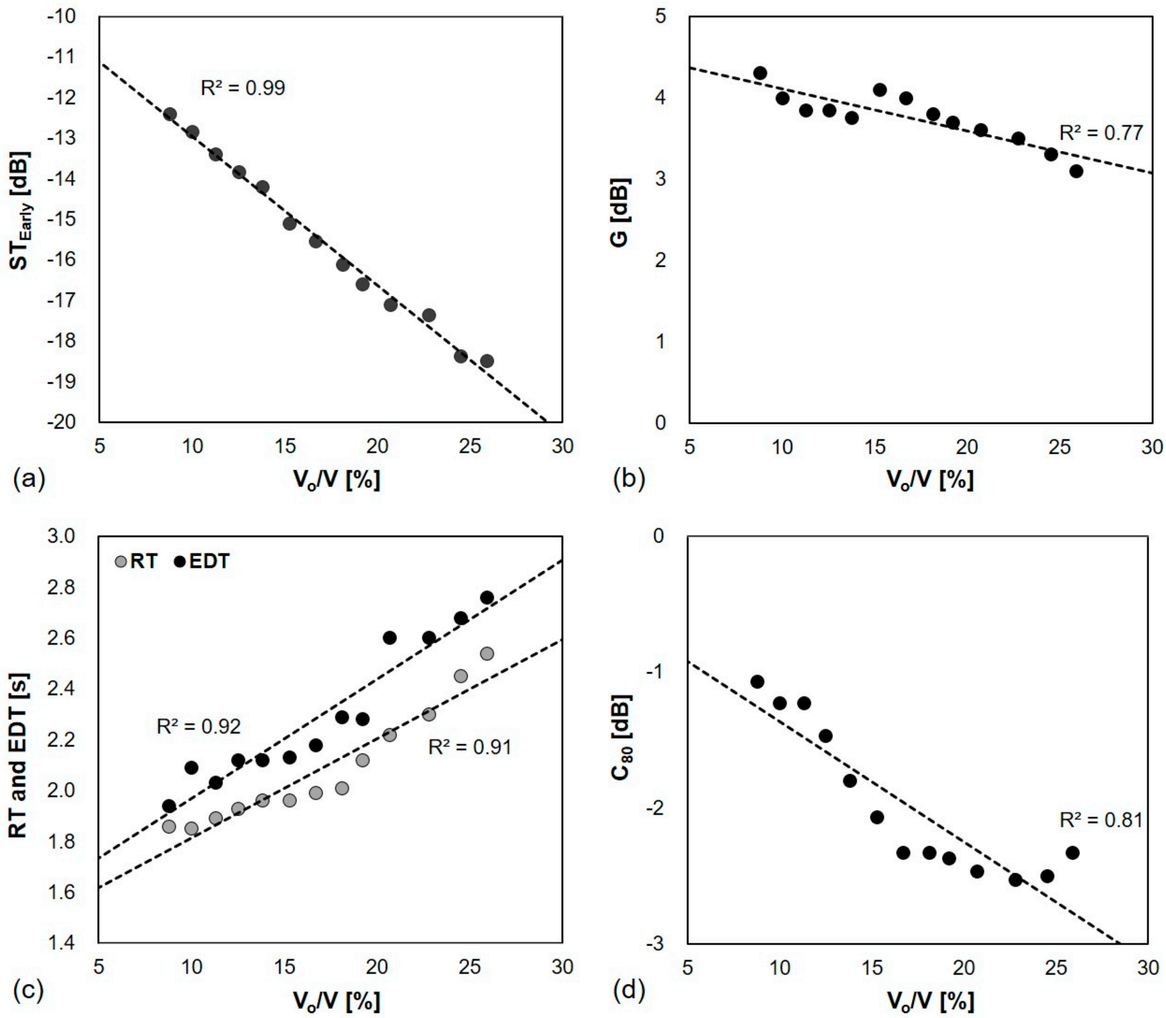


Figure 2. Variations in acoustic parameters according to V_o/V (all parameters are calculated by averaging over all measurement points). (**a**) stage support (ST_{Early}), (**b**) strength (G), (**c**) reverberation time (RT) and early decay time (EDT), and (**d**) clarity(C_{80}).

3. Experiment B: Stage Volume Ratio for Various Hall Shapes

3.1. Method

3.1.1. Selection of Concert Halls

To apply the tendency observed above to the simple model, the effects of the stage volume ratios in actual concert halls of various shapes should be analyzed and generalized. To that end, nine models whose stage volumes could be varied easily were selected from among the 11 European concert halls provided in the Odeon software version 14. Similarly to the halls surveyed in Table 1, the nine concert halls selected for this study were composed of four shoebox-shaped halls (Boston Symphony Hall, BO; Vienna Großer Musikvereinssaal, VM; Amsterdam Concertgebouw, AM; London Royal Festival Hall, LF), two fan-shaped halls (Salzburg Festspielhaus, SA; Gothenberg Konserthus, GK), and three halls of other shapes (Edinburgh Usher Hall, EB; London Barbican Concert hall, LB; Stuttgart Liederhalle Beethovensaal, ST). Table 3 outlines the basic characteristics of these halls. When selecting the concert halls, those whose stage volumes could not be clearly determined, such as vineyard halls, or those for which stage shape modeling was difficult were excluded.

The number of seats in the nine concert halls ranged from 1286 to 2907, the volume per seat ranged from 6.27 m^2/seat to 9.42 m^2/seat, and the stage area (S_o) ranged from 145 m^2 to 340 m^2. When the ratio of the stage area to the total hall area was compared, the shoebox-shaped halls (BO, VM, AM, LF) had small stage area ratios of 8–11%, and the fan-shaped halls (SA, GK) had large stage area ratios of 19–22%. This characteristic often appears in concert halls on university campuses that have colleges of music. In these concert halls, the auditorium area is less than 50% of those of large concert halls, but the stage area is similar to that of a general symphony hall, allowing orchestra performance. V_o showed a range of 1128–3385 m^2. V_o/V of most halls with a stage area of less than 200 m^2 was higher than 10%. The halls with stage areas of more than 200 m^2 had similar or slightly higher V_o/V even though the stage areas were 1.5–2 times those of the halls, which had stage areas of approximately 150 m^2. In other words, the stage area was widely distributed, while the stage volume ratio was similar.

3.1.2. Computer Simulation

To examine the effects of the stage volume on the auditorium, the stage volume was increased in 10% increments from −20% to 30% relative to the existing reference stage. Models with stage volume ratios of less than −20% were not generated, considering the orchestra riser, because if the stage volume is decreased to less than −20%, the size of the orchestra riser is also reduced, which affects the orchestra layout, making it difficult to examine the effects of only stage volume changes. The Auto-CAD 2016 software was used for modeling. The stage volume was varied by adjusting the depth, whereas, the stage height and width were fixed to the maximum values, while separating the auditorium and stage based on the stage end. The nine concert halls modeled in six steps were simulated using Odeon version 14. In the same way, as in Experiment 1, the surface sound absorption coefficient of the library models was based on the measured data of the unoccupied concert hall. Hence, the surface material was adjusted to make the data similar to the measured data, even in the occupied state. When simulating an occupied concert hall, the sound absorption coefficients for highly, moderately, and lightly upholstered occupied chairs, proposed by Beranek and Hidaka [36], were applied to the seats of each concert hall. To analyze the room acoustic parameters, the transition order was set to the second order, and the impulse response length was set to 5000 ms. In addition, 15,000 late rays were used, which is higher than the recommended value, for comparison with the other models.

To set the sound receiving points, the hall auditorium was divided into 2 × 2 m grids, and one point was allocated to each grid. In the case of ST, which is an asymmetric hall, the grids were expanded to the entire auditorium for even distribution. As a result, one or more sound receiving points were set per 25 seats. The solitary sound source was positioned at 1.5 m height (1 m from the stage end and 1 m to the right) in all the nine halls. ISO 3382-1 requires that the sound source be located at a position that represents the performers well. In this study, it was difficult to generalize the location of the sound source because different concert halls have different shapes and stage floor areas, which also change the actual orchestra layout. Hence, the sound source was located based on the positions of solo performers who perform at approximately the same location. In addition, the sound source was fixed to one point to prevent changing the source-to-receiver distance. To evaluate the acoustics of the audience, the reverberation time (RT_{30}), early decay time (EDT), strength (G) was calculated as an average of 500 and 1000 Hz according to the frequency range specified in ISO 3382. Also, the clarity (C_{80}) and bass ratio, and bass index were analyzed according to previous research [10,28]. C_{80} was expressed as an average of 500, 1000, and 2000 Hz. The bass ratio was calculated as (RT_{125Hz} + RT_{250Hz}) / (RT_{500Hz} + RT_{1000Hz}), and the same has been related to bass richness and timbre [28]. Likewise, the bass index represents properties of the concert hall bass sound determined by subtracting the average G value in the 500–1000 Hz middle frequency range from that calculated at 125 Hz [10]. Because the main purpose of Experiment B was to examine the changes in audience acoustics, the stage-related acoustic index ST_{Early} was not calculated, unlike in Experiment A. Table 4 lists the simulation data of the basic reference model. RT ranged from 1.73 s to 2.56 s, which encompassed the required RT range for a general concert hall (1.8–2.0 s). The other acoustic parameters also showed variously distributed values; thus, they could be sufficiently generalized through the investigation of the nine halls used in this study.

Table 3. Data used to evaluate the stage volume ratio in nine existing concert halls.

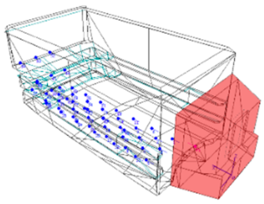
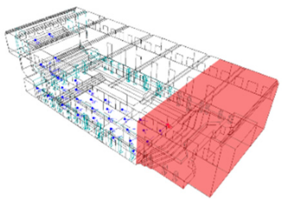
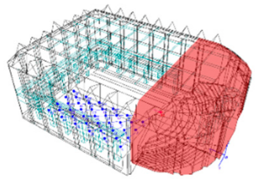
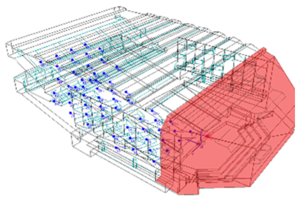
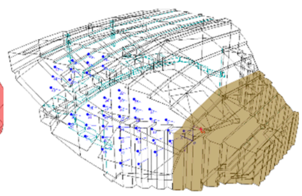
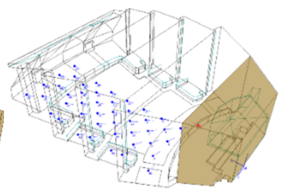
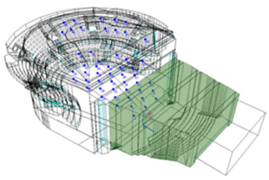
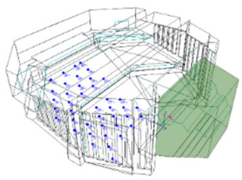
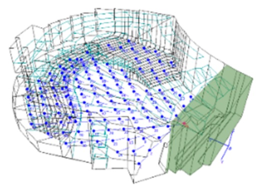
Hall	**Symphony Hall Boston (BO)**	**Großer Musikvereinssaal Vienna (VM)**	**Concertgebouw Amsterdam (AM)**
Model			
Shape	Shoebox	Shoebox	Shoebox
Seats	2625	1680	2037
Receivers	54	33	39
V/V_o [m^3]	18,750/2027	15,000/2355	18,780/1940
S/S_o [m^2]	1523/159	1118/151	1285/145
Hall	**Royal Festival Hall London (LF)**	**Festspielhaus Salzburg (SA)**	**Konserthus Gothenberg (GK)**
Model			
Shape	Shoebox	Fan	Fan
Seats	2901	2158	1286
Receivers	59	47	44
V/V_o [m^3]	21,950/2167	15,500/1380	11,900/1128
S/S_o [m^2]	2145/226	1555/342	836/171
Hall	**Usher Hall Edinburgh (EB)**	**Barbican Concert Hall London (LB)**	**Liederhalle, Beethovensaal Stuttgart (ST)**
Model			
Shape	Other	Other	Other
Seats	2502	1803	2000
Receivers	51	41	122
V/V_o [m^3]	15,700/2225	17,000/2028	16,000/1559
S/S_o [m^2]	1369/243	1445/218	1533/178

Table 4. Acoustical parameter of nine concert halls with reference models (all parameters were simulated in the unoccupied condition except RT30 and Bass Ratio).

		RT_{30}	EDT	C_{80}	G	Bass Ratio	Bass Index
BO	Mean	2.20	2.45	−1.69	0.1	1.01	5.1
	SD	0.10	0.19	1.87	0.3	0.02	1.7
VM	Mean	2.56	2.91	−1.19	−0.1	0.80	6.8
	SD	0.12	0.14	2.18	0.3	0.02	2.7
AM	Mean	2.34	2.40	−0.33	−0.2	0.96	5.9
	SD	0.04	0.08	1.04	−0.1	0.01	1.0
LF	Mean	1.53	1.40	1.53	−0.5	0.92	2.5
	SD	0.06	0.22	2.34	0.5	0.02	2.4
SA	Mean	1.96	1.94	−0.55	0.1	0.99	5.2
	SD	0.05	0.19	2.11	0.3	0.01	1.6
GK	Mean	1.73	1.78	0.5	0.7	1.11	5.8
	SD	0.10	0.11	1.6	0.3	0.02	1.3
EB	Mean	1.81	1.88	0.03	−1.0	0.84	4.6
	SD	0.10	0.19	1.68	0.4	0.02	2.4
LB	Mean	1.97	2.07	−1.58	−0.5	0.97	0.7
	SD	0.05	0.10	1.71	0.2	0.02	1.5
ST	Mean	1.97	2.00	−0.42	−0.5	0.91	3.8
	SD	0.17	0.14	1.84	0.3	0.03	2.0

3.2. Results and Discussion

3.2.1. Effect of Stage Volume Ratio on Acoustic Parameters

Figure 3 shows the simulation results of the concert hall acoustic parameters according to V_o/V, and Appendices A and B lists the specific values. First, the RT increases with increasing stage volume ratio. The EB and VM halls, which have larger stage volumes relative to the total volume, show the largest change of 0.49 s at the maxima. Moreover, the change in RT according to the stage volume ratio is the highest at 0.08 for EB; it is also high at 0.06 for rectangular halls, such as VM and AM.

Similar to the RT, the EDT also has a positive correlation with the stage volume ratio in general. Furthermore, the change in EDT according to the variation of the stage volume ratio is 0.37 s at the maximum, which is very high (19% higher than the average EDT of the six simulation cases).

In contrast to the RT and EDT, C_{80} generally decreases with increasing stage volume ratio; this parameter is more sensitive to the stage volume ratio than the reverberation-related indices. The change rates of C_{80} in the fan-shaped and other halls are higher than those in the shoebox-shaped halls. The maximum change in C_{80} is −0.22 dB/(V_o/V) in GK hall. The difference between the maximum and minimum values is also high at more than 0.5 in halls other than the shoebox-shaped halls. In GK, the clarity decreases by up to 1.0 dB. This considerable difference could be attributable to the fact that the stage volume has a significant effect on the generation of initial reflection of the sound from the sound source on the stage. It increases or decreases the path of the reflected sound, reaching the auditorium, and these effects are strongly reflected in the C_{80} value.

The loudness of a concert hall is determined by the G value, which represents the sound strength and is considered the most sensitive acoustic parameter [37]. In the present study, even when the stage volume changed greatly, G changed by less than 1 dB, although there was a general decreasing tendency, as shown in Figure 3d. The ST hall shows a different tendency from the other halls. Its G value increases with increasing stage volume ratio, because it has a greater average room height and average room length than the other halls. Consequently, it was verified through computer simulation that even though the G value of the back seats decreased as the stage became deeper, the reflections from the back wall of the stage reached the front row of the auditorium instead of the stage floor, increasing G by up to 0.3 dB.

The bass ratios of the halls ranged from 0.8 to 1.1 on average, as shown in Figure 4e. They show a clear decreasing tendency with increasing stage volume, except in the case of the LB hall. In every hall except LB, the bass ratio exhibits a general decreasing tendency with similar slopes. This trend is evident because the sound absorption area increases with increasing stage volume, and the bass reverberation in the auditorium tends to weaken as the relative sound absorption property at low frequencies increase substantially. In the case of EB, the difference between the maximum and minimum bass ratios with changing stage volume is 0.08, which appears to be the result of the significantly higher RT corresponding to the range of 500–1000 Hz with increasing stage volume. This conclusion can be inferred from the fact that the change in RT is the largest for EB in Figure 4a. In the case of LB, the base properties do not change much with variation in the stage volume ratio, which appears to be due to the significant effect of the large canopy covering parts of the stage and auditorium even when the stage volume was changed.

When compared with the bass ratio results, most of the halls show a decreasing tendency of the bass index as the stage volume ratio increases. In particular, the fan-shaped halls show a greater lowering of the bass index. However, unlike the bass ratio, the bass index increases or remains constant in the VM, LF, and LB halls with increasing stage volume ratio, because the bass index is greatly influenced by the weight per unit area of the side wall and ceiling and the sound absorption coefficient of the material in the middle frequency range. Consequently, as the stage volume increases, the G value at 125 Hz increases more than that in the middle frequency range owing to the material characteristics of the side and back walls and floor of the stage.

3.2.2. Influence of Stage Absorption on Concert Hall Acoustics

The floor and wall areas of the stage change according to the stage volume of the concert hall, which changes the total sound absorption of the hall. The sound absorption coefficient of the internal finishing of the hall is a critical index that determines the sound absorption coefficient of the room. Thus, the sound absorption coefficient (A_c) was determined by dividing the total sound absorption inside the concert hall by the total surface area. Figure 4 shows the distributions of the acoustic parameters of the nine halls based on the sound absorption coefficient. RT, EDT, and G generally exhibit decreasing tendencies with increasing sound absorption coefficient. C_{80} increases continuously, but the bass ratio and bass index decrease again after increasing to a certain level.

Standard (simultaneous) regression analysis was performed to examine the effects of total volume, stage volume ratio, stage area ratio, and sound absorption coefficient on the room acoustic parameters of the concert hall and the contribution of each influencing factor. Results obtained are summarized in Table 5. The total R^2 for each parameter is statistically significant ($p < 0.01$). The model shows the highest explanatory power for RT and EDT, and the variation of the sound absorption coefficient of the concert hall according to the volume change exhibit the largest effects on RT and EDT. The regression coefficient of the stage volume ratio is also statistically significant. With a stage volume ratio increase of 1%, the RT and EDT are expected to increase by 0.03 s and 0.05 s, respectively. Furthermore, regarding the standardized regression coefficient, the stage volume ratio is approximately 0.3, which is 38% of the sound absorption coefficient of 0.7. Moreover, based on the comparison of the independent contributions of the stage volume ratio and sound absorption coefficient, the contribution of the sound absorption coefficient to RT and EDT is higher at 0.46 and 0.44. However, the contributions of the stage volume ratio are 0.06 (RT) and 0.09 (EDT), respectively, indicating an influence of approximately 15–20% on average relative to the sound absorption coefficient. This finding suggests that stage volume is an important factor that determines the reverberation of the concert hall. The C_{80} prediction model also shows a high explanatory power of 0.51. The regression coefficient of V and V_o/V are not significant, but those of S_o/S and A_c are significant. One interesting factor is that in the case of C_{80}, the regression coefficient of the stage area ratio is −0.06, which is similar to that of the stage volume ratio, but the independent contribution is 0.04, which indicates more than four times greater influence than that of the volume. In other words, C_{80} is greatly affected by the initially reflected sound from the stage floor of the concert hall. Based on this result, it can be said that some degree of clarity can be achieved without affecting other acoustic parameters, such as RT and EDT by reducing the stage area when it is difficult to change the stage volume significantly.

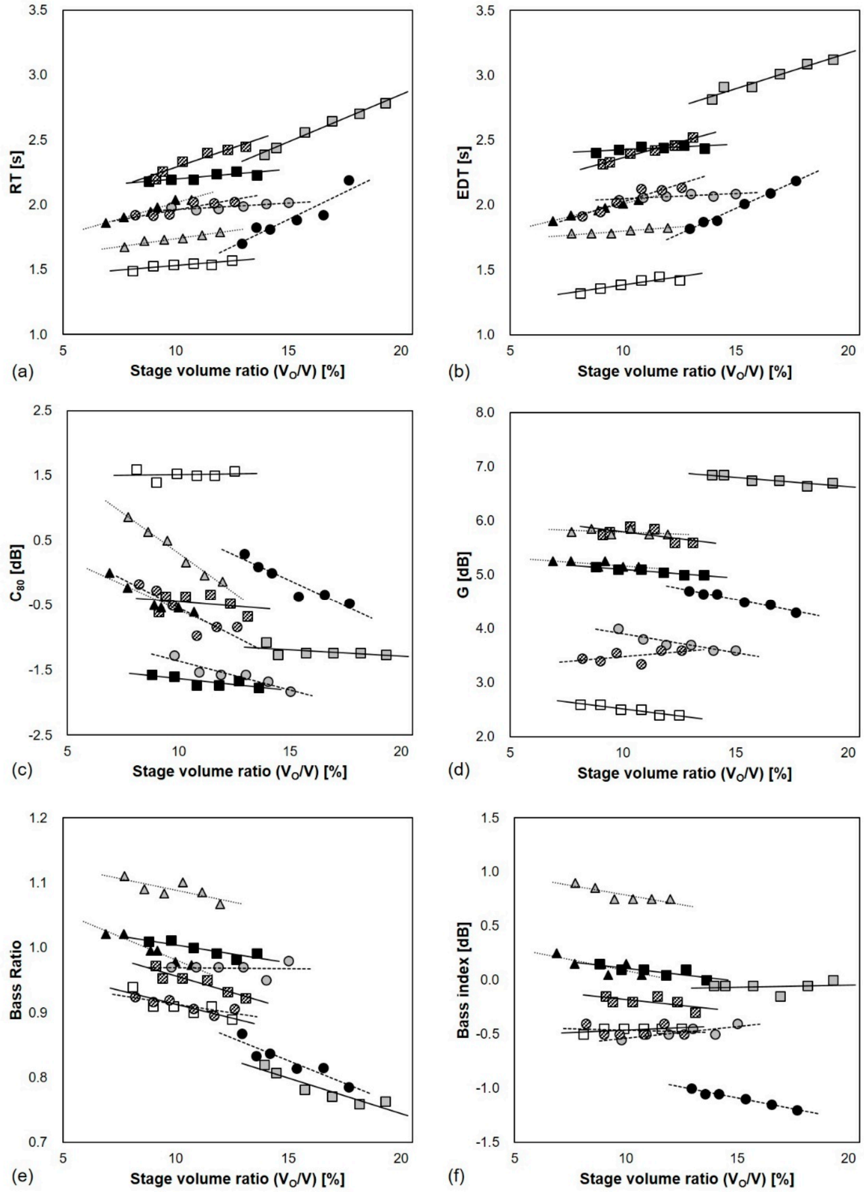


Figure 3. Variations in acoustic parameters according to V_o/V in the computer simulation (all parameters are calculated by averaging over all measurement points). (**a**) RT, (**b**) EDT, (**c**) C80, (**d**) G, (**e**) bass ratio, and (**f**) bass index. (■: BO, ■: VM, ▨: AM, □: LF, ▲: SA, △: GK, ●: EB, ○: LB, ◍: ST).

The change in G is less than 1 dB even when the stage volume ratio changes considerably in Figure 3. This result suggests that the regression coefficient of the stage volume is statistically insignificant, although the regression model is significant. Only the change in the sound absorption coefficient, due to the increased area around the stage substantially affects G. As the stage volume increases, the back and side walls of the stage become farther away and the path of the sound from the sound source to the sound receiving point becomes longer. These effects do not cause significant differences, as can be deduced based on the change in G between the seats with changing source-to-receiver distance. Therefore, the effect of the stage volume on G is rather small.

The effects of the stage volume ratio on the bass ratio and bass index are greater when compared with the prediction models of other acoustic parameters. In particular, the bass ratio is statistically significant as R^2 is 0.59 when V_o/V is −0.02. The independent contribution is also the highest at 0.39. In the case of the bass index as well, V_o/V has a significant regression coefficient along with A_c; its independent contribution is also similar. The strength of the bass sounds in the concert hall is closely related to the warmth. Thus, the smaller the stage volume, the more acoustical warmth is provided. However, the reduction in the stage volume ratio is also accompanied by reductions in RT and EDT. Therefore, it should be designed to have an appropriate volume ratio.

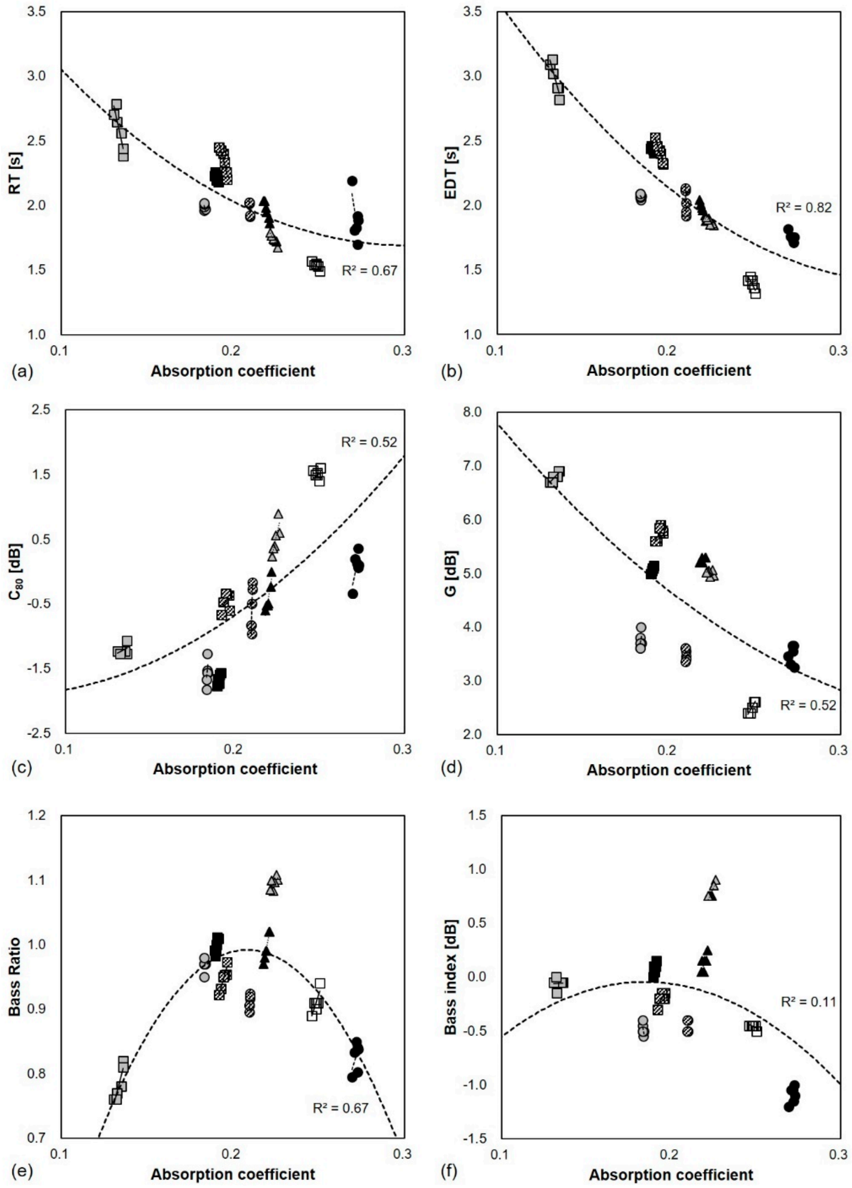


Figure 4. Variations in acoustic parameters according to Ac of the concert hall interior in the computer simulation (all parameters are calculated by averaging over all measurement points). (**a**) RT, (**b**) EDT, (**c**) C80, (**d**) G, (**e**) bass ratio, and (**f**) bass index. (■: BO, ■: VM, ▨: AM, □: LF, ▲: SA, △: GK, ●: EB, ○: LB, ⊘: ST).

Table 5. Summary of the linear regression of acoustic parameters with stage design factors.

	Unstandardized Coefficients	Standardized Coefficients	t	p	Correlation			ΔR^2
					Zero-Order	Partial	Part	
RT (Adjust $R^2 = 0.73$, $p < 0.01$)								
(Constant)	2.69		12.43	<0.01				
V	0.00	0.06	0.81	0.43	0.01	0.11	0.06	0.00
V_o/V	0.03	0.27	3.32	<0.01	0.53	0.43	0.24	0.06
S_o/S	0.01	0.15	1.85	0.07	0.13	0.26	0.13	0.02
A_c	−6.11	−0.74	−9.53	<0.01	−0.79	−0.81	−0.68	0.46
EDT (Adjust $R^2 = 0.77$, $p < 0.01$)								
(Constant)	3.29		13.83	<0.01				
V	0.00	−0.06	−0.83	0.41	−0.09	−0.12	−0.05	0.00
V_o/V	0.05	0.34	4.51	<0.01	0.56	0.53	0.30	0.09
S_o/S	0.01	0.06	0.80	0.43	0.08	0.11	0.05	0.00
A_c	−8.27	−0.73	−10.38	<0.01	−0.82	−0.83	−0.67	0.44
C_{80} (Adjust $R^2 = 0.51$, $p < 0.01$)								
(Constant)	−3.19		−3.94	<0.01				
V	0.00	0.04	0.41	0.67	0.11	0.06	0.04	0.00
V_o/V	−0.03	−0.09	−0.84	0.40	−0.37	−0.12	−0.08	0.01
S_o/S	−0.06	−0.24	−2.20	<0.05	−0.18	−0.30	−0.21	0.04
A_c	17.47	0.68	6.49	<0.01	0.68	0.68	0.63	0.39
G (Adjust $R^2 = 0.52$, $p < 0.01$)								
(Constant)	11.00		9.38	<0.01				
V	0.00	−0.50	−5.12	<0.01	−0.53	−0.59	−0.49	0.24
V_o/V	0.05	0.10	0.92	0.36	0.25	0.13	0.09	0.01
S_o/S	0.06	0.06	0.60	0.55	0.12	0.09	0.06	0.00
A_c	−18.58	−0.49	−4.75	<0.01	−0.53	−0.56	−0.45	0.20
Bass Ratio (Adjust $R^2 = 0.59$, $p < 0.01$)								
(Constant)	1.38		18.16	<0.01				
V	0.00	−0.30	−3.29	<0.01	−0.31	−0.43	−0.29	0.08
V_o/V	−0.02	−0.72	−7.13	<0.01	−0.73	−0.71	−0.62	0.39
S_o/S	0.00	−0.05	−0.49	0.63	−0.24	−0.07	−0.04	0.00
A_c	−0.07	−0.03	−0.30	0.77	0.15	−0.04	−0.03	0.01
Bass Index (Adjust $R^2 = 0.54$, $p < 0.01$)								
(Constant)	3.44		7.60	<0.01				
V	0.00	−0.47	−4.95	<0.01	−0.49	−0.58	−0.46	0.21
V_o/V	−0.08	−0.46	−4.32	<0.01	−0.39	−0.53	−0.40	0.16
S_o/S	−0.01	−0.10	−0.98	0.33	−0.24	−0.14	−0.09	0.01
A_c	−5.65	−0.47	−4.22	<0.01	−0.33	−0.52	−0.39	0.15

3.2.3. Comparing Effect of Total Volume and Stage Volume Ratio

As observed in this study, the total volume changes in accordance with changes in the stage volume ratio. Table 5 describes the effects of changes in values of V_o/V and total volume on other acoustic parameters. Overall, it has been observed that RT of a concert hall is predominantly affected by the total volume along with a significant sound absorption effect of the internal finishing material [38]. However, when examining standard regression coefficients for RT and EDT, no statistically significant difference was observed when performing V and V_o/V result comparisons. However, results pertaining to the stage volume ratio revealed a statistically significant correlation. This indicates that changes of the order of 20–30% in stage volume can be considered small in relation to the total volume, and therefore, the impact of changes in stage volume ratio is more significant compared to those in total volume. In addition, the regression model for bass ratio demonstrates the independent contribution of V_o/V to be 0.39—approximately 5 times that of V alone (0.08). This suggests that even in concert halls with the same total volume, the reverberation and warmth felt within the auditorium may differ depending on the ratio of the stage to auditorium volumes. This implies that to achieve the target reverberation time condition during the concert hall design stage, the total volume can be changed as a first option. However, if the total volume cannot be significantly altered or interiors of an existing hall need to be renovated, an improvement in reverberation and bass characteristics of the hall can exclusively be realized via changes in the stage volume.

However, a major limitation of this study is that only those scenarios wherein the total volume changes along with the stage volume have been investigated herein. Thus, future research endeavors in this regard must account for changes in audience acoustics, due to changes in the volume ratio of the stage and other parts, while the total volume of the hall remained fixed. Furthermore, in this study, the material used for hall construction was considered constant to maintain the unique acoustic characteristics of the hall. However, each hall possesses a different stage shape and material characteristics. As described in Table 5, material characteristics demonstrate the largest effect on hall acoustics; hence, there was a limit to the suggestion of an absolute value for the appropriate stage volume ratio. Therefore, an appropriate stage volume ratio must be identified in follow-up research endeavors by unifying the stage material and/or other methods.

4. Conclusions

The changes in the acoustic parameters of the audience according to the change in V_o/V in concert halls were investigated using computer simulation models for nine concert halls, including the Boston Symphony Hall. Firstly, in the evaluation of the simple model, the change patterns of the representative acoustic parameters of the stage and the auditorium, according to the change in the stage volume were examined. As the stage volume ratio increased, ST_{Early} of the stage, which is greatly affected by the initial reflection sound, decreased, as did G and C_{80} of the auditorium. Furthermore, the RT and EDT of the auditorium increased linearly with the stage volume ratio. Computer simulations were conducted for nine concert halls to verify the tendencies of these room acoustic parameters for various shapes of concert halls. Consequently, when the stage volume ratio changed from −20% to 30%, the RT and EDT increased, whereas, C_{80} and G decreased, indicating the possibility of generalization of the tendencies in the simple model. Furthermore, the bass ratio and bass index representing the bass properties of the concert hall decreased as the stage volume ratio increased.

When the stage area and sound absorption coefficient, which change with the volume of the concert hall, were considered together, the variation in the sound absorption coefficient with increasing sound absorption area of the concert hall had the largest effect on the reverberation, clarity, and loudness. However, the stage volume ratio by itself had an effect of approximately 15% on the average relative to the sound absorption coefficient toward RT and EDT. Thus, it can be seen that the stage volume ratio is an important factor that should be considered in acoustic design. In particular, the independent contribution of the bass ratio was 0.39, suggesting a larger influence of the stage volume ratio on the bass ratio than on the other design elements. The bass index also revealed a higher contribution than the sound absorption coefficient of the concert hall. Therefore, the stage volume ratio can be lowered to achieve the appropriate warmth of the concert hall efficiently without significantly decreasing the RT and EDT.

Because this study was conducted using computer simulations, the results may differ from the effects of the stage volume ratio in actual halls. Nevertheless, the study results confirm that the stage volume ratio should be considered as an important design element for concert halls. The simulation results of various concert halls could provide architects, acoustic experts, and engineers with useful data for realizing efficient acoustic designs in the future. Furthermore, optimized acoustic design in the volume aspect rather than indiscriminately large concert halls could contribute to maintaining or securing sustainable space in urban cities.

Author Contributions: Conceptualization, J.Y.J. and H.I.J.; methodology, R.S.; software, R.S.; validation, R.S.; investigation, R.S. and H.I.J.; data curation, R.S.; writing—original draft preparation, H.I.J.; writing—review and editing, H.I.J.; supervision, J.Y.J.; project administration, J.Y.J.; funding acquisition, J.Y.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Bio and Medical Technology Development Program of the National Research Foundation (NRF) and funded by the Korean government (MSIT) [grant number 2019M3E5D1A01069363].

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Linear characteristics of acoustic parameters in nine concert halls; m: regression coefficient, R^2: explanation power of linear regression model, Max: maximum value with the change of V_o/V, Min: minimum value with the change of V_o/V, Diff: difference between maximum and minimum value, Avg.: average value

Acoustical Parameter		BO	VM	AM	LF	SA	GK	EB	LB	ST
RT [s]	m	0.01	0.06	0.06	0.01	0.05	0.02	0.08	0.01	0.03
	R^2	0.71	0.98	0.93	0.79	0.96	0.95	0.85	0.72	0.81
	Max	2.26	2.79	2.45	1.57	2.04	1.79	2.19	2.02	2.03
	Min	2.18	2.39	2.20	1.49	1.86	1.68	1.70	1.96	1.92
	Diff.	0.08	0.40	0.25	0.08	0.18	0.12	0.49	0.06	0.11
	Avg.	2.22	2.59	2.35	1.54	1.96	1.74	1.89	1.99	1.97
EDT [s]	m	0.01	0.05	0.05	0.03	0.04	0.01	0.08	0.01	0.05
	R^2	0.55	0.95	0.97	0.82	0.99	0.86	0.99	0.72	0.89
	Max	2.46	3.13	2.53	1.45	2.04	1.83	2.19	2.09	2.14
	Min	2.41	2.82	2.32	1.32	1.88	1.78	1.82	2.04	1.92
	Diff	0.05	0.31	0.21	0.13	0.17	0.05	0.37	0.05	0.22
	Avg.	2.44	2.98	2.41	1.39	1.96	1.80	1.98	2.07	2.04
C_{80} [dB]	m	−0.04	−0.02	−0.03	0.00	−0.16	−0.22	−0.16	−0.09	−0.18
	R^2	0.64	0.31	0.10	0.01	0.88	0.99	0.89	0.88	0.78
	Max	−1.57	−1.07	−0.33	1.60	0.00	0.87	0.30	−1.27	−0.17
	Min	−1.77	−1.27	−0.67	1.40	−0.60	−0.13	−0.47	−1.83	−0.97
	Diff	0.20	0.20	0.33	0.20	0.60	1.00	0.77	0.56	0.80
	Avg.	−1.68	−1.22	−0.47	1.52	−0.40	0.33	−0.13	−1.57	−0.59
G [dB]	m	−0.03	−0.03	−0.05	−0.05	−0.03	−0.01	−0.08	−0.07	0.04
	R^2	0.94	0.81	0.42	0.91	0.56	0.23	0.97	0.86	0.32
	Max	5.15	6.85	5.90	2.60	5.25	5.85	4.70	4.00	3.60
	Min	5.00	6.65	5.60	2.40	5.15	5.75	4.30	3.60	3.35
	Diff	0.15	0.20	0.30	0.20	0.10	0.10	0.40	0.40	0.25
	Avg.	5.07	6.76	5.75	2.50	5.20	5.79	4.54	3.73	3.49
Bass Ratio	m	−0.01	−0.01	−0.01	−0.01	−0.01	−0.01	−0.01	−0.00	−0.01
	R^2	0.78	0.86	0.87	0.70	0.96	0.59	0.87	0.00	0.73
	Max	1.01	0.82	0.97	0.94	1.02	1.11	0.87	0.98	0.92
	Min	0.98	0.76	0.92	0.89	0.97	1.07	0.79	0.95	0.90
	Diff	0.03	0.06	0.05	0.05	0.05	0.04	0.08	0.03	0.03
	Avg.	1.00	0.78	0.95	0.91	1.00	1.09	0.83	0.97	0.91
Bass index [dB]	m	−0.02	0.00	−0.02	0.01	−0.04	−0.03	−0.04	0.02	−0.01
	R^2	0.68	0.04	0.42	0.44	0.59	0.72	0.98	0.69	0.03
	Max	0.15	0.00	−0.15	−0.45	0.25	0.90	−1.00	−0.40	−0.40
	Min	0.00	−0.15	−0.30	−0.50	0.05	0.75	−1.20	−0.55	−0.50
	Diff	0.15	0.15	0.15	0.05	0.20	0.15	0.20	0.15	0.10
	Avg.	0.08	−0.06	−0.20	−0.46	0.13	0.79	−1.09	−0.48	−0.47

Appendix B

Values of reverberation time (RT) and strength (G) for different frequency ranges used for calculating the bass ratio and bass index according to values of V_o/V obtained via computer simulation

Acoustical Parameter	Stage Volume [%]	BO	VM	AM	LF	SA	GK	EB	LB	ST
$RT_{125-250Hz}$ [s]	−20	2.20	1.96	2.14	1.40	1.90	1.86	1.48	1.92	1.78
	−10	2.22	1.97	2.16	1.39	1.95	1.88	1.52	1.90	1.76
	0	2.20	2.00	2.23	1.40	1.94	1.88	1.52	1.91	1.77
	10	2.22	2.04	2.28	1.40	1.97	1.91	1.54	1.93	1.84
	20	2.22	2.06	2.26	1.40	1.99	1.92	1.57	1.91	1.81
	30	2.21	2.13	2.26	1.40	1.98	1.91	1.72	1.98	1.84
$RT_{500-1000Hz}$ [s]	−20	2.18	2.39	2.20	1.49	1.86	1.68	1.70	1.98	1.92
	−10	2.20	2.44	2.26	1.53	1.91	1.72	1.83	1.96	1.92
	0	2.20	2.56	2.34	1.54	1.95	1.73	1.81	1.97	1.93
	10	2.24	2.65	2.40	1.55	1.98	1.74	1.89	1.99	2.03
	20	2.26	2.71	2.43	1.54	2.04	1.77	1.92	2.01	2.02
	30	2.23	2.79	2.45	1.57	2.04	1.79	2.19	2.02	2.03
G_{125} [dB]	−20	5.30	6.80	5.60	2.10	5.50	6.70	3.70	3.45	3.05
	−10	5.20	6.80	5.60	2.15	5.40	6.70	3.60	3.30	2.90
	0	5.20	6.70	5.70	2.05	5.30	6.50	3.60	3.20	3.05
	10	5.10	6.60	5.70	2.05	5.30	6.60	3.40	3.25	2.85
	20	5.10	6.60	5.40	1.95	5.30	6.50	3.30	3.10	3.20
	30	5.00	6.70	5.30	1.95	5.20	6.50	3.10	3.20	3.10
G_{125} [dB]	−20	5.15	6.85	5.75	2.60	5.25	5.80	4.70	4.00	3.45
	−10	5.10	6.85	5.80	2.60	5.25	5.85	4.65	3.80	3.40
	0	5.10	6.75	5.90	2.50	5.15	5.75	4.65	3.70	3.55
	10	5.05	6.75	5.85	2.50	5.25	5.85	4.50	3.70	3.35
	20	5.00	6.65	5.60	2.40	5.15	5.75	4.45	3.60	3.60
	30	5.00	6.70	5.60	2.40	5.15	5.75	4.30	3.60	3.60

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