Chronological analysis of architectural and acoustical indices in music performance halls

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This study aims to identify the changes in architectural and acoustical indices in halls for music performance built in the 18th through the 20th Centuries. Seventy-one halls are classified in five specific periods from the Classical Period (1751–1820) to the Contemporary Period (1981–2000) based on chronology in music and architectural acoustics. Architectural indices such as room shape, seating capacity, room volume, balcony configuration, and the like as well as acoustical indices such as RT, EDT, G, C80, IACC, and the like for the halls found in the literature are chronologically tabulated and statistically analyzed to identify trends and relationships in architectural and acoustical design for each of the historical periods identified. Some indices appear correlated with each other. © *2007 Acoustical Society of America.* [DOI: 10.1121/1.2713663]

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I. INTRODUCTION

From Greek amphitheaters originally used for ancient theatric performances to 20th Century contemporary halls for various types of performances, architectural as well as acoustical design technologies involved in these performance venues have progressed enormously and are still evolving. Over the last century, acousticians have better understood the relations between overall acoustical qualities of the performance halls and room geometric indices such as shape, volume, dimensions, and the like. Accordingly, better room acoustical qualities have resulted from proper geometric design development.

This paper explores the changes in architectural and room acoustical indices in halls, primarily used for music performances and built in the 18th through the 20th Centuries. Seventy-one halls including fifty-nine concert halls and twelve multipurpose halls are investigated. Most were selected from *Concert Halls and Opera Houses: How They Sound* (1996) and *Concert Halls and Opera Houses: Music, Acoustics, and Architecture* (2004) by Beranek which present acoustical data of representative performance halls in the world. The halls are classified in five specific periods on the basis of chronology in music and architectural acoustics from the Classical Period (1751–1820) to the Contemporary Period (1981–2000). Architectural and acoustical indices are then chronologically surveyed and tabulated, and relationships among those indices are further investigated to identify trends in architectural and acoustical design for each of the classified historical periods. Understanding of how, over time, architectural indices of these spaces have changed in relation to room acoustical indices and how the recent design of such spaces is occurring should support both acousticians and architects in their design process.

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II. RESEARCH METHOD

Seventy-one halls constructed before the 21st Century are chronologically classified in three major musical eras: Classical (1751–1820), Romantic (1821–1900), and Modern (1901–2000) eras. See Table I. The 20th Century era is subdivided into three specific periods: Pre-Modern (period of the first half a century before World War II), Modern I (period of three decades after World War II), and Modern II (contemporary period from 1981 to 2000). Talaske *et al.* (1982) and Hoffman *et al.* (2003) have remarked that "The past two decades have seen a remarkable growth in number and technical quality of facilities devoted to the performing arts" in the introductory sections for the books of *Halls for Music Performance: Two Decades of Experience, 1962-1982* (1982) and of *Halls for Music Performance: Another Two Decades of Experience 1982-2002*. (2003).

About 70% (50 halls) out of the total 71 halls were constructed within the last 50 years during the Modern I and II Periods from 1951 to 2000. However, because only one music hall is found in the Classical Period, this period is excluded from most of the following analyses.

The chronological analyses are grounded on the collected materials such as graphics, architectural drawings, and acoustical data from previously published documents and the technical literature. Specifically, architectural and acoustical indices listed in Table II are chronologically tabulated and

TABLE I. Chronological distribution of the halls studied.

Chronological period	Concert hall	Multiuse hall	Subtotal
Classical (1751–1820)	1	0	1
Romantic (1821–1900)	8	1	9
Pre-Modern (1901–1950)	9	2	11
Modern I (1951–1980)	19	4	23
Modern II (1981–2000)	22	5	27
Total	59	12	71

TABLE II. List of architectural and acoustical indices investigated.

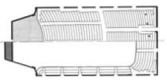
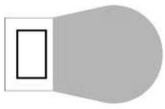
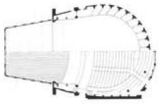
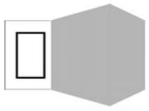
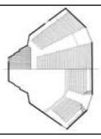
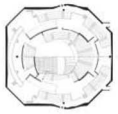
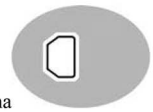
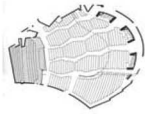
Architectural design indices		
Room indices	Balcony overhang indices	Room acoustical indices
Room shape	Overhang depth (D)	Reverberation time (RT)
Room volume	Opening height (H)	Early decay time (EDT)
Seating capacity	Depth to height ratio (D/H)	Bass ratio (BR)
Volume per seat	Vertical angle of view (θ)	Loudness or strength (G)
Room length	Number of overhangs	Early-to-late energy index (C80)
Room width		Lateral energy fraction (LF)
Room height		Interaural cross correlation (IACC)
		Binaural quality index (BQI)
		Initial time delay gap (ITDG)

statistically analyzed to identify design trends observed in music performance hall history.

III. GEOMETRIC CLASSIFICATION METHOD

Haan and Fricke (1992) attempted to geometrically categorize auditoria in five types in their survey of auditoria: rectangular, horseshoe, fan-shaped, arena, and geometric style. The geometric classification of room shapes in this study also basically follows these five categories, but a few different terms are used: *rectangular* is replaced with *shoebox*, and *geometric* with *irregular*, because the latter terms of *shoebox* and *irregular* are commonly used in the literature. Typical configurations of the room shapes are illustrated with some examples in Table III. The room shapes are categorized primarily on the basis of architectural plan views but also with reference to the longitudinal section views as well as the audience seating arrangements. Specifically, a hall with parallel side walls and a planar rear wall is classified in the shoebox style, a hall with oblique side walls that widen outward is classified in the fan-shaped style, and a hall with a continuously curved wall from the side to the rear is classified in the horseshoe style. A hall with a stage surrounded fully by seating areas is classified in the arena style. Note that semisurrounded halls, which can be classified as a room shape of *semiarena*, are included in the group of *arena* and statistically investigated in most analyses. Lastly, the irregular style includes a hall with a combined configuration, such as parallel side walls with a curved rear wall, and a hall with one oddly angled major surface or more. For example, Meyerson Symphony Hall in Dallas, TX, which has parallel side

TABLE III. Configurations of the room shape typologies (not to scale).

Category	Typical configuration	Example	
Shoebox			Boston Symphony Hall Boston, MA, US
Horseshoe			Bass Performance Hall Fort Worth, TX, US
Fan-shaped			Patria Hall Budapest, Hungary
Arena	 Arena		Boettcher Concert Hall Denver, CO, US
	 Semi-arena		Waterfront Hall Belfast, Ireland
Irregular			Liederhalle Beethovensaal Stuttgart, Germany

* Drawings adopted from *Concert Halls and Opera Houses* by Beranek (2004).
* Halls with a stage area positioned aside from the center of the hall were subcategorized in the semiarena style.

TABLE IV. Chronological trends in room shape typologies.[b]

	Romantic (1821–1900)		Pre-Modern (1901–1950)		Modern I (1951–1980)		Modern II (1981–2000)		Overall	
Room shape	No.	%	No.	%	No.	%	No.	%	No.	%
Shoebox	6	66.7	1	9.1	8	34.8	7	25.9	23	32.4
Fan-shaped	0	0.0	6	54.5	6	26.1	4	14.8	16	22.5
Arena/Semi	1	11.1	0	0.0	5	21.7	8	29.6	14	19.7
Horseshoe	2	22.2	4	36.4	1	4.3	3	11.1	10	14.1
Irregular	0	0.0	0	0.0	3	13.0	5	18.5	8	11.3
Total	9	100.0	11	100.0	23	100.0	27	100.0	71	100.0

Note that the total number of shoebox halls (23) includes 1 shoebox hall found in the Classical Period.

walls with an opera house style curved rear wall, and Liederhalle Beethovensaal in Stuttgart, Germany, which has an inversely curved side wall, are classified in this irregular style.

IV. CHRONOLOGICAL PHASES IN ARCHITECTURAL DESIGN INDICES

In the following discussion of trends in room shape, seating capacity, volume, volume per seat, and dimensions, some statistical analyses exclude Royal Albert Hall in London or Music Shed in Lenox, MA, or both halls, because these halls are considered statistical outliers in some cases.

A. Trend in room shape typologies

As shown in Table IV, the halls are categorized in five primary room shape typologies across the chronological periods defined earlier. Shoebox halls are found to be the most widely used room shape for music performances across all time periods. A larger number of shoebox halls are observed in all periods except the Pre-Modern Period (1901–1950). Two more specific trends may further extend this discussion of trend in room shape. One is that fan-shaped halls were developed during the Pre-Modern Period and became another primary room shape. For visual as well as acoustical intimacy, fan-shaped halls were a widely used room shape for multipurpose halls from the Pre-Modern Period to the present time. In fact, all the multipurpose halls (12 halls) investigated here were built since the Pre-Modern Period and 7 halls (about 58%) among them are fan-shaped. However, this result may not be a strongly supportive piece of evidence due to the relatively small sample size of the multipurpose halls. The other trend is that the room shapes have become diverse since the Modern I Period. While one or two room shapes were predominant in the Romantic and Pre-Modern Periods, additional shapes have been employed often since the Modern I Period. The use of arena or semiarena style has gradually increased during the Modern I and Modern II Periods, although the shoebox has still been the most used room shape. Irregular room shapes are regularly observed in these periods. Music performance halls coupled with a surround reverberation chamber represent a noteworthy recent room configuration. These "room-coupled" halls in this study are categorized in the above-mentioned five primary room shapes on the basis of their primary room shape in plan without the reverberation chambers as a modified room shape.

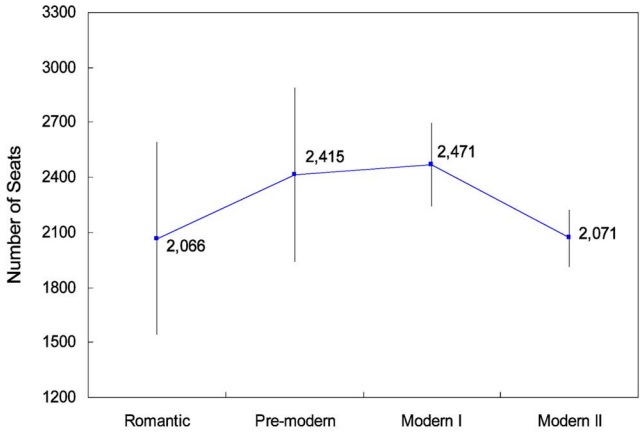
B. Trend in seating capacity

Compared to the Romantic Period (1821–1900), the average seating capacity in the Pre-Modern Period (1901–1950) increased abruptly by approximately 17% (350 seats) from approximately 2070 to 2420 seats. See Table V and Fig. 1(a). In the Modern I Period (1951–1980), the seating capacity continuously increased to approximately 2470 seats but in the Modern II Period (1981–2000), the seating capacity decreased to approximately 2070 seats. During the Modern II Period, the average seating capacity decreased nearly down to that in the Romantic Period and approached that of 23 shoebox halls of all time periods surveyed, which is about 2000. The increase in the two middle periods appears relevant to the increase of fan-shaped or multipurpose fan-

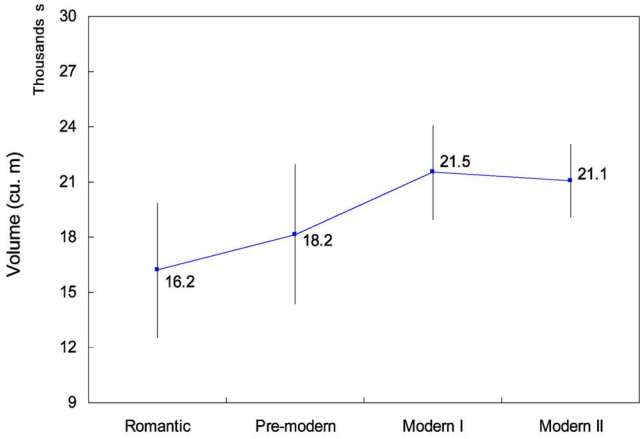
TABLE V. Chronological trends in architectural design indices (average values).

					Room dimensions (m)		
Chronological periods[a]		No. of seats	Room volume (m^3)[b]	Volume per seat (m^3/seat)	Height	Width	Length
Romantic (1821–1900)	9 halls	2066	16 208	7.84	17.6	22.4	30.7
Pre-Modern (1901–1950)	11 halls	2415	18 156	7.52	18.1	29.1	33.0
Modern I (1951–1980)	23 halls	2471	21 512	8.71	16.3	33.5	35.1
Modern II (1981–2000)	27 halls	2071	21 065	10.17	19.7	29.5	30.6
Overall	71 halls	2326	21 282	9.15	18.2	30.5	32.8
(without Albert Hall and Music Shed)		2244	20 028	8.93	18.0	29.8	32.3

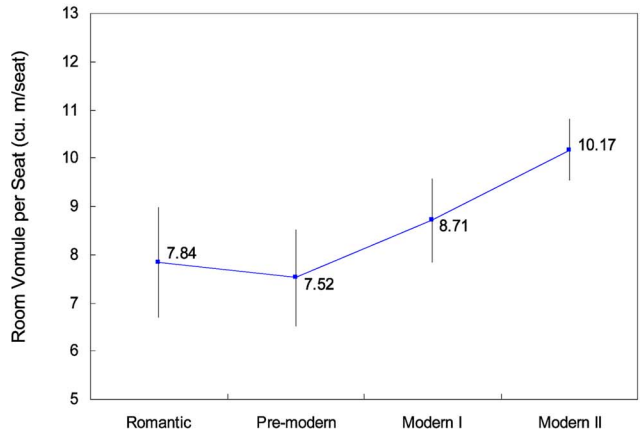
[a]Royal Albert Hall and Music Shed were excluded from the periods of Romantic and Modern I, respectively, because these halls were considered as statistical outliers.
[b]Room volume includes the volume of the main hall and the orchestra enclosure.



(a)



(b)



(c)

FIG. 1. (Color online) Chronological trends in architectural indices with 95% confidence intervals. (a) Seating capacity, (b) room volume, and (c) room volume per seat.

shaped halls during these periods, which hold a larger number of seats at a comparable distance from the stage. This observation is supported by demonstratable increases in average room width from 22.4 to 29.1 m observed in the Pre-Modern Period and up to 33.5 m in the Modern I Period. The average seating capacity of the fan-shaped halls (15 halls) excluding the Music Shed reaches about 2600 seats.

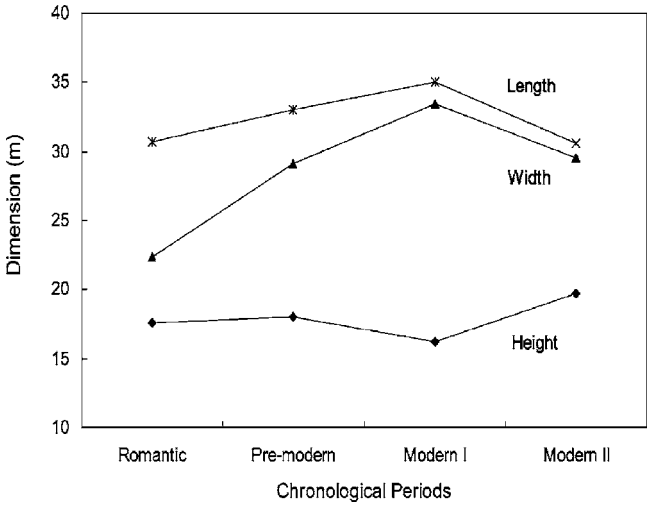


FIG. 2. Chronological trends in room dimensions.

C. Trends in room volume and room volume per seat

The overall trend in room volume generally follows the seating capacity across time periods. See Table V and Fig. 1(b). The average room volume increased from approximately 16200 to 21500 m^3 until the Modern I Period. It has stayed the same or decreased slightly since then. The average room volume per seat however was maintained at about 7.7 m^3/seat during the Romantic and Pre-Modern Periods. It has tended to increase gradually by 1.35 m^3/seat per period since then. See Table V and Fig. 1(c). The value of 10.2 m^3/seat reached during the last period (Modern II) is the highest in all time periods.

To summarize prime features observed in the architectural indices of seating capacity, volume and volume per seat during the last chronological period (Modern II) compared to Modern I, the seating capacity decreased by approximately 16% (400 seats) while the room volume decreased by only 2% (450 m^3). On the other hand, the room volume per seat increased by approximately 17% (1.5 m^3/seat).

D. Trends in room dimensions

Room length and width change similarly over the time periods. See Table V and Fig. 2. The average room length and width increased until the Modern I Period to maximum values of 35.1 and 33.5 m, respectively, and decreased to 30.6 and 29.5 m, respectively, since then. On the contrary, the average room height slightly decreased until the Modern I Period. It increased to about 20 m during the Modern II Period. The increase in width and length observed until the Modern I Period seems related to the increase in the number of large scale fan-shaped halls. In fact, the average values of width and length obtained in the fan-shaped halls are larger by about 7 and 3 m, respectively, in comparison to the overall average values obtained in the 71 halls total. Further, the chronological trend in room volume was found to have a significantly closer relationship with room width than length. See Figs. 1(b) and 2. The statistical correlation coefficient of *adjusted R-square* between room volume and room width is 0.71 at 95% confidence level.

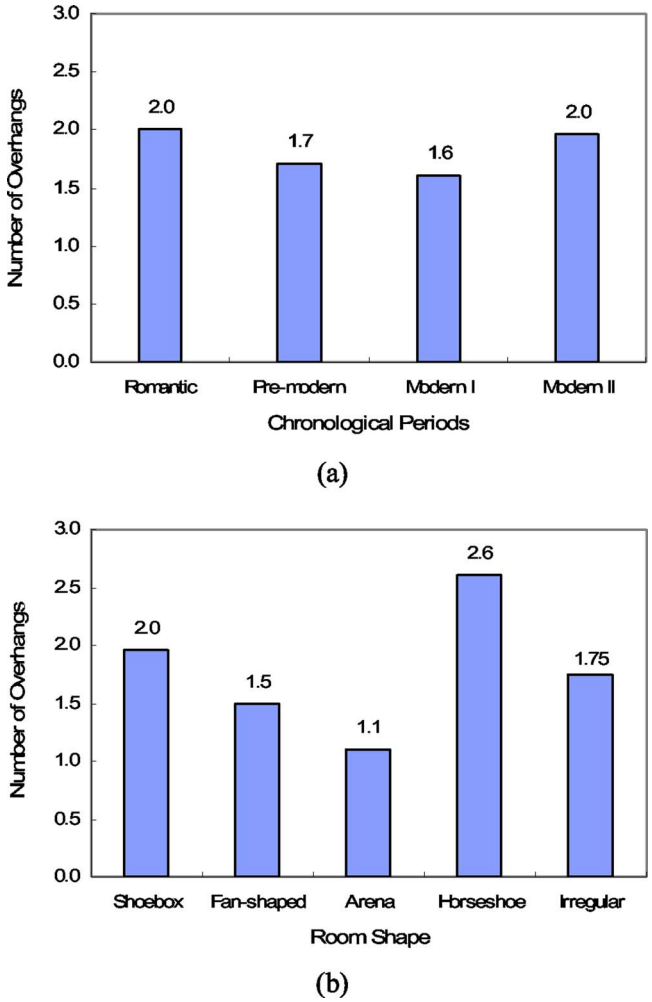


FIG. 3. (Color online) Average number of rear balcony overhangs. (a) Chronological trend in number of rear balcony overhangs. (b) Average number of rear balcony overhangs versus room shape.

V. CHRONOLOGICAL PHASES IN BALCONY OVERHANG DESIGN INDICES

A. Trend in number of rear balcony overhangs

In the following examination of balcony overlays, simply raised or parterre seating is excluded. The last two centuries (Romantic to Modern II Periods) have seen insignificant change in average number of rear balcony overhangs. See Fig. 3(a). The average number of rear balcony overhangs in the 71 halls studied here is 1.8. Thus, music performance halls of the sizes examined usually include about two rear balcony overhangs. The number of rear balcony overhangs in the Modern I Period is slightly lower and those in both Romantic and Modern II Periods are slightly higher than the overall average.

The average number of rear balcony overhangs seems to be greatly influenced by room shape. As shown in Fig. 3(b), the arena halls generally have only one rear balcony overhang, while the horseshoe style halls usually have three overhangs. There are one or two overhangs in the fan-shaped halls. For example, as shown in Fig. 3(a), the average number of rear balcony overhangs in the Modern I Period is below the overall average. This resulted from the fact that there are many fan-shaped or arena halls (11 halls out of 23 halls), which have fewer overhangs, but few horseshoe halls are found in this period.

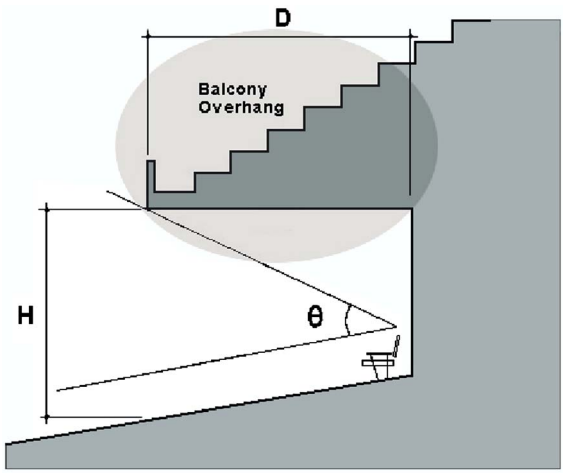


FIG. 4. (Color online) Geometric features of a balcony overhang. *D*: depth of balcony overhang, *H*: opening height, and θ: vertical angle of view.

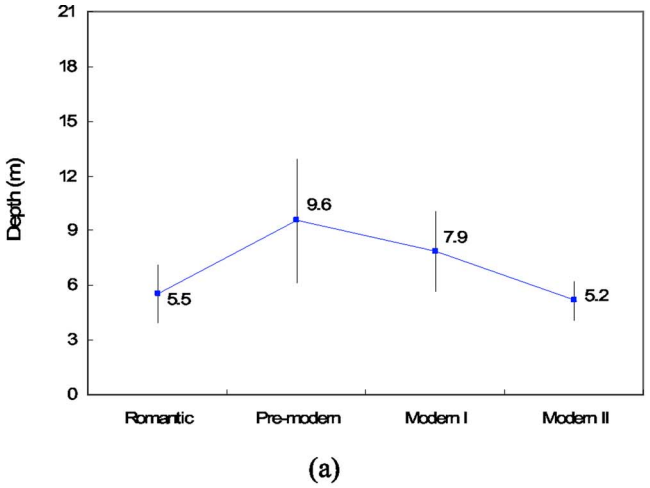
B. Trends in overhang depth (*D*), opening height (*H*), and *D*/*H* ratio

Geometric features of a generic balcony are annotated in Fig. 4. Over the last two centuries, insignificant changes in the average balcony overhang height (*H*) measured at the opening aperture occurred. See Fig. 5. However, there have

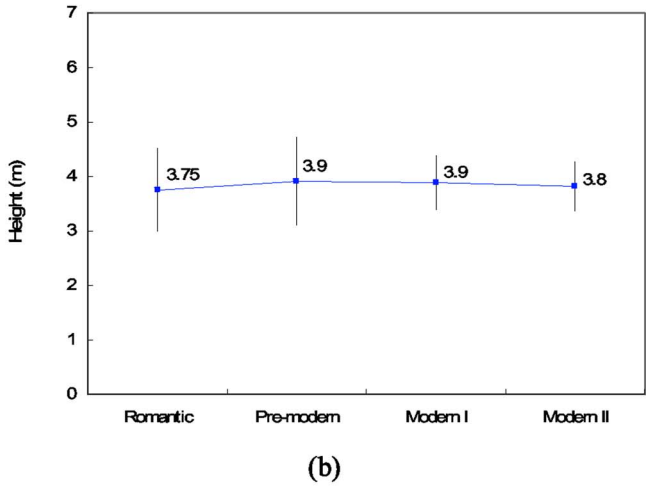
TABLE VI. Chronological trends in acoustical indices I (average values, unoccupied values, or noted otherwise).

Chronological periods[a]		RT (s) at mid: Occupied	RT (s) at mid: Unoccupied	EDT (s) at mid	BR	*G* (dB) at mid	ITDG (ms)
Romantic (1821–1900)	9 halls	1.81	2.42	2.42	1.14	5.2	20
Pre-modern (1901–1950)	11 halls	1.61	1.91	1.96	1.18	3.8	28
Modern I (1951–1980)	23 halls	1.76	2.10	1.96	1.05	2.8	26
Modern II (1981–2000)	27 halls	1.94	2.30	2.21	1.11	3.3	29
Overall	71 halls	1.82	2.21	2.15	1.11	3.5	26
(Without Albert Hall)		1.81	2.20	2.14	1.11	3.6	26
(Without Albert Hall and Music Shed)		1.81	2.18	2.12	1.11	3.6	27

[a]Royal Albert Hall and Music Shed were excluded from the periods of Romantic and Modern I, respectively.



(a)



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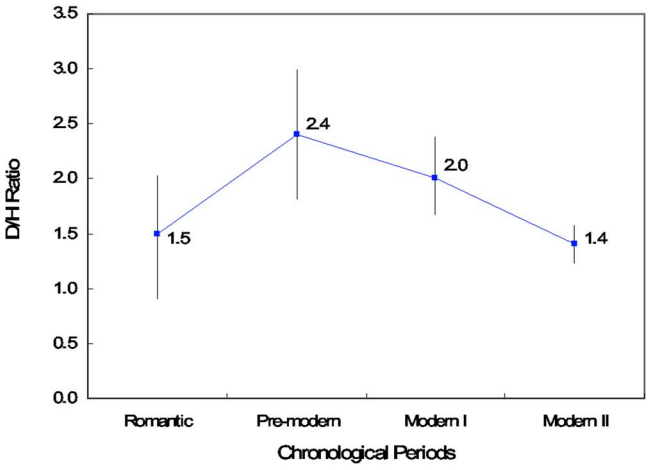

(c)

FIG. 5. (Color online) Chronological trends in balcony overhang design indices with 95% confidence intervals. (a) Overhang depth (D), (b) overhang opening height (H), and (c) depth to height (D/H) ratio.

been remarkable changes in average of D/H ratios along with remarkable changes in average overhang depth (D). The values of these two indices—average D and D/H ratio—grew significantly until the Pre-Modern Period, and have noticeably decreased since then. For example, the D/H ratio increased from approximately 1.5 to 2.4 for the halls constructed during the Pre-Modern Period, and decreased to 1.4

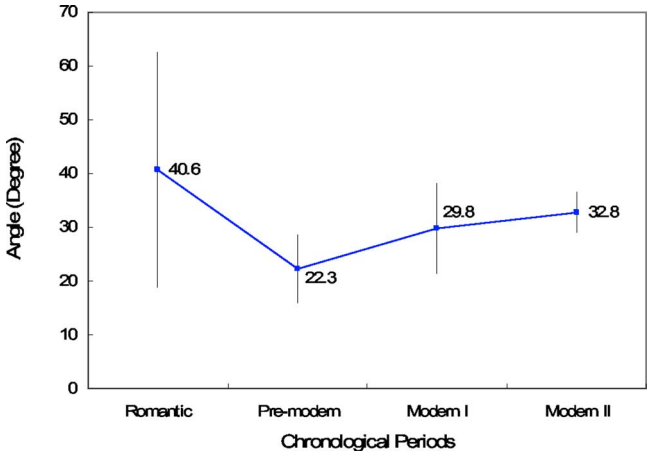

FIG. 6. (Color online) Chronological trend in vertical view angle with 95% confidence intervals.

for the halls opened in the Modern II Period. A primary reason for the former ascending tendency can be inferred from the increase in number of deep balcony overhangs found in fan-shaped halls. In fact, 6 halls (55%) out of 11 halls found in the Pre-Modern Period are fan-shaped, and the average D of these fan-shaped halls reaches 11.1 m. This depth is unusually larger, being deeper by 65% (4.4 m) than the overall average depth of the 71 halls, which is 6.7 m. The increase in number of arena halls (refer to Table IV), which have rather a shallow overhang depth (4.7 m on average), appears reasonable for the latter descending tendency observed both in average D and D/H ratio since the Pre-Modern Period.

C. Trend in vertical angle of view (θ)

As shown in Fig. 6, the trend in vertical angle of view (θ) was found contrary to the trend in overhang depth (D) or D/H ratio discussed earlier. Audience seated at the deepest row under the balcony constructed during the Pre-Modern Period was exposed to a quite narrow vertical view angle of approximately 22°. The average θ has increased to approximately 33° as the D and the D/H ratio have decreased since then.

VI. CHRONOLOGICAL PHASES IN ROOM ACOUSTICAL INDICES

The chronological changes in the room acoustical indices are specified in Tables VI and VII. The acoustical indices examined here are based on the unoccupied data. Otherwise, a description is added in the following discussion—for example, occupied RT.

Trends in RT, EDT, G, and C80. Average values both in EDT and occupied RT decreased to approximately 1.95 and 1.6 s, respectively, from the Romantic through the Pre-Modern Periods but since have gradually increased. See Figs. 7 and 9(a). Those values increased by approximately 0.25 and 0.3 s, respectively, during the Modern II Period compared to the Pre-Modern Period. On the contrary, the C80 trend has an inverse relationship to the EDT or occupied RT trend over periods. The average value of C80 increased

TABLE VII. Chronological trends in acoustical indices II (average values, unoccupied values, or noted otherwise).

Chronological periods[a]		C80 (dB) 500–2000	LF_E 125–1000[b]	IACC 500–2000 $IACC_E$[c]	IACC 500–2000 $IACC_L$	BQI (1-$IACC_E$)
Romantic (1821–1900)	9 halls	−2.1	0.19	0.42	0.14	0.58
Pre-modern (1901–1950)	11 halls	0.5	0.16	0.45	0.23	0.55
Modern I (1951–1980)	23 halls	−0.3	0.16	0.53	0.13	0.47
Modern II (1981–2000)	27 halls	−0.9	0.19	0.42	0.15	0.58
Overall	71 halls	−0.7	0.17	0.45	0.15	0.55
(Without Albert Hall)		−0.7	0.17	0.45	0.15	0.55
(Without Albert Hall and Music Shed)		−0.7	0.18	0.44	0.15	0.56

[a]Royal Albert Hall and Music Shed were excluded from the periods of Romantic and Modern I, respectively.
[b]Early lateral energy fraction in 80 ms.
[c]Early interaural cross correlation in 80 ms.

from −2.1 to 0.5 dB during the Pre-Modern Period and has gradually decreased to −0.9 dB since then. See Fig. 9(c). The trend in *G* value was found to be somewhat different from those observed in the above-mentioned acoustical indices. The average *G* value decreased by 2.4 dB from 5.2 to 2.8 dB from the Romantic to the Modern I Periods and then increased by 0.5 dB in the Modern II Period. Figure 8(b) shows the trend in *G*.

VII. CORRELATIONS BETWEEN ARCHITECTURAL DESIGN INDICES AND ROOM ACOUSTICAL INDICES

Fairly robust relationships exist between trends in several architectural indices and acoustical indices across chronological periods. First, the trend in acoustical index of *G* has a close relationship with room volume or room width. Those relationships are compared in Fig. 8. The *G* values decreased from the Romantic through Modern I Periods, as the room volume and the room width increased, and the *G* values have increased since then, as the room volume and width have decreased. The statistical correlation coefficient of *adjusted R-square* at 95% confidence level is 0.87 between *G* and room volume, and is 0.95 between *G* and room width. As stated earlier, the *adjusted R-square* between room volume and room width is 0.71.

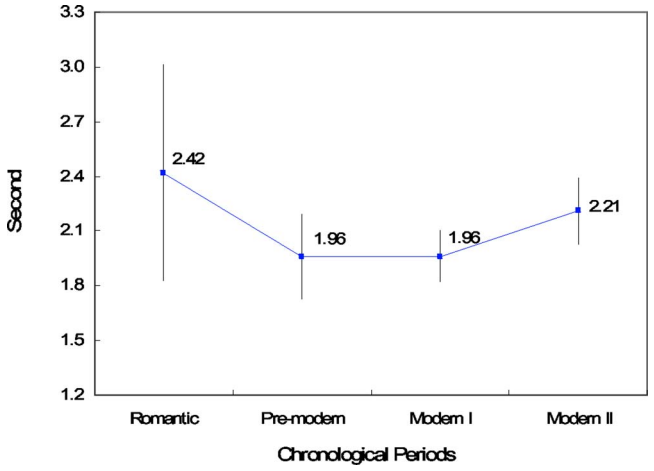

FIG. 7. (Color online) Chronological trend in EDT at midfrequencies with 95% confidence intervals.

Second, early IACC ($IACC_E$) follows trends in both room width and room length. However, the above-noted relationship may not be clearly identified in a statistical way due to the limited $IACC_E$ data obtained in each of the time periods.

Third, Fig. 9 compares the trends in room volume per seat with occupied RT and C80. Statistical analysis on this comparison showed that these variables are also closely related to each other. The occupied RT has increased and the C80 has decreased in the 20th Century from the Pre-Modern through the Modern II Periods, as the room volume per seat has increased. The *adjusted R-square* at 95% confidence level is 0.58 between the room volume per seat and the occupied RT averaged through each of the chronological periods.

VIII. CONCLUSIONS

Statistically significant correlations in trends of architectural and acoustical indices in halls for music performance are observed from the 18th through 20th Centuries. Some indices among them are strongly correlated with each other. Note that, from the basic statistical results, large deviations are found among several architectural indices within some of the chronological periods, such as balcony overhang design indices of vertical view angle (θ) and number of balcony overhangs. The average number of rear balcony overhangs in the Modern I Period is 1.6 and its standard deviation is 1.0. Therefore, the chronological classification method used for these architectural design indices of balcony overhangs does not appear to be established. As discussed in the text, these balcony overhang design indices are primarily dependent on room shapes prevalent in each chronological period.

To summarize the statistically significant correlations among architectural and acoustical indices observed across the chronological periods identified, first, the chronological trends between average room volume and average room width were found to be closely correlated with each other. Second, the trend in acoustical index of *G* has a strong relationship with both room volume and room width. In particu-

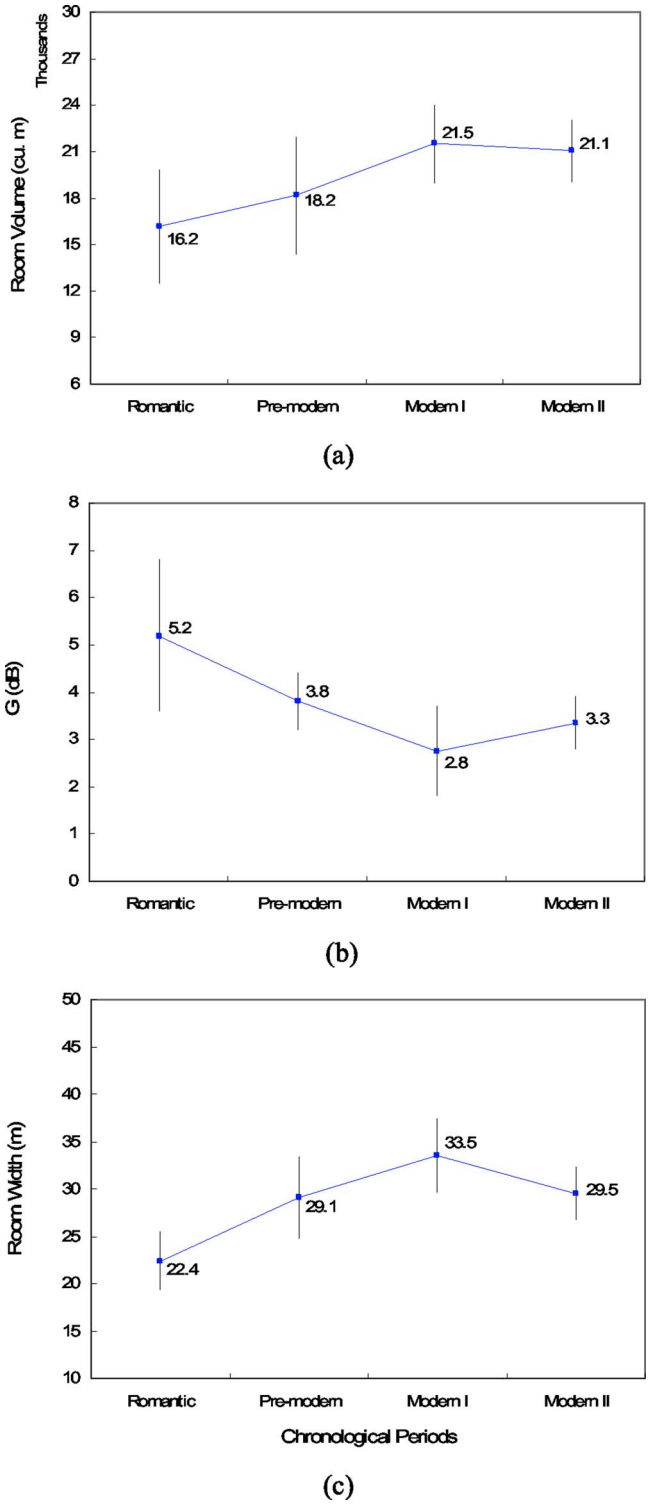

FIG. 8. (Color online) Comparison of the chronological trends of G with room volume and width with 95% confidence intervals. (a) Room volume, (b) G, and (c) room width.

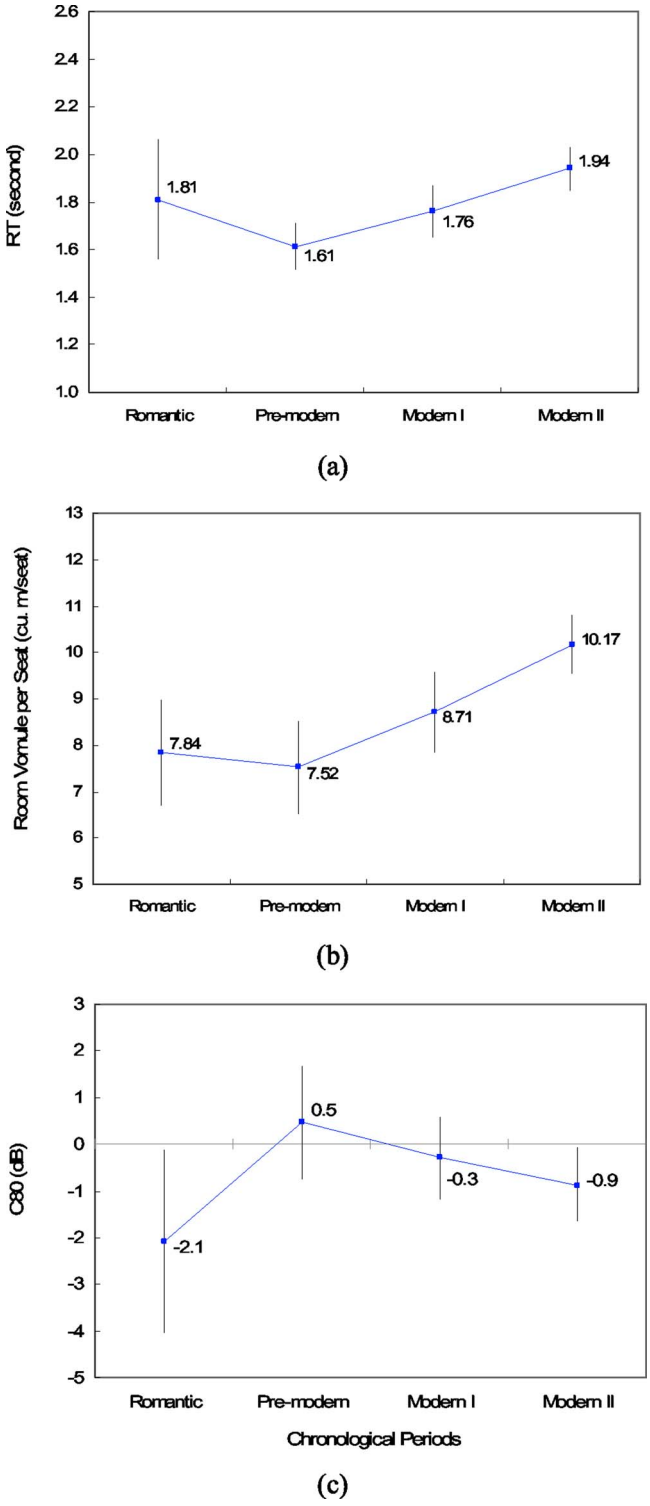

FIG. 9. (Color online) Comparison of the chronological trends of room volume/seat with occupied RT and C80 with 95% confidence intervals. (a) Occupied RT, (b) room volume per seat, and (c) C80.

lar, the statistical correlation coefficient of *adjusted R-square* between G and room width reaches 0.95 at 95% confidence level. Third, the trends observed in acoustical index of either average occupied RT or average C80 were found to be closely related to the trend in average room volume per seat. Last, $IACC_E$ has relationships following room width and length. The above-mentioned relationships argue that some acoustical indices are strongly dependent on several specific architectural design indices for music performance halls.

Over the past two decade modern period (Modern II: 1981–2000), seating capacity, width, and length have all trended toward reduction even as the room volume has remained relatively constant. This resulted in an increasing room volume per seat ratio. Music performance halls of the

sizes examined generally include two balcony overhangs at the back. The average D and D/H ratio of the first rear balcony overhangs tended to be lower than in prior periods. The average D/H ratio in particular was reduced to approximately 1.4, which is the lowest value over all chronological periods. Notably, acoustical quality has generally improved through the latter half of the 20th Century compared to the former half. The average occupied RT obtained in the past two decades reaches 1.94 s, which is the highest value ever in all periods. The average unoccupied RT and the average EDT are 2.3 and 2.2 s, respectively. These are higher by approximately 0.1 and 0.05 s, respectively, than the overall averages of the 71 halls. The average BQI (1-IACC$_E$) is 0.58, or slightly higher than the overall average of the 71 halls, and the average G and C80 values are 3.3 and −0.9 dB, respectively.

Architectural design development of a performance hall will be continuously linked closely with advancement of room acoustical technologies. Reviewing and understanding of the above-mentioned trends and relationships identified among architectural design indices and room acoustical indices in history should contribute toward acousticians and architects in their new design development.

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