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Neural network predictions of acoustical parameters in multi-purpose performance halls

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A detailed binaural sound measurement was carried out in two multi-purpose performance halls of different seating capacities and designs in Hong Kong in the present study. The effectiveness of using neural network in the predictions of the acoustical properties using a limited number of measurement points was examined. The root-mean-square deviation from measurements, statistical parameter distribution matching, and the results of a *t*-test for vanishing mean difference between simulations and measurements were adopted as the evaluation criteria for the neural network performance. The audience locations relative to the sound source were used as the inputs to the neural network. Results show that the neural network training scheme using nine uniformly located measurement points in each specific hall area is the best choice regardless of the hall setting and design. It is also found that the neural network prediction of hall spaciousness does not require a large amount of training data, but the accuracy of the reverberance related parameter predictions increases with increasing volume of training data.
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I. INTRODUCTION

Performance halls are important venues for conducting leisure and cultural activities for the well beings of the citizens. Their indoor environmental quality is playing a crucial role in affecting the delivery of their functions, and their acoustical performance has attracted the attention of many researchers and professionals in the past many decades (for instance, Barron[1] and Beranek[2]). Hong Kong is a densely populated city with limited flat land areas for urban development. The performance halls here are therefore usually used for both concerts, musicals, opera, and speech delivery (that is, as auditoria).

The importance of the acoustics of performance halls leads to the vigorous research and development of indices for the objective assessment of hall acoustical quality (for instance, Bradley[3]) apart from subjective assessments by experts (for instance, Giménez *et al.*[4] and Lokki *et al.*[5]). The reverberation time (RT) is the first index adopted probably because of its simplicity and extensive use in room acoustics design.[6] However, it has been accepted that RT is not the sole criterion for large hall design. Many other indices which are found to have correlations with subjective human feelings have been proposed in the past few decades. The clarity (C_{80}) and definition (D_{50}), which describe the early-to-late arriving sound energy ratio, were proposed by Reichardt *et al.*[7] and Thiele,[8] respectively, to cater for the balance between clarity and reverberation for improved intelligibility. Ando and Imamura[9] and Barron and Marshall[10] found that the interaural cross-correlation coefficient (IACC) has good correlation with subjective preference for sound field and the perceived spatial impression, respectively, while Hidaka *et al.*[11] suggested it to be a measure of concert hall acoustical quality. The index sound strength (G) describes the loudness of sound in a large hall.[6] Beranek[12] further discussed the importance of G in a recent study. The early decay time (EDT), which emphasizes the early portion of the sound energy decay, has also been proposed.[6] There are still many others, such as the early lateral fraction, apparent source width, and center times. Okano *et al.*[13] studied the relationship between IACC, the early lateral fraction, and the apparent source width in concert halls. The bass ratio (BR) has also been discussed.[14]

Many of the above-mentioned acoustical indices vary from location to location inside a large performance hall and are binaural in general. However, it is very time consuming to carry out extensive measurements of these indices in a performance hall. The measurements done by Barron and Lee[15] and the monoaural measurements of Akama *et al.*[16] are certainly the most extensive two in existing literature to the knowledge of the authors. Since the acoustical properties are functions of spatial locations[15,16] and binaural differences are expected while it is impractical to carry out numerous measurements inside a hall for its evaluation, a neural network analysis is used in the present study to examine the effectiveness of predictions using a limited number of measurements. A relatively typical performance hall and a less typical one are included in the present study. They are named Hall A and Hall B, respectively, in the foregoing discussions. It is hoped that a simple framework for evaluating the acoustical properties of performance halls can be established.

II. HALL DETAILS AND MEASUREMENT SETUP

Hall A is of the typical design with a rectangular layout and a seating capacity of 1372 (stall: 589, upper stall: 443, balcony: 340), while Hall B is a smaller hall with a fan-like

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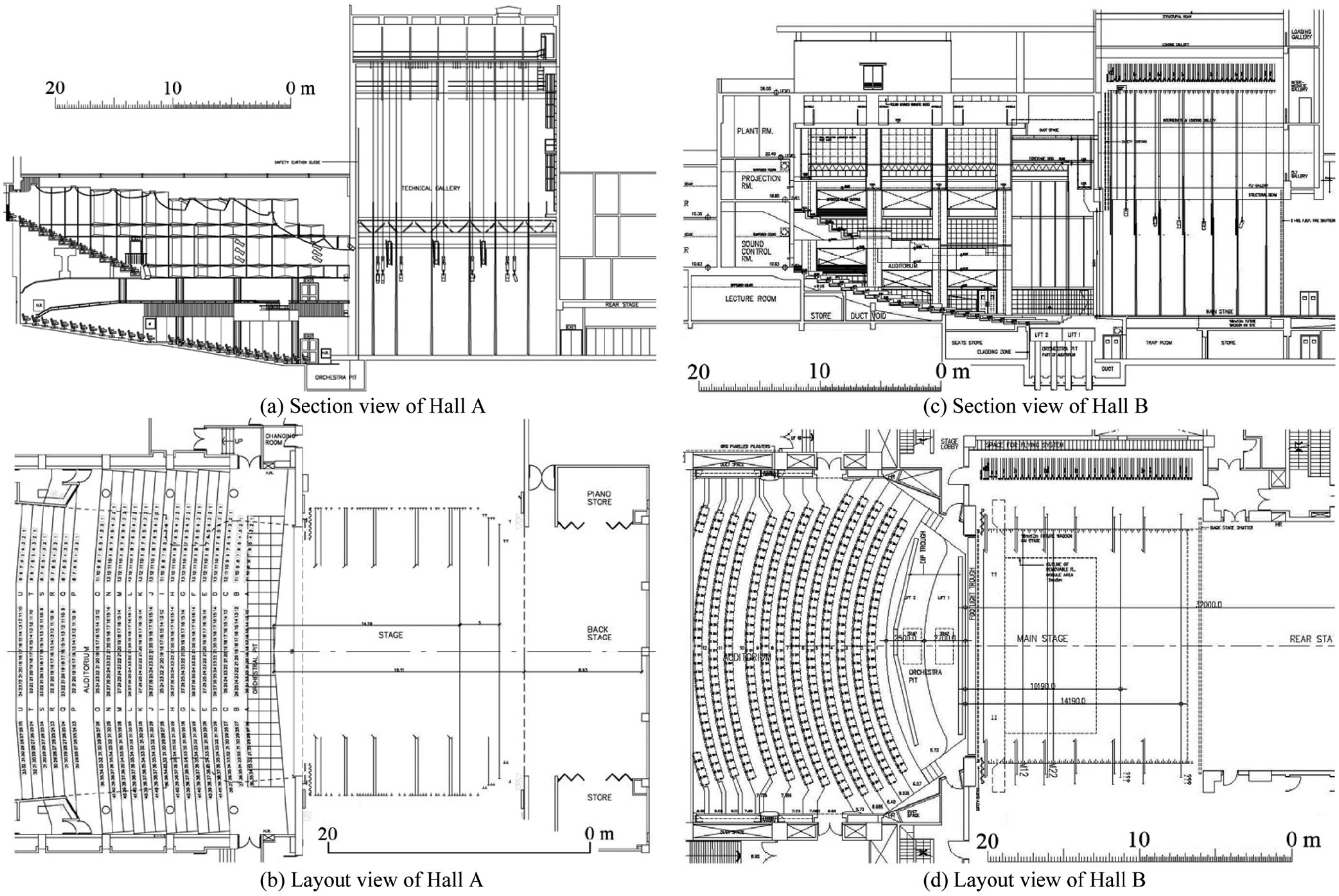

(a) Section view of Hall A
(c) Section view of Hall B
(b) Layout view of Hall A
(d) Layout view of Hall B

FIG. 1. Section and layout views of Hall A and Hall B.

seating layout and a seating capacity of 919 (stall: 527, upper stall: 203, balcony: 189). Figure 1 illustrates the designs and dimensions of these two performance halls. The walls of these halls, except those areas between the first audience row and the stage, are covered by soft materials and the floor by wood tiles. However, the balcony edge and parapet follow the curvature of the seating plan, which is different for the different halls. Both the proscenium and concert hall settings of these halls are included in the present study.

Binaural measurements using a Brüel & Kjær type 4100 Head-and-Torso Simulator (HATS) were used to capture the sound fields inside the hall generated by a Brüel & Kjær type 4296 omnidirectional sound source located 1 m inward from the edge of the stage on the stage centerline. The source was set at the height level of a standing human's mouth (1.6 m). The maximum length sequence procedure implemented by the DIRAC system[17] was used to obtain the binaural sound decay patterns. Each measurement lasted for 5.5 s and it was found that a longer measurement duration of 10.9 s did not result in significant differences in the data. The DIRAC software calculated the acoustical indices C_{80}, D_{50}, RT, EDT, and IACC in octave bands. The formulas for these indices can be found in BS EN ISO 3382 (Ref. 18) and some standard textbooks such as Kutturff.[6] Thus, they are not presented here. During the measurements, the signal-to-noise ratios were all kept higher than 20 dB over the whole audio frequency range. The background noise level was around 30 dBA and the generated sound levels varied from 70 to 80 dBA during the measurements.

A total of 182 (stall: 73, upper stall: 56, balcony: 53) and 84 (stall: 48, upper stall: 18, balcony: 18) binaural measurements were carried out inside Hall A and Hall B, respectively, so as to provide sufficient data for the neural network training and error analysis. These measurement points were basically evenly distributed inside each hall area (Fig. 2). Although the number of measurement locations is just about 10% of the total hall capacity, their distributions should already be sufficient to reflect the acoustical properties of the halls. Although Barron[19] suggests that the RT is relatively uniform inside a concert hall, the acoustical properties inside the current multi-purpose performance halls are believed to be location dependent. In the present study, a spherical co-ordinate system centered at the sound source is adopted (Fig. 3). The inputs to the neural network analysis are the distance between the receiver and the source d, the azimuthal angle ϕ, and the elevation angle θ.

III. NEURAL NETWORK ANALYSIS

The acoustic propagation inside a large hall with balconies is too complicated for analytical study. Thus, the artificial neural network approach appears very useful in finding out the functional relationships between various parameters though in rather implicit formats (for instance, Nannariello

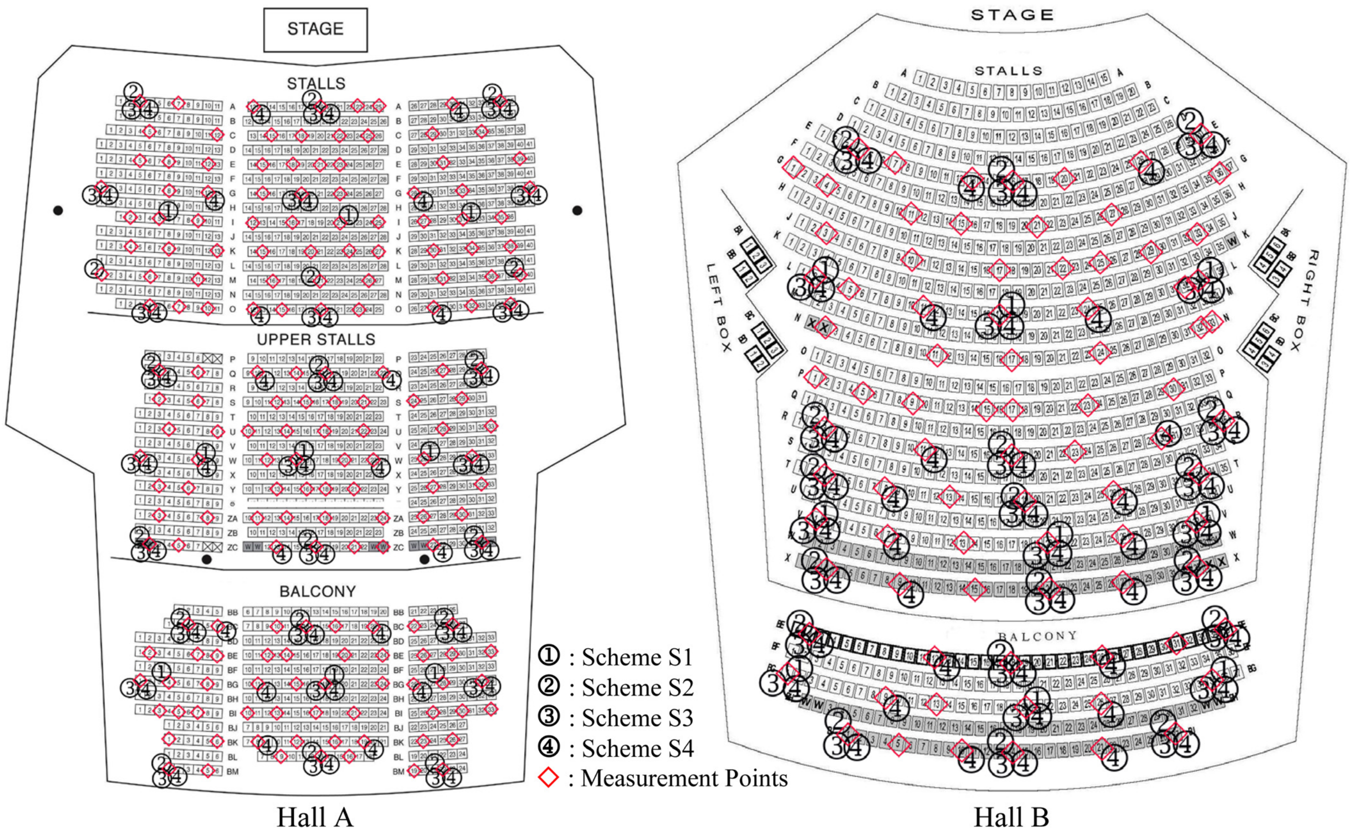

FIG. 2. (Color online) Measurement point distributions in performance halls and the four training schemes adopted.

and Fricke[20] and Lu and Kang[21]). There are many different algorithms in existing literature as indicated in Genaro *et al.*[22] and for simplicity, a feed-forward network with one hidden layer was adopted in the present study. The transfer functions used in the hidden and output layers were of the tan-sigmoid and linear types, respectively. No input weighting and bias were applied and the number of neurons in the hidden layer was arbitrarily chosen to be twice the number of inputs. The Levenberg-Marquardt algorithm was adopted as the training algorithm. The computation was implemented using MATLAB and the default stop criteria of MATLAB was adopted for each simulation.[23] The C_{80} results generated using two hidden layers for the concert setting case of Hall A were in general very similar to those obtained using one hidden layer, but the computation time was substantially longer. It is believed that this should also be the situation for the other parameters and thus the two hidden layer scheme was not chosen for the present study.

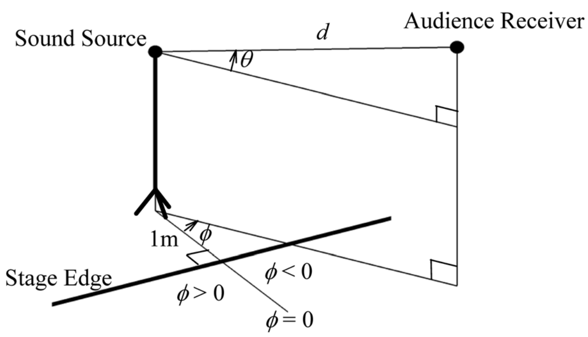

FIG. 3. Definitions of various angles and distances as inputs to neural network.

The effectiveness of neural network predictions by four different training schemes (denoted as S1, S2, S3, and S4)

TABLE I. Results of a paired comparison *t*-test for vanishing differences (95% confidence level).

Hall	Stage setting	Parameter	Octave band center frequency (Hz)						
			125	250	500	1000	2000	4000	8000
A	Concert	C_{80}	0.06	**4.03**	**12.3**	**9.16**	**3.99**	**2.59**	**2.93**
		D_{50}	0.95	**4.28**	**9.88**	**7.39**	2.18	0.98	0.81
		EDT	0.00	**2.47**	**6.71**	**3.09**	0.05	**3.43**	**4.00**
		RT	0.54	0.27	**2.71**	1.24	1.88	**2.82**	**4.06**
		BR		1.13			—	—	—
	Proscenium	C_{80}	0.15	0.31	1.00	0.09	1.28	2.16	**3.49**
		D_{50}	1.18	0.13	1.06	1.22	1.78	**2.60**	**3.64**
		EDT	1.60	0.80	0.38	0.95	0.17	0.70	**3.14**
		RT	0.22	2.01	0.56	0.27	0.30	0.56	2.09
		BR		0.86			—	—	—
B	Concert	C_{80}	1.27	0.16	2.10	0.42	0.33	0.77	0.54
		D_{50}	1.11	0.57	1.80	0.77	0.96	0.38	1.55
		EDT	0.54	0.57	0.79	0.90	0.72	0.47	1.90
		RT	1.55	0.36	0.28	1.19	0.30	0.06	**4.83**
		BR		1.42			—	—	—
	Proscenium	C_{80}	0.79	2.00	0.62	1.89	0.03	1.61	1.49
		D_{50}	0.48	**2.66**	0.58	**2.32**	0.35	1.27	2.26
		EDT	0.49	0.27	0.78	**2.69**	0.88	0.58	0.29
		RT	0.91	0.45	0.92	2.14	1.53	2.03	0.40
		BR		0.70			—	—	—

TABLE II(A). Simple statistics of the acoustical parameters of Hall A.

Stage setting	Parameter	Octave band center frequency (Hz)[a]						
		125	250	500	1000	2000	4000	8000
Concert	$C_{80,L}$ (dB)	0.13 (1.97)	0.84 (1.94)	1.34 (1.67)	1.36 (1.70)	0.55 (1.95)	2.06 (2.02)	2.75 (2.03)
	$C_{80,R}$ (dB)	0.13 (2.03)	0.64 (1.94)	0.55 (1.87)	0.64 (1.81)	0.17 (1.94)	1.68 (2.17)	2.27 (2.15)
	$D_{50,L}$	0.34 (0.12)	0.37 (0.11)	0.40 (0.11)	0.42 (0.11)	0.36 (0.12)	0.44 (0.12)	0.47 (0.11)
	$D_{50,R}$	0.34 (0.12)	0.36 (0.11)	0.36 (0.11)	0.38 (0.12)	0.35 (0.12)	0.44 (0.13)	0.46 (0.12)
	EDT_L (s)	1.44 (0.27)	1.28 (0.19)	1.24 (0.13)	1.47 (0.15)	1.42 (0.13)	1.25 (0.15)	1.07 (0.14)
	EDT_R (s)	1.44 (0.26)	1.29 (0.18)	1.28 (0.13)	1.49 (0.12)	1.42 (0.13)	1.28 (0.15)	1.11 (0.12)
	RT_L (s)	1.51 (0.12)	1.37 (0.08)	1.30 (0.04)	1.48 (0.04)	1.43 (0.03)	1.28 (0.04)	1.02 (0.03)
	RT_R (s)	1.51 (0.13)	1.37 (0.08)	1.31 (0.05)	1.47 (0.04)	1.43 (0.03)	1.29 (0.03)	1.03 (0.03)
	$IACC_{0,+}$	0.97 (0.02)	0.93 (0.02)	0.76 (0.07)	0.62 (0.12)	0.46 (0.13)	0.36 (0.15)	0.29 (0.11)
	$IACC_{0,80}$	0.98 (0.02)	0.96 (0.03)	0.83 (0.10)	0.71 (0.17)	0.57 (0.21)	0.52 (0.19)	0.41 (0.17)
	$IACC_{80,+}$	0.97 (0.01)	0.92 (0.03)	0.72 (0.06)	0.58 (0.06)	0.44 (0.06)	0.33 (0.07)	0.27 (0.05)
	BR	1.03 (0.06)				—	—	—
Proscenium	$C_{80,L}$ (dB)	1.86 (2.65)	3.20 (2.04)	3.83 (1.87)	3.82 (1.81)	3.89 (2.05)	5.31 (2.09)	5.51 (1.99)
	$C_{80,R}$ (dB)	1.85 (2.62)	3.17 (2.19)	3.72 (1.94)	3.83 (1.99)	3.71 (2.10)	4.90 (2.18)	4.87 (1.95)
	$D_{50,L}$	0.43 (0.15)	0.50 (0.13)	0.52 (0.10)	0.55 (0.11)	0.53 (0.12)	0.60 (0.12)	0.61 (0.12)
	$D_{50,R}$	0.44 (0.15)	0.49 (0.12)	0.52 (0.10)	0.54 (0.11)	0.51 (0.11)	0.57 (0.12)	0.56 (0.12)
	EDT_L (s)	1.23 (0.30)	1.08 (0.19)	1.03 (0.13)	1.17 (0.12)	1.11 (0.18)	0.98 (0.18)	0.86 (0.18)
	EDT_R (s)	1.25 (0.31)	1.09 (0.21)	1.02 (0.14)	1.16 (0.16)	1.10 (0.16)	0.99 (0.17)	0.91 (0.14)
	RT_L (s)	1.50 (0.25)	1.36 (0.13)	1.13 (0.06)	1.22 (0.04)	1.20 (0.05)	1.11 (0.04)	0.93 (0.03)
	RT_R (s)	1.50 (0.26)	1.34 (0.14)	1.13 (0.06)	1.22 (0.03)	1.20 (0.04)	1.11 (0.04)	0.94 (0.04)
	$IACC_{0,+}$	0.90 (0.06)	0.74 (0.10)	0.36 (0.14)	0.31 (0.16)	0.31 (0.13)	0.32 (0.14)	0.21 (0.10)
	$IACC_{0,80}$	0.93 (0.08)	0.83 (0.13)	0.57 (0.20)	0.51 (0.19)	0.52 (0.18)	0.50 (0.17)	0.36 (0.17)
	$IACC_{80,+}$	0.88 (0.06)	0.68 (0.10)	0.23 (0.11)	0.17 (0.07)	0.19 (0.08)	0.18 (0.07)	0.10 (0.03)
	BR	1.21 (0.15)				—	—	—

[a]Numbers not in parentheses represent mean values and those inside parentheses represent standard deviations.

TABLE II(B). Simple statistics of the acoustical parameters of Hall B.

Stage setting	Parameter	Octave band center frequency (Hz)[a]						
		125	250	500	1000	2000	4000	8000
Concert	$C_{80,L}$ (dB)	0.25 (2.08)	0.62 (1.87)	0.93 (1.50)	2.25 (1.00)	1.92 (1.01)	3.02 (1.32)	2.93 (1.27)
	$C_{80,R}$ (dB)	0.12 (2.02)	0.64 (1.97)	0.72 (1.21)	2.29 (1.04)	1.96 (1.22)	2.92 (1.65)	2.84 (1.44)
	$D_{50,L}$	0.34 (0.11)	0.36 (0.12)	0.39 (0.09)	0.50 (0.06)	0.46 (0.07)	0.53 (0.08)	0.49 (0.08)
	$D_{50,R}$	0.34 (0.12)	0.35 (0.12)	0.38 (0.08)	0.50 (0.07)	0.47 (0.08)	0.53 (0.11)	0.51 (0.10)
	EDT_L (s)	1.26 (0.21)	1.26 (0.18)	1.38 (0.12)	1.41 (0.10)	1.30 (0.08)	1.19 (0.11)	1.03 (0.09)
	EDT_R (s)	1.26 (0.21)	1.25 (0.18)	1.37 (0.10)	1.40 (0.11)	1.31 (0.08)	1.20 (0.13)	1.06 (0.09)
	RT_L (s)	1.26 (0.21)	1.26 (0.18)	1.38 (0.12)	1.41 (0.10)	1.30 (0.08)	1.19 (0.11)	1.03 (0.09)
	RT_R (s)	1.35 (0.10)	1.38 (0.08)	1.46 (0.04)	1.51 (0.03)	1.44 (0.02)	1.29 (0.03)	1.12 (0.02)
	$IACC_{0,+}$	0.90 (0.04)	0.80 (0.07)	0.42 (0.11)	0.32 (0.10)	0.19 (0.06)	0.20 (0.09)	0.14 (0.05)
	$IACC_{0,80}$	0.93 (0.06)	0.86 (0.10)	0.61 (0.13)	0.53 (0.13)	0.41 (0.11)	0.37 (0.13)	0.28 (0.09)
	$IACC_{80,+}$	0.89 (0.05)	0.77 (0.07)	0.33 (0.12)	0.15 (0.07)	0.09 (0.02)	0.09 (0.03)	0.07 (0.02)
	BR	0.83 (0.28)				—	—	—
Proscenium	$C_{80,L}$ (dB)	2.66 (2.25)	3.64 (2.59)	4.26 (2.04)	5.36 (1.67)	6.20 (2.18)	7.38 (2.63)	7.20 (2.12)
	$C_{80,R}$ (dB)	2.58 (2.32)	3.89 (2.40)	4.33 (1.96)	5.12 (1.78)	6.20 (2.34)	7.07 (2.76)	6.84 (2.32)
	$D_{50,L}$	0.47 (0.13)	0.53 0.14	0.55 0.12	0.58 0.11	0.62 0.12	0.66 0.12	0.66 0.11
	$D_{50,R}$	0.47 (0.13)	0.55 (0.13)	0.55 (0.12)	0.56 (0.12)	0.61 (0.13)	0.65 (0.12)	0.64 (0.11)
	EDT_L (s)	1.24 (0.27)	1.09 (0.21)	1.08 (0.17)	0.96 (0.16)	0.87 (0.19)	0.73 (0.20)	0.68 (0.16)
	EDT_R (s)	1.25 (0.28)	1.09 (0.23)	1.09 (0.15)	1.00 (0.13)	0.85 (0.19)	0.74 (0.18)	0.69 (0.15)
	RT_L (s)	1.81 (0.24)	1.52 (0.18)	1.35 (0.11)	1.25 (0.07)	1.15 (0.05)	0.99 (0.03)	0.82 (0.03)
	RT_R (s)	1.79 (0.26)	1.53 (0.18)	1.33 (0.09)	1.27 (0.06)	1.16 (0.04)	0.98 (0.04)	0.82 (0.03)
	$IACC_{0,+}$	0.91 (0.04)	0.81 (0.07)	0.47 (0.11)	0.39 (0.11)	0.36 (0.15)	0.37 (0.15)	0.26 (0.13)
	$IACC_{0,80}$	0.93 (0.05)	0.87 (0.11)	0.61 (0.14)	0.52 (0.13)	0.49 (0.17)	0.50 (0.16)	0.38 (0.15)
	$IACC_{80,+}$	0.90 (0.04)	0.75 (0.07)	0.32 (0.10)	0.25 (0.10)	0.23 (0.11)	0.24 (0.13)	0.15 (0.06)
	BR	1.28 (0.12)				—	—	—

[a]Numbers not in parentheses represent mean values and those inside parentheses represent standard deviations.

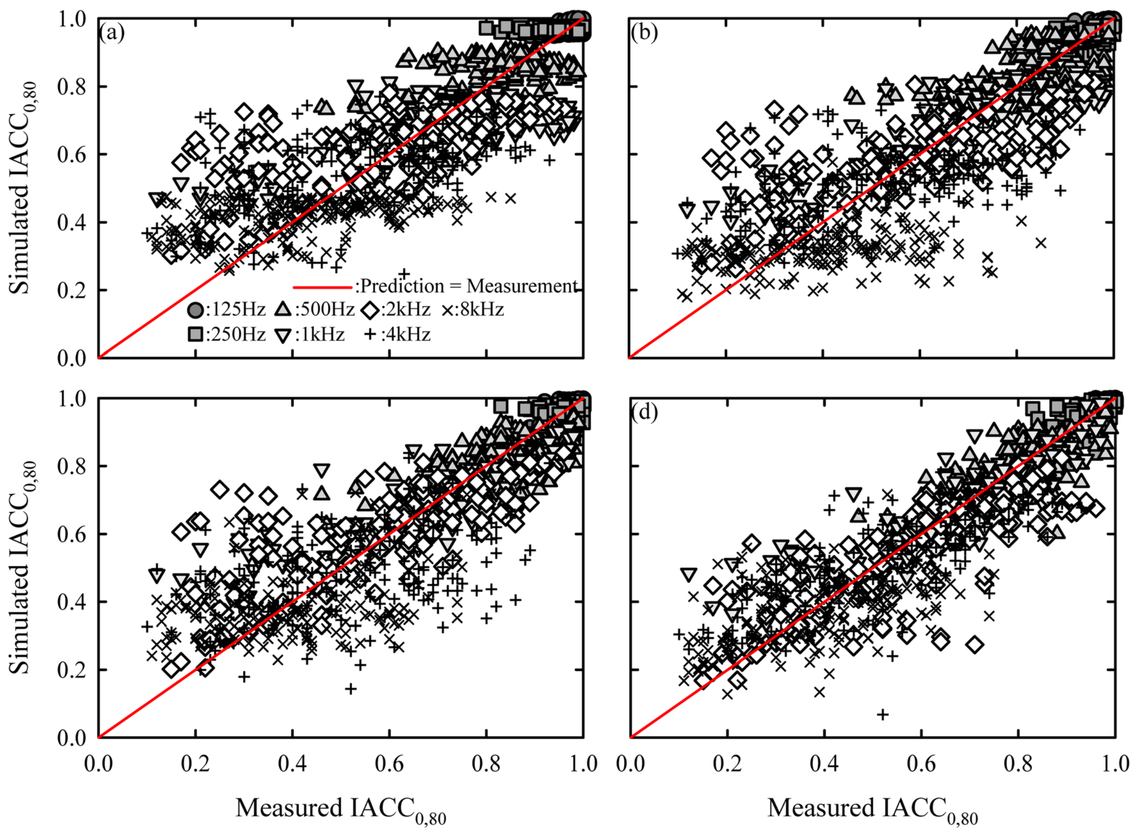

FIG. 4. (Color online) Comparison between simulated $IACC_{0,80}$ and measurements for Hall A under a concert setting. ○: 125 Hz; □: 250 Hz; △: 500 Hz; ▽: 1000 Hz; ◇: 2000 Hz; +: 4000 Hz; ×: 8000 Hz; ————: line of "simulation = measurement".

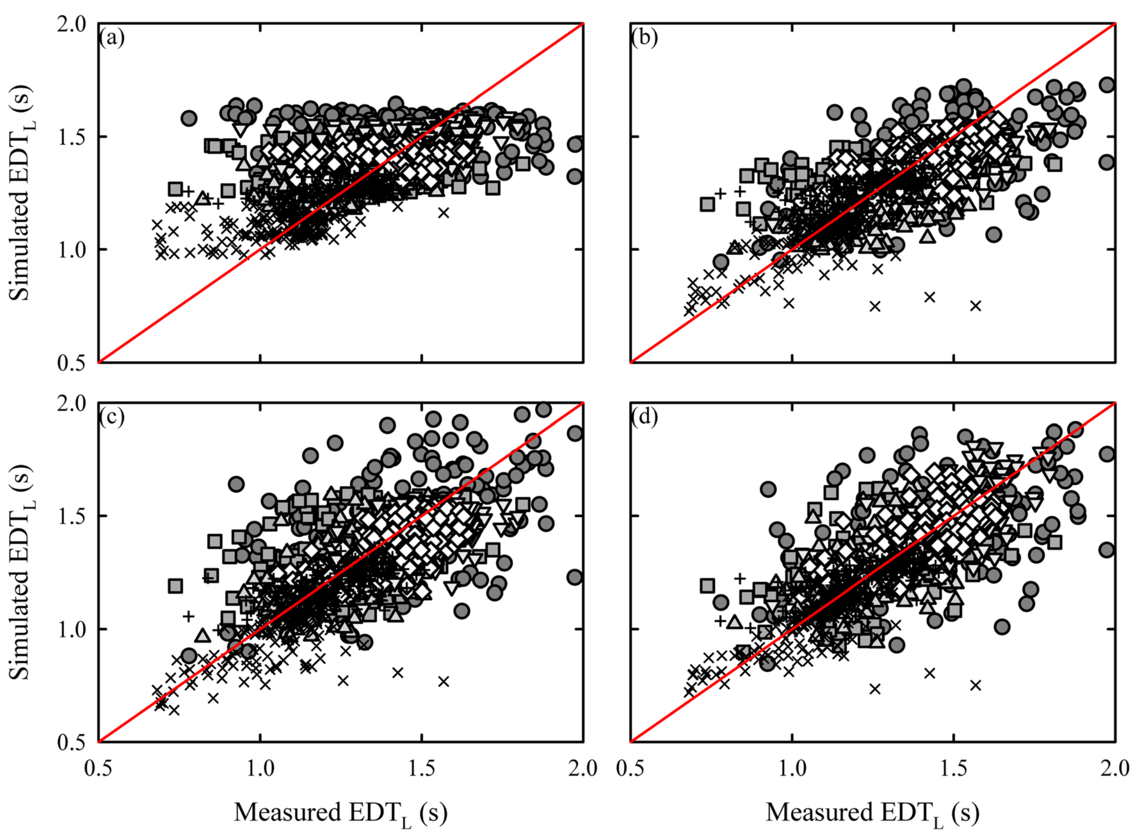

FIG. 5. (Color online) Comparison between simulated EDT_L and measurements for Hall A under a concert setting. Legends: Same as those for Fig. 4.

will be discussed. The measurement points used for providing training data to the neural network in these four schemes are shown in Fig. 2. S1 is the simplest scheme which includes three measurement points spanning basically evenly in the middle region of a particular sub-area in each hall. S2 includes measurement points on the near and far boundary (relative to the stage) of each sub-area, while S3 is a combination of S1 and S2. S4 requires the maximum number of training points and is basically S3 with a better span-wise resolution. S4 for Hall B is actually an undesirable option

TABLE III. Root-mean-square differences between simulations and measurements for Hall A.

		Octave band center frequency (Hz)[a]						
Scheme	Parameter	125	250	500	1000	2000	4000	8000
S1	$C_{80,L}$ (dB)	1.95/2.57	2.12/2.50	1.79/1.66	1.47/1.44	1.84/1.78	2.01/1.90	1.93/1.68
	$C_{80,R}$ (dB)	2.14/2.46	2.31/2.29	2.16/2.01	1.63/1.54	1.78/1.60	2.07/2.21	2.24/1.75
	$D_{50,L}$	0.12/0.16	0.13/0.14	0.10/0.09	0.09/0.09	0.12/0.10	0.12/0.12	0.11/0.13
	$D_{50,R}$	0.13/0.17	0.13/0.14	0.12/0.11	0.09/0.08	0.10/0.10	0.13/0.12	0.12/0.11
	EDT_L (s)	0.29/0.30	0.22/0.25	0.13/0.14	0.15/0.16	0.13/0.18	0.14/0.18	0.14/0.21
	EDT_R (s)	0.32/0.33	0.19/0.23	0.14/0.13	0.14/0.15	0.13/0.14	0.14/0.18	0.12/0.15
	RT_L (s)	0.15/0.26	0.08/0.15	0.04/0.06	0.05/0.04	0.03/0.04	0.03/0.04	0.03/0.03
	RT_R (s)	0.16/0.27	0.08/0.16	0.05/0.06	0.04/0.04	0.03/0.04	0.03/0.03	0.04/0.03
	$IACC_{0,+}$	0.01/0.05	0.02/0.09	0.06/0.14	0.09/0.11	0.12/0.12	0.13/0.14	0.11/0.10
	$IACC_{0,80}$	0.02/0.07	0.04/0.13	0.09/0.18	0.13/0.12	0.16/0.14	0.17/0.16	0.16/0.16
	$IACC_{80,+}$	0.01/0.05	0.02/0.11	0.05/0.13	0.06/0.07	0.06/0.07	0.06/0.07	0.06/0.03
	BR			0.07/0.13		—	—	—
S2	$C_{80,L}$ (dB)	1.77/1.83	2.10/2.16	1.19/1.11	0.98/0.95	1.57/1.28	1.54/1.68	1.31/1.45
	$C_{80,R}$ (dB)	1.86/1.90	1.73/2.11	1.14/1.27	0.87/0.94	1.48/1.54	1.51/1.82	1.36/1.36
	$D_{50,L}$	0.11/0.12	0.08/0.12	0.07/0.07	0.08/0.06	0.09/0.09	0.12/0.12	0.10/0.11
	$D_{50,R}$	0.12/0.13	0.09/0.12	0.07/0.08	0.05/0.07	0.07/0.10	0.10/0.13	0.09/0.11
	EDT_L (s)	0.23/0.28	0.17/0.18	0.13/0.13	0.14/0.11	0.10/0.17	0.13/0.16	0.12/0.17
	EDT_R (s)	0.23/0.31	0.17/0.19	0.12/0.13	0.12/0.13	0.12/0.16	0.12/0.16	0.09/0.14
	RT_L (s)	0.12/0.27	0.08/0.14	0.04/0.07	0.04/0.05	0.03/0.04	0.03/0.03	0.03/0.02
	RT_R (s)	0.16/0.27	0.09/0.16	0.05/0.06	0.04/0.04	0.03/0.03	0.03/0.02	0.03/0.03
	$IACC_{0,+}$	0.01/0.04	0.03/0.10	0.08/0.17	0.09/0.10	0.10/0.10	0.14/0.13	0.10/0.09
	$IACC_{0,80}$	0.02/0.06	0.03/0.10	0.10/0.19	0.11/0.11	0.15/0.11	0.18/0.14	0.18/0.14
	$IACC_{80,+}$	0.01/0.04	0.03/0.12	0.07/0.15	0.06/0.07	0.05/0.06	0.06/0.06	0.05/0.03
	BR			0.06/0.12		—	—	—
S3	$C_{80,L}$ (dB)	1.76/1.84	2.14/2.48	1.17/0.98	1.17/1.24	1.32/1.33	1.54/1.47	1.60/1.54
	$C_{80,R}$ (dB)	1.81/1.85	1.90/2.18	1.17/1.19	0.96/0.95	1.01/1.55	1.55/1.84	1.56/1.56
	$D_{50,L}$	0.10/0.12	0.08/0.12	0.06/0.06	0.07/0.08	0.10/0.09	0.11/0.10	0.11/0.10
	$D_{50,R}$	0.10/0.12	0.10/0.13	0.07/0.07	0.05/0.07	0.08/0.09	0.10/0.12	0.08/0.11
	EDT_L (s)	0.26/0.29	0.19/0.20	0.14/0.13	0.14/0.14	0.11/0.16	0.13/0.15	0.13/0.18
	EDT_R (s)	0.25/0.29	0.17/0.21	0.10/0.12	0.10/0.13	0.10/0.17	0.12/0.17	0.09/0.15
	RT_L (s)	0.14/0.24	0.10/0.15	0.04/0.06	0.04/0.04	0.03/0.03	0.04/0.03	0.03/0.03
	RT_R (s)	0.14/0.33	0.09/0.16	0.05/0.06	0.04/0.03	0.03/0.03	0.03/0.03	0.03/0.03
	$IACC_{0,+}$	0.01/0.04	0.03/0.10	0.06/0.13	0.08/0.09	0.09/0.11	0.14/0.11	0.11/0.07
	$IACC_{0,80}$	0.02/0.05	0.04/0.10	0.08/0.15	0.10/0.13	0.14/0.13	0.18/0.13	0.15/0.10
	$IACC_{80,+}$	0.01/0.05	0.03/0.11	0.05/0.12	0.06/0.07	0.05/0.06	0.06/0.06	0.06/0.03
	BR			0.06/0.13		—	—	—
S4	$C_{80,L}$ (dB)	1.52/1.72	1.50/2.09	1.11/0.94	0.98/0.92	1.27/1.04	1.25/1.18	1.27/1.15
	$C_{80,R}$ (dB)	1.59/1.87	1.54/2.00	1.27/1.03	0.71/0.91	0.88/1.19	1.08/1.46	1.19/1.31
	$D_{50,L}$	0.10/0.12	0.08/0.11	0.06/0.06	0.07/0.06	0.09/0.07	0.09/0.08	0.08/0.08
	$D_{50,R}$	0.10/0.12	0.08/0.11	0.06/0.06	0.05/0.06	0.07/0.08	0.08/0.09	0.08/0.09
	EDT_L (s)	0.24/0.24	0.16/0.16	0.13/0.12	0.11/0.09	0.10/0.16	0.12/0.15	0.12/0.18
	EDT_R (s)	0.25/0.26	0.15/0.17	0.11/0.13	0.10/0.12	0.10/0.12	0.09/0.16	0.08/0.15
	RT_L (s)	0.14/0.24	0.08/0.13	0.04/0.06	0.04/0.04	0.03/0.03	0.03/0.03	0.03/0.03
	RT_R (s)	0.13/0.29	0.08/0.16	0.04/0.06	0.05/0.03	0.03/0.03	0.03/0.03	0.03/0.03
	$IACC_{0,+}$	0.01/0.03	0.02/0.08	0.05/0.11	0.06/0.09	0.08/0.08	0.11/0.10	0.09/0.07
	$IACC_{0,80}$	0.01/0.04	0.03/0.09	0.07/0.14	0.08/0.10	0.12/0.11	0.13/0.13	0.13/0.11
	$IACC_{80,+}$	0.01/0.05	0.02/0.09	0.06/0.11	0.05/0.07	0.04/0.07	0.05/0.05	0.04/0.03
	BR			0.06/0.12		—	—	—

[a]Concert/proscenium.

because of the relatively large number of training points required in the upper stall and the balcony area due to Hall B being small.

The measured data, together with the corresponding spherical co-ordinates, form the outputs of and inputs to the network, respectively, during the training stage. The acoustical parameters at all the measurement points are then simulated using the trained networks. Owing to the difference in the layouts of the halls investigated, the data from the two halls are analyzed separately. There is then no need to separate the balcony and stall areas in the network analysis as the elevation angle θ should be sufficient for differentiating measurement points in the stall and the balcony sub-areas. It should be noted that the neural network simulation varies every time after the network is initialized.[23] Therefore, the simulated results for each scheme presented hereinafter are taken to be the arithmetic averages over many simulations. In the present study, 100 and 200 simulations are adopted for the study of the concert hall and proscenium setting, respectively, to ensure data convergence. The root-mean-square differences between simulations and measurements converge to within a tolerance comparable to that of measurement (not shown here).

IV. RESULTS AND DISCUSSIONS

The binaural measurement produced two sets of acoustical data at each measurement location—one from the left microphone and the other from the right one, except for the IACC. A Student-*t* test analysis was then performed to check whether there were significant differences between the left- and right-hand side data in the first place. Table I summarizes the *t*-test results obtained at 95% confidence level. For a two-tail test with a degree of freedom of 181, the critical *t*-value is 2.26, over which the null hypothesis of "vanishing mean difference" will be rejected. The corresponding critical *t*-value for a degree of freedom of 83 is 2.28. It is noticed that Hall A is not symmetrical acoustically under the concert stage setting, especially in the middle frequency band and at high frequencies. The hall is more symmetrical in terms of

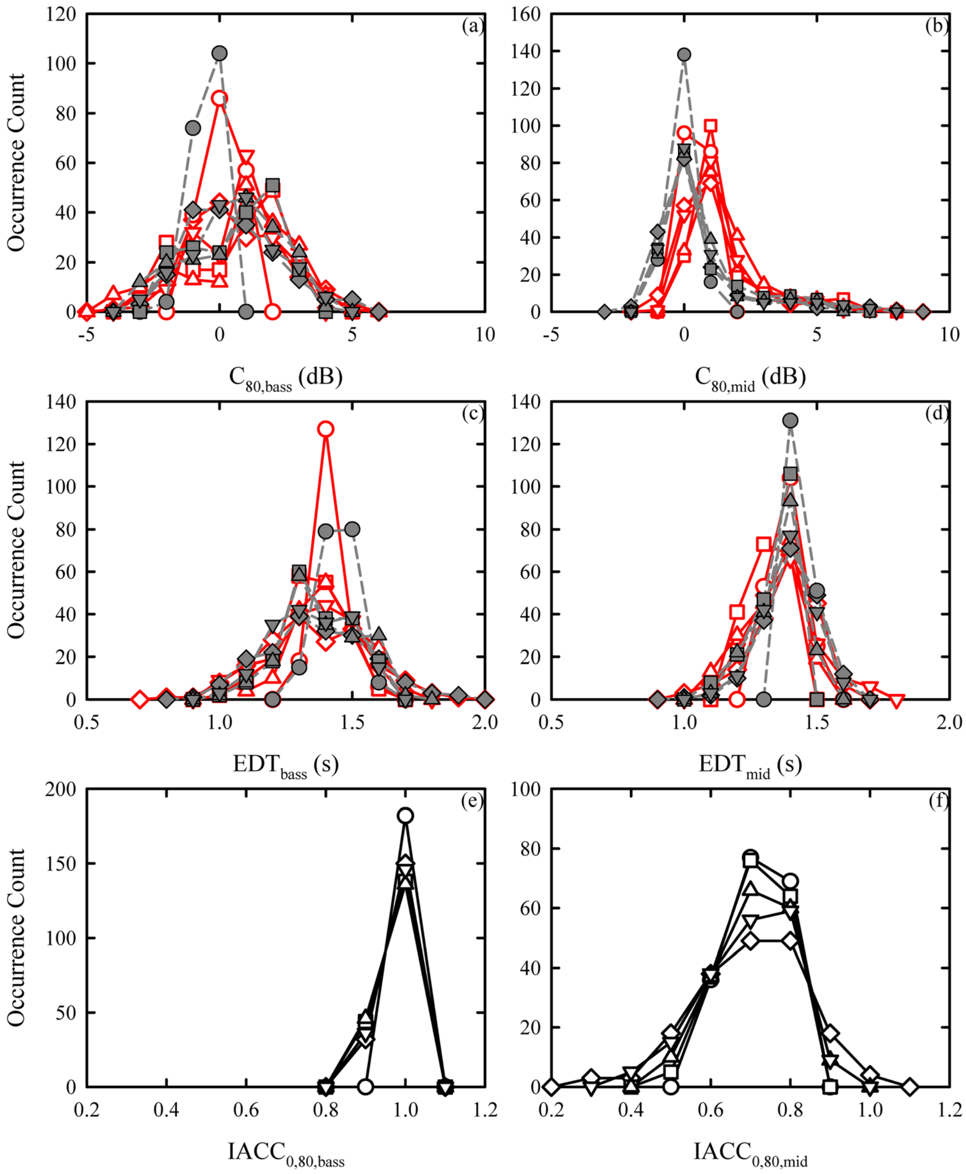

FIG. 6. (Color online) Statistical distributions of acoustical parameters under concert setting of Hall A. (a) $C_{80,\mathrm{bass}}$; (b) $C_{80,\mathrm{mid}}$; (c) $\mathrm{EDT}_{\mathrm{bass}}$; (d) $\mathrm{EDT}_{\mathrm{mid}}$; (e) $\mathrm{IACC}_{0,80,\mathrm{bass}}$; (f) $\mathrm{IACC}_{0,80,\mathrm{mid}}$. ◇: measurement; ○: S1; □: S2; △: S3; ▽: S4. Closed symbols: Right of HATS; open symbols: Left of HATS (except for $\mathrm{IACC}_{0,80}$).

acoustical properties in the proscenium stage case, and the symmetry basically becomes worse at higher frequencies. The corresponding symmetry of Hall B is acceptable. Owing to the asymmetry of the acoustical properties, the left and right microphone data from the HATS, except the BR, are analyzed separately in the present study. The BR data in the foregoing analysis are average between the left and right HATS microphone data. The source strength G is found to be well correlated with distance d if the data in the balcony and within the stall areas are separately analyzed (not shown here). There is thus no need to predict G using a neural network and it is therefore not included in the present study. In the present study, all the acoustical parameters, except G, do not show a significant dependence on distance d alone. In order to provide a general overview of the acoustical parameters and facilitate foregoing discussions, a summary of the simple statistics of the measured acoustical parameters is presented in Tables II(a) and II(b). The suffices L and R denote the left and right side of the HATS, respectively, in the foregoing discussions.

A. Hall A

1. Concert setting

The BR is a single value rating for a location inside the hall and thus it is discussed in the first place. Actually the BR does not vary much within the hall under the concert stage setting as indicated in Table II(a). The root-mean-square difference between the neural network predictions and the 182 measurements for training schemes S1, S2, S3, and S4 are 0.07, 0.06, 0.06, and 0.06, respectively. These values are very small as the BRs are around unity. It appears that S1 is not a bad option for evaluating the BR of the hall given its simplicity and acceptable prediction deviation.

The IACCs are frequency-dependent. Figure 4 shows the comparisons between the simulated $IACC_{0,80}$ [also denoted as $IACC_E$ (Ref. 9)] and the measured values for the four training schemes. The measured $IACC_{0,80}$ decreases but its range increases as frequency increases no matter which scheme is adopted. The differences between simulations and measurements also increase with frequency. One can observe that S4 gives the best performance while S1 results

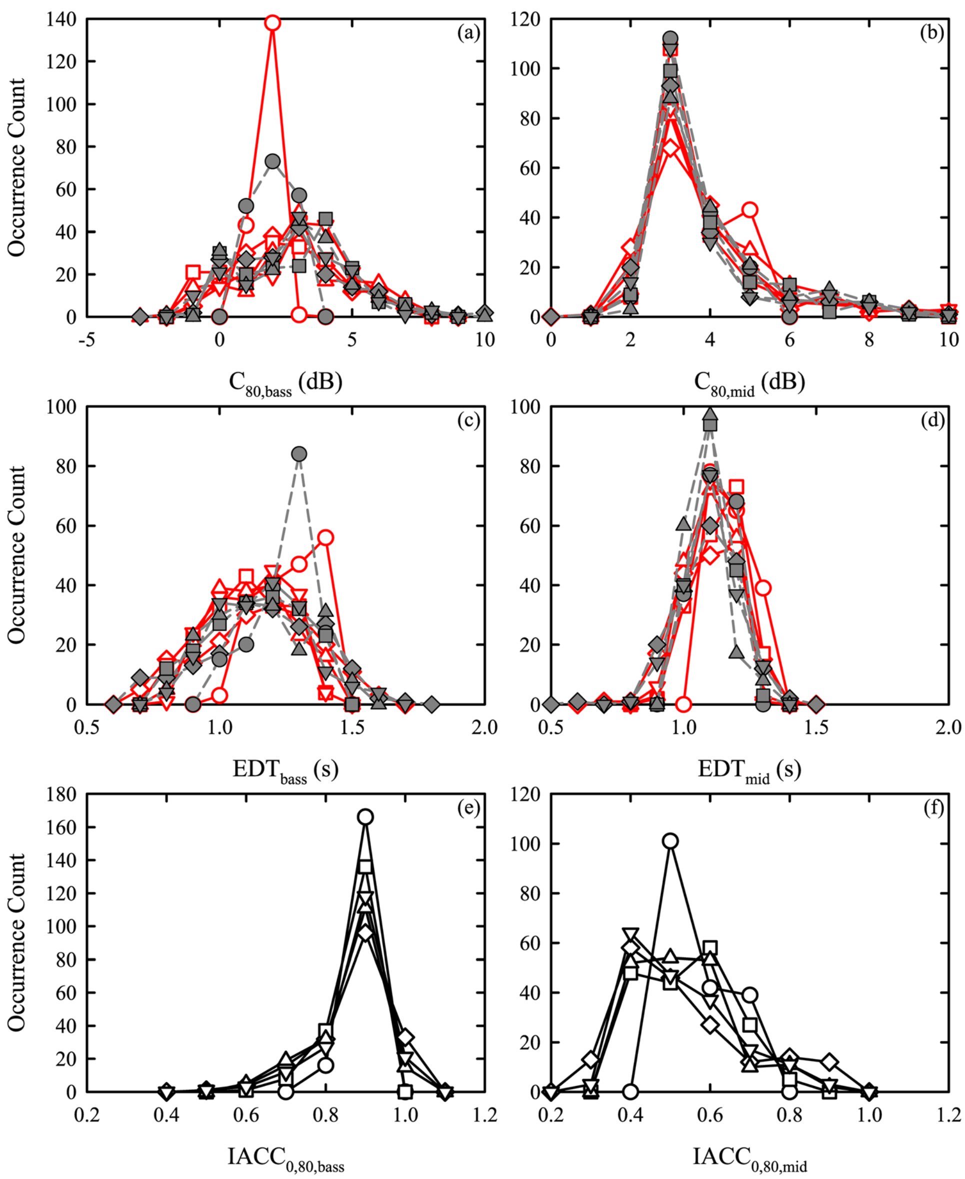

FIG. 7. (Color online) Statistical distributions of acoustical parameters under proscenium setting of Hall A. (a) $C_{80,bass}$; (b) $C_{80,mid}$; (c) EDT_{bass}; (d) EDT_{mid}; (e) $IACC_{0,80,bass}$; (f) $IACC_{0,80,mid}$. Legends: Same as those for Fig. 6.

in the worst. The performances of S2 and S3 are comparable, but S3 appears to be a slightly better scheme. The relative performance between the four schemes is not unexpected because of the number of data points put into the neural network training. However, the aim of the present study is to examine the possibility of using limited data points for the acoustical assessment of a performing hall and it will be discussed in detail later. It can be observed that the simulated $IACC_{0,80}$ values are all positive and are less than unity despite the lack of physical consideration in the neural network

TABLE IV. Paired *t*-test statistics for vanishing differences between simulations and measurements under a concert setting of Hall A (95% confidence level).

		Octave band center frequency (Hz)						
Scheme	Parameter	125	250	500	1000	2000	4000	8000
S1	$C_{80,L}$ (dB)	−1.28	−4.66	−4.68	−5.93	−5.13	−3.71	−6.55
	$C_{80,R}$ (dB)	−4.36	−7.88	−6.16	−1.75	−3.57	−6.55	−6.74
	$D_{50,L}$	−6.18	−4.72	−2.16	−7.67	−3.74	−1.15	−1.64
	$D_{50,R}$	−8.86	−4.69	−6.37	−5.07	−3.96	−5.26	−6.38
	EDT_L (s)	2.56	4.82	5.33	−0.46	−1.85	1.70	4.35
	EDT_R (s)	5.66	1.99	4.20	5.81	−0.71	1.52	0.31
	RT_L (s)	−7.67	−0.61	4.46	3.24	6.06	−0.05	0.05
	RT_R (s)	−8.55	2.47	−2.07	4.58	−4.92	2.98	−0.94
	$IACC_{0,+}$	−1.43	6.03	1.14	−0.76	5.57	1.48	0.75
	$IACC_{0,80}$	−0.66	5.32	3.15	−1.89	2.65	1.51	0.94
	$IACC_{80,+}$	−0.66	2.73	1.96	7.24	6.82	0.10	6.26
	BR			−6.02		—	—	—
S2	$C_{80,L}$ (dB)	4.05	−1.82	7.64	1.68	6.14	2.71	0.78
	$C_{80,R}$ (dB)	1.63	1.57	2.93	0.04	2.66	−1.11	−6.15
	$D_{50,L}$	0.77	−3.18	−0.29	−7.80	−2.16	2.16	0.17
	$D_{50,R}$	2.51	2.00	0.18	−2.17	0.86	0.99	1.03
	EDT_L (s)	−2.78	2.10	−7.91	−10.3	−3.05	3.19	−1.92
	EDT_R (s)	−1.85	2.60	−5.68	−11.5	−4.09	0.78	−1.16
	RT_L (s)	−0.85	2.38	0.56	−3.33	−0.71	−0.37	7.32
	RT_R (s)	7.59	3.32	−1.22	−4.03	2.45	3.31	−2.59
	$IACC_{0,+}$	2.00	−7.23	−0.23	1.96	2.78	5.39	−1.75
	$IACC_{0,80}$	0.49	−6.94	0.84	−0.37	0.79	−0.71	−5.55
	$IACC_{80,+}$	1.99	−6.79	0.77	8.52	1.99	2.31	2.74
	BR			4.16		—	—	—
S3	$C_{80,L}$ (dB)	0.09	1.84	5.16	7.79	2.20	2.77	4.38
	$C_{80,R}$ (dB)	−0.64	1.17	0.66	3.53	−2.30	0.98	1.67
	$D_{50,L}$	−2.21	−1.53	−2.45	−1.95	−4.34	−0.48	1.65
	$D_{50,R}$	−0.05	1.02	−1.26	−0.79	−6.50	−1.71	0.36
	EDT_L (s)	2.22	2.35	−0.86	−9.57	−6.46	−3.72	−5.88
	EDT_R (s)	0.91	1.76	0.39	−8.87	−7.65	−5.40	−7.12
	RT_L (s)	3.68	−2.06	−2.15	−3.29	−1.93	−1.22	−0.38
	RT_R (s)	2.06	1.51	−3.13	3.37	−0.67	−2.20	−1.59
	$IACC_{0,+}$	1.00	−4.73	−0.12	4.26	4.21	2.85	1.70
	$IACC_{0,80}$	−3.50	−4.36	−0.91	−0.40	1.96	−2.81	−0.72
	$IACC_{80,+}$	1.91	−1.16	1.67	8.87	1.20	3.14	4.03
	BR			3.47		—	—	—
S4	$C_{80,L}$ (dB)	2.94	−1.83	3.22	1.17	−2.58	3.60	1.56
	$C_{80,R}$ (dB)	0.38	2.16	3.26	0.53	−1.71	−2.81	1.26
	$D_{50,L}$	2.64	−1.43	0.65	2.98	−2.13	3.09	3.23
	$D_{50,R}$	2.56	0.47	2.85	2.69	−3.38	1.55	3.25
	EDT_L (s)	−0.81	0.33	1.48	−1.28	−0.30	−0.95	−2.79
	EDT_R (s)	−2.42	1.00	0.54	−1.15	−1.24	−2.88	2.73
	RT_L (s)	2.02	0.07	−3.06	−4.19	−0.97	−0.02	−0.57
	RT_R (s)	−0.29	0.71	−0.52	−1.66	−1.09	−1.66	−1.47
	$IACC_{0,+}$	3.87	−2.42	−1.62	−0.82	−2.91	3.36	2.73
	$IACC_{0,80}$	0.67	−2.12	−0.98	1.20	−3.54	−0.97	−1.21
	$IACC_{80,+}$	4.11	−1.53	−1.79	1.68	−3.21	−0.21	1.81
	BR			2.00		—	—	—

TABLE V. Paired *t*-test statistics for vanishing differences between simulations and measurements under proscenium setting of Hall A (95% confidence level).

		Octave band center frequency (Hz)						
Scheme	Parameter	125	250	500	1000	2000	4000	8000
S1	$C_{80,L}$ (dB)	−3.63	−5.84	−4.19	−3.35	−2.13	−0.73	0.59
	$C_{80,R}$ (dB)	−2.47	−4.57	−5.03	−2.40	−1.38	−4.92	−2.89
	$D_{50,L}$	−5.62	−3.50	−4.61	−4.36	−1.06	1.82	2.95
	$D_{50,R}$	−6.97	−5.24	−7.01	−3.14	−1.54	−2.31	0.94
	EDT_L (s)	3.41	10.7	4.34	12.3	4.73	4.28	5.96
	EDT_R (s)	2.29	5.36	1.94	2.26	2.50	4.14	3.94
	RT_L (s)	−5.69	4.05	2.83	−0.78	2.06	4.02	0.97
	RT_R (s)	−5.02	−2.77	−2.29	6.37	−0.32	−5.35	2.79
	$IACC_{0,+}$	0.89	−1.57	0.38	0.15	−1.82	2.44	5.72
	$IACC_{0,80}$	0.06	5.40	4.99	−0.22	1.42	3.79	5.56
	$IACC_{80,+}$	0.42	−7.71	−4.90	0.01	−1.37	−2.04	−3.83
	BR			−5.26		—	—	—
S2	$C_{80,L}$ (dB)	1.16	−3.67	−3.31	−1.17	−0.61	3.28	3.80
	$C_{80,R}$ (dB)	1.50	2.14	−3.12	−0.56	3.09	0.02	0.77
	$D_{50,L}$	1.29	−0.08	−1.23	0.21	2.81	3.60	4.10
	$D_{50,R}$	3.59	5.97	2.59	2.86	4.02	4.46	4.03
	EDT_L (s)	−2.42	−5.03	3.25	3.81	3.41	−0.06	−1.98
	EDT_R (s)	−3.20	1.17	0.36	−0.81	2.34	1.43	−2.60
	RT_L (s)	−3.39	−0.75	−4.99	3.20	−1.32	−4.88	1.54
	RT_R (s)	−0.82	−1.45	0.03	−5.12	0.53	1.84	3.14
	$IACC_{0,+}$	1.92	−7.52	−1.03	7.45	1.74	3.39	1.33
	$IACC_{0,80}$	1.59	−3.19	−1.29	3.87	2.20	−0.37	−3.05
	$IACC_{80,+}$	2.02	−7.51	6.17	1.92	−0.94	1.17	2.14
	BR			−1.66		—	—	—
S3	$C_{80,L}$ (dB)	0.17	2.21	−1.17	3.58	0.57	1.60	4.26
	$C_{80,R}$ (dB)	0.00	2.56	1.85	3.44	0.94	4.22	5.34
	$D_{50,L}$	−0.86	1.61	−1.90	3.86	1.02	1.68	1.49
	$D_{50,R}$	2.16	4.19	−1.00	2.65	1.15	3.50	5.89
	EDT_L (s)	0.61	−4.65	0.96	−2.71	1.12	−1.45	−3.47
	EDT_R (s)	0.14	−1.42	−2.00	−2.82	1.77	−1.43	−2.42
	RT_L (s)	2.26	−0.29	1.21	3.00	0.83	−2.36	−2.36
	RT_R (s)	3.02	−0.69	0.84	−0.05	1.11	0.27	5.43
	$IACC_{0,+}$	−3.75	−3.58	−1.22	2.76	2.55	2.09	3.14
	$IACC_{0,80}$	−4.03	−1.44	1.65	−1.89	−0.13	1.59	2.64
	$IACC_{80,+}$	−0.18	−5.63	4.25	1.63	−0.59	0.92	2.89
	BR			1.00		—	—	—
S4	$C_{80,L}$ (dB)	2.84	2.47	1.75	1.39	−2.77	−1.66	1.61
	$C_{80,R}$ (dB)	2.35	−0.32	2.66	−0.27	−5.16	−0.95	4.04
	$D_{50,L}$	3.59	2.65	1.59	1.66	−2.29	−1.16	0.85
	$D_{50,R}$	4.61	3.51	1.83	2.17	−4.25	−1.53	4.06
	EDT_L (s)	−1.53	−2.27	−1.04	−0.87	3.48	−1.31	−4.14
	EDT_R (s)	−2.06	1.94	−0.30	0.37	1.08	−0.20	0.05
	RT_L (s)	−1.58	−1.66	2.78	−0.44	−1.79	−2.74	−4.07
	RT_R (s)	0.48	−0.46	0.09	−1.87	0.37	2.42	3.78
	$IACC_{0,+}$	1.45	−0.88	1.79	1.32	−2.72	−1.49	−0.25
	$IACC_{0,80}$	−0.56	−0.43	0.41	−2.12	−1.91	−2.23	0.06
	$IACC_{80,+}$	1.95	−1.80	0.42	3.33	−0.11	2.32	−0.66
	BR			−0.04		—	—	—

algorithm. It is not the case if the number of simulations for the data average is insufficient.

Figure 5 illustrates the differences between the simulated EDT_L and the corresponding measured data. The EDT values fluctuate within wide ranges as shown in Table II(a) and Fig. 5. This time, the performances of S2, S3, and S4 are comparable, with S2 slightly better especially at low frequencies. The EDT_L simulated by S1 has a relatively narrow range. It is probably due to the narrower data input range to the neural network simulation. It should be noted that the behaviors of the EDT_R's are reasonably similar to those of their left-hand side counterparts (not shown here). The RT values are relatively uniform within a concert hall as suggested by Barron,[19] and can be inferred from Table II(a), and thus are not discussed. Under such uniformity, a similarity in the performances of the four training schemes is rather anticipated for RT.

The clarity C_{80} is in decibel scale which can be negative or positive and thus this parameter varies over a wide range and has large standard deviations as indicated in Table II(a). The differences between simulations and measurements are also relatively large (not graphically shown here), probably because of the large spatial variation of this parameter which tends to reduce the neural network simulation accuracy. However, such differences do not show any definite trend of variation with frequency. S1 gives the worst simulations under such a large fluctuating C_{80} range and this is rather expected. The definition D_{50} is not very meaningful for concert activity and thus the corresponding results are not presented.

In the rest of this section, the overall differences between neural network simulations and measurements will be examined by using first the root-mean-square differences, followed by the consideration of statistical distributions, and finally by a Student *t*-test analysis for point-to-point discrepancy checking. The following analysis is mainly focused on the reverberance parameters C_{80} and EDT, and the early hall spaciousness $IACC_{0,80}$, as D_{50} may not be so relevant for a concert hall situation and the RTs are relatively uniform within the hall under the concert hall setting.

Table III illustrates the root-mean-square differences between simulated results and measurements for all the acoustical parameters included in the present study. The convergence tolerance for C_{80} is of $O(10^{-2})$ while those of the other parameters are of $O(10^{-3})$. S4 in general gives the smallest differences. S1 remains the worst performer, but the overall root-mean-square differences at frequencies higher than the 250 Hz octave band resulted from the application of S1, except for C_{80}, are acceptable practically when compared to those obtained from S2, S3, and even S4. The performances of S2 and S3 are similar, but the former is a bit better in handling the parameters related to reverberance (D_{50}, EDT, and C_{80}) and the latter the mid-frequency hall spaciousness (1-$IACC_{E3}$ (Refs. 11 and 20)]. Although S4 gives the least overall differences between simulations and measurements, the required large number of measurement points for training the neural network and the relatively small improvements over S2 and S3 (comparable to measurement uncertainty) make it not an attractive option. The neural network simulation results obtained using schemes S3

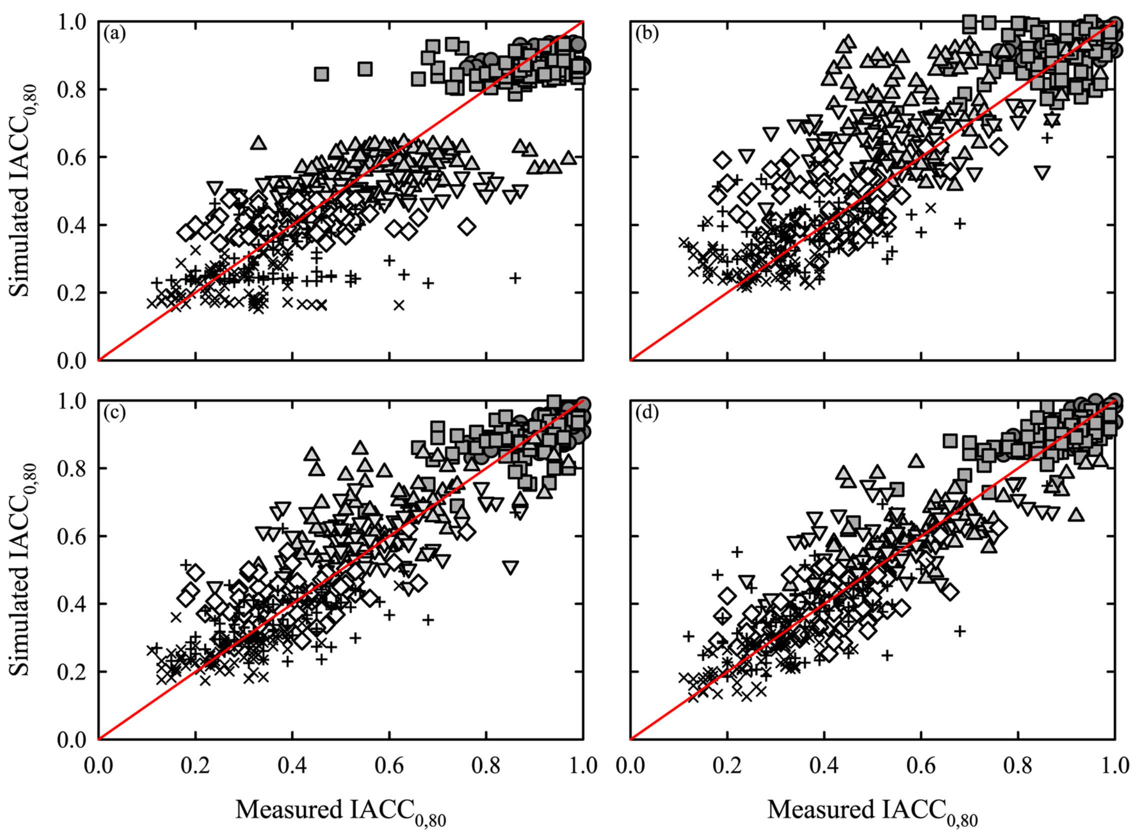

FIG. 8. (Color online) Comparison between simulated $IACC_{0,80}$ and measurements for Hall B under a concert setting. Legends: Same as those for Fig. 4.

and S4 by considering each seating area separately do not show better predictions and thus are not presented.

It is also worthwhile to understand how the neural network algorithm can predict the statistical distributions of the acoustical parameters inside the performance hall. Figures 6(a) and 6(b) illustrate the measured and simulated distributions of C_{80} under the concert setting within the bass frequency ($C_{80,\mathrm{bass}}$) and mid-frequency ranges ($C_{80,\mathrm{mid}}$), respectively. The bin widths of the distributions are set to 1 dB. The bass frequency covers the octave band 125 and 250 Hz, while the mid-frequency includes the octave band from 500 to 2000 Hz.[19] Logarithmic averaging is used in obtaining the clarities. One can observe that all four schemes fail to predict the statistical distribution of $C_{80,\mathrm{bass}}$ (both right

TABLE VI. Root-mean-square differences between simulations and measurements for Hall B.

		Octave band center frequency (Hz)[a]						
Scheme	Parameter	125	250	500	1000	2000	4000	8000
S1	$C_{80,L}$ (dB)	2.35/1.84	1.85/2.32	1.53/1.40	0.95/1.04	0.98/1.45	1.52/1.55	1.36/1.33
	$C_{80,R}$ (dB)	3.23/2.38	1.99/1.98	1.26/1.39	1.10/1.16	1.27/1.46	1.84/1.87	1.88/1.46
	$D_{50,L}$	0.12/0.13	0.13/0.13	0.10/0.09	0.06/0.08	0.07/0.09	0.08/0.10	0.08/0.08
	$D_{50,R}$	0.13/0.13	0.13/0.13	0.08/0.09	0.07/0.09	0.08/0.09	0.11/0.11	0.11/0.09
	EDT_L (s)	0.20/0.24	0.19/0.22	0.14/0.17	0.09/0.13	0.08/0.12	0.13/0.11	0.08/0.10
	EDT_R (s)	0.19/0.27	0.17/0.21	0.12/0.16	0.14/0.11	0.08/0.12	0.12/0.13	0.09/0.09
	RT_L (s)	0.11/0.26	0.09/0.18	0.05/0.11	0.04/0.10	0.03/0.04	0.02/0.03	0.02/0.03
	RT_R (s)	0.12/0.26	0.09/0.17	0.04/0.10	0.06/0.06	0.02/0.04	0.03/0.03	0.02/0.02
	$IACC_{0,+}$	0.04/0.04	0.07/0.07	0.13/0.10	0.10/0.10	0.06/0.12	0.08/0.12	0.06/0.09
	$IACC_{0,80}$	0.07/0.07	0.10/0.11	0.12/0.13	0.13/0.12	0.11/0.15	0.15/0.15	0.11/0.13
	$IACC_{80,+}$	0.05/0.04	0.07/0.07	0.12/0.11	0.07/0.09	0.02/0.08	0.03/0.11	0.02/0.05
	BR			0.05/0.04		—	—	—
S2	$C_{80,L}$ (dB)	1.75/2.10	1.94/1.89	1.28/1.06	0.91/0.94	0.96/1.17	1.32/1.35	1.15/1.25
	$C_{80,R}$ (dB)	1.67/1.88	1.65/1.55	1.20/0.95	1.02/0.86	1.07/1.20	1.48/1.29	1.37/1.35
	$D_{50,L}$	0.10/0.17	0.10/0.11	0.06/0.08	0.05/0.06	0.06/0.09	0.08/0.09	0.08/0.08
	$D_{50,R}$	0.10/0.13	0.10/0.11	0.07/0.08	0.06/0.07	0.08/0.10	0.10/0.10	0.09/0.10
	EDT_L (s)	0.20/0.27	0.23/0.15	0.10/0.14	0.09/0.11	0.09/0.12	0.09/0.16	0.07/0.12
	EDT_R (s)	0.18/0.31	0.18/0.19	0.10/0.13	0.11/0.10	0.07/0.10	0.12/0.11	0.08/0.09
	RT_L (s)	0.10/0.27	0.11/0.19	0.06/0.11	0.04/0.08	0.03/0.04	0.02/0.03	0.01/0.03
	RT_R (s)	0.10/0.29	0.08/0.16	0.04/0.12	0.04/0.07	0.02/0.04	0.03/0.03	0.02/0.02
	$IACC_{0,+}$	0.05/0.03	0.09/0.08	0.19/0.09	0.14/0.08	0.09/0.12	0.10/0.11	0.06/0.07
	$IACC_{0,80}$	0.05/0.05	0.10/0.11	0.21/0.14	0.18/0.12	0.13/0.12	0.12/0.12	0.10/0.10
	$IACC_{80,+}$	0.07/0.05	0.11/0.08	0.22/0.09	0.09/0.07	0.02/0.08	0.03/0.11	0.02/0.05
	BR			0.05/0.05		—	—	—
S3	$C_{80,L}$ (dB)	1.86/1.71	1.74/1.70	0.94/0.91	0.68/0.75	0.76/1.06	1.09/1.34	0.92/1.18
	$C_{80,R}$ (dB)	1.79/1.94	1.70/1.49	0.85/0.89	1.00/0.64	1.12/1.11	1.59/1.15	1.43/1.19
	$D_{50,L}$	0.11/0.12	0.09/0.12	0.06/0.06	0.04/0.05	0.06/0.09	0.08/0.09	0.06/0.07
	$D_{50,R}$	0.10/0.11	0.08/0.11	0.05/0.06	0.06/0.05	0.07/0.08	0.10/0.08	0.09/0.07
	EDT_L (s)	0.21/0.23	0.21/0.14	0.10/0.13	0.09/0.10	0.07/0.09	0.10/0.13	0.06/0.10
	EDT_R (s)	0.18/0.24	0.18/0.16	0.09/0.13	0.09/0.09	0.07/0.09	0.12/0.11	0.06/0.08
	RT_L (s)	0.09/0.27	0.11/0.17	0.05/0.10	0.04/0.08	0.03/0.04	0.02/0.03	0.01/0.03
	RT_R (s)	0.10/0.27	0.09/0.15	0.04/0.10	0.05/0.06	0.02/0.04	0.02/0.03	0.02/0.02
	$IACC_{0,+}$	0.04/0.03	0.06/0.06	0.14/0.06	0.10/0.06	0.06/0.09	0.09/0.09	0.04/0.06
	$IACC_{0,80}$	0.05/0.05	0.08/0.09	0.12/0.10	0.12/0.09	0.10/0.10	0.11/0.11	0.07/0.09
	$IACC_{80,+}$	0.05/0.04	0.07/0.07	0.15/0.09	0.07/0.06	0.02/0.07	0.03/0.10	0.02/0.05
	BR			0.04/0.04		—	—	—
S4	$C_{80,L}$ (dB)	1.51/1.48	1.24/1.41	1.19/0.70	0.57/0.72	0.71/0.88	0.87/1.04	0.86/1.06
	$C_{80,R}$ (dB)	1.43/1.42	1.37/1.33	0.97/0.77	0.92/0.63	1.05/0.87	1.43/0.94	1.31/0.96
	$D_{50,L}$	0.08/0.11	0.08/0.09	0.05/0.05	0.04/0.05	0.05/0.07	0.06/0.08	0.05/0.05
	$D_{50,R}$	0.07/0.11	0.07/0.08	0.05/0.05	0.06/0.04	0.07/0.06	0.09/0.07	0.10/0.05
	EDT_L (s)	0.18/0.19	0.19/0.12	0.11/0.11	0.09/0.08	0.06/0.08	0.09/0.11	0.07/0.07
	EDT_R (s)	0.15/0.23	0.16/0.15	0.08/0.13	0.10/0.08	0.05/0.08	0.10/0.09	0.06/0.07
	RT_L (s)	0.08/0.25	0.08/0.16	0.04/0.10	0.04/0.08	0.02/0.03	0.02/0.03	0.01/0.02
	RT_R (s)	0.10/0.27	0.07/0.14	0.04/0.10	0.03/0.06	0.02/0.03	0.02/0.02	0.02/0.02
	$IACC_{0,+}$	0.04/0.03	0.05/0.06	0.10/0.06	0.09/0.05	0.06/0.08	0.08/0.07	0.04/0.05
	$IACC_{0,80}$	0.04/0.04	0.07/0.09	0.10/0.10	0.11/0.07	0.09/0.08	0.11/0.07	0.06/0.07
	$IACC_{80,+}$	0.04/0.03	0.06/0.06	0.11/0.08	0.06/0.05	0.02/0.06	0.03/0.10	0.02/0.04
	BR			0.04/0.04		—	—	—

[a]Concert/proscenium.

and left charities). Their performances are much better for estimating the mid-frequency clarity. S3 and S4 give comparable performances when $C_{80,mid}$'s are concerned.

The situations for EDT are quite similar to those of C_{80} as shown in Figs. 6(c) and 6(d). The bin width for the EDT distribution is 0.1 s. For the bass frequency range, only S4 can give a reasonable prediction of the distribution. S2 and S3 again give comparable performances, while S1 is a failure. Both S3 and S4 are acceptable for the mid-frequency EDT distribution predictions. In principle, S2, S3, and S4 predict the modes of the distributions of bass and mid-frequency EDTs very well.

As the IACC values are within 0 and 1, the bin width of the $IACC_{0,80}$ distribution is chosen to be 0.1. The bass frequency $IACC_{0,80}$ (that is, $IACC_{E3,bass}$) fluctuates over a very narrow range between 0.85 and 1.0, such that all four schemes result in similar predicted distributions [Fig. 7(e)]. For the mid-frequency $IACC_{0,80}$, the greater number of training data provided to the scheme, the better performance that scheme will produce [Fig. 6(f)]. However, the mode of distribution is predicted with good accuracy no matter which scheme is used. One can observe also that S3 and S4 are giving similar predictions.

Table IV summarizes the paired *t*-test statistics with the null hypothesis being "vanishing mean difference between simulation and measurement" and it is a point-by-point comparison test. Again, the 95% confidence level is adopted. Those failed tests are highlighted in bold letters in Table IV (with test statistics higher than 2.26). The negative test statistics indicates that the tendency for the mean of the simulation being smaller than that of the measurement. It should be noted that the small root-mean-square difference and similarity in statistical distribution does not necessarily imply a point-by-point "vanishing difference." A smaller parameter standard deviation (higher spatial uniformity) in fact will result in a higher chance of null hypothesis rejection because of small variances of the two tested distributions, even though the simulated values are acceptably close to the measurements. The RT is an example for such phenomenon. Though the neural network simulation gives a better performance in general as the number of training data increases, it is found that the simulation of the mid-frequency hall

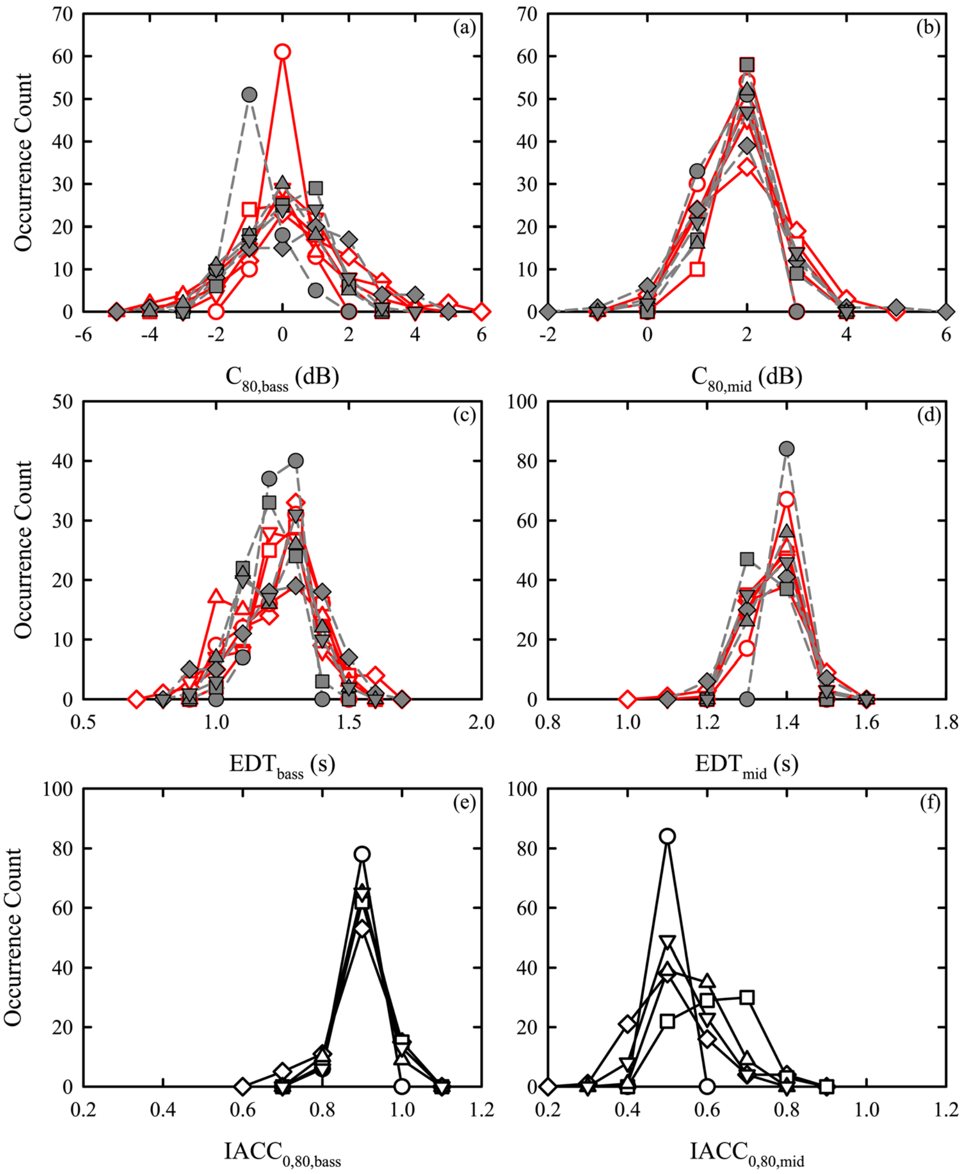

FIG. 9. (Color online) Statistical distributions of acoustical parameters under a concert setting of Hall B. (a) $C_{80,bass}$; (b) $C_{80,mid}$; (c) EDT_{bass}; (d) EDT_{mid}; (e) $IACC_{0,80,bass}$; (f) $IACC_{0,80,mid}$. Legends: Same as those for Fig. 6.

spaciousness $IACC_{0,80}$ does not require a large number of training data. The reverberance parameters (C_{80} and EDT) on the contrary need a larger number of training data before the "vanishing difference" condition can be achieved.

2. Proscenium setting

The proscenium setting is mainly used during opera and dancing performances. One can observe from Table II(a) that the spatial variations of the acoustical parameters are larger under this condition than under the concert setting, probably because of the weaker reverberation under the proscenium condition. As many of the essential features of the data variations have been illustrated in Sec. IV A 1, this section focuses on the differences between simulations and measurements.

The root-mean-square differences between simulations and measurements of the four training schemes adopted in the present study under the proscenium setting condition are presented in Table III. The performances of the four schemes are similar to those observed under the concert hall setting, but the root-mean-square differences under the proscenium are in general slightly higher than those obtained under the concert hall setting probably because of the larger spatial variations of the parameters with the proscenium stage. Under the less reverberant proscenium setting, the parameters at low frequencies are less uniform and this has a significant adverse effect on the IACCs as the correlations between the left- and right-hand signals are deteriorated, resulting in a higher percentage increase in the abovementioned differences over those under the concert hall setting in the bass frequency range than at higher frequencies for the IACCs. Again, the separation of different hall areas in the neural network analysis does not result in better simulations, showing that the elevation angle θ has been representing these areas satisfactorily.

Figure 7 illustrates the effectiveness of the four schemes in predicting the statistical distributions of the C_{80}, EDT, and $IACC_{0,80}$ in the bass frequency and mid-frequency ranges under the proscenium setting. The same bin widths as those for Fig. 6 are adopted. Although the bass frequency data may not be so relevant for the activities on proscenium stage, they are included here for the sake of completeness. One can observe that S1 fails to predict the distributions of the C_{80}'s in the bass frequency range [Fig. 7(a)]. S4 gives a closer prediction but is still not satisfactory despite the large number of training data used. S3 appears to be the best scheme at the bass frequency range for C_{80}'s. The mode of $C_{80,\mathrm{mid}}$ is correctly predicted by all schemes as shown in Fig. 7(b). It appears that S3 is again the best in terms of both distribution shape and spread range.

For the bass frequency EDTs, S2, S3, and S4 give similar simulations while S1 is again a failure [Fig. 7(c)]. Similar to the case of $C_{80,\mathrm{bass}}$, the performance of S4 is a bit lag behind those of S2 and S3 in the case of EDT_{bass}. The results shown in Fig. 7(d) suggest that all four schemes are performing similarly in the prediction of the statistical distribution of EDT_{mid}, but none of them predict the right kurtosis of the measured distribution. As in the case of $C_{80,\mathrm{mid}}$, sharper distributions are simulated by the neural network.

S3 and S4 give good predictions of the bass frequency $IACC_{0,80}$ distributions, but all schemes can predict accurately the mode of the measured distribution [Fig. 7(e)]. However, only S4 can result in a distribution similar to that

TABLE VII. Paired *t*-test statistics for vanishing differences between simulations and measurements under a concert setting of Hall B (95% confidence level).

		Octave band center frequency (Hz)						
Scheme	Parameter	125	250	500	1000	2000	4000	8000
S1	$C_{80,L}$ (dB)	−5.82	0.69	−1.64	−3.18	2.73	4.27	5.22
	$C_{80,R}$ (dB)	−12.03	−1.54	−0.42	−4.15	2.13	4.39	3.85
	$D_{50,L}$	−5.99	−3.27	−5.07	0.45	1.80	2.76	2.62
	$D_{50,R}$	−7.88	−2.62	−2.79	0.67	0.91	1.71	0.59
	EDT_L (s)	−0.93	−1.07	0.20	−0.69	−1.05	−6.57	−3.51
	EDT_R (s)	−0.83	0.12	4.70	6.01	0.26	0.00	−2.15
	RT_L (s)	−2.30	−6.53	3.28	2.57	−1.09	0.34	1.41
	RT_R (s)	0.11	−1.69	−1.72	−6.46	−1.22	−3.71	−0.10
	$IACC_{0,+}$	−1.84	0.35	−2.48	−1.98	2.64	−1.01	−4.78
	$IACC_{0,80}$	−7.06	−0.69	−1.64	−2.10	0.39	−4.12	−3.90
	$IACC_{80,+}$	−0.84	1.62	0.59	−2.06	0.81	−0.75	0.45
	BR			−3.20		—	—	—
S2	$C_{80,L}$ (dB)	−2.45	−5.78	3.04	4.93	−0.08	−2.91	−1.28
	$C_{80,R}$ (dB)	−1.24	−1.98	5.78	1.41	0.53	−0.45	−3.71
	$D_{50,L}$	−4.57	−1.97	2.66	4.72	2.30	1.91	1.52
	$D_{50,R}$	−4.22	−6.42	5.51	4.52	0.21	0.66	−1.63
	EDT_L (s)	−2.46	3.16	1.40	−1.08	−3.05	0.81	1.71
	EDT_R (s)	−1.85	−3.32	−0.71	−2.22	−0.95	−0.48	0.54
	RT_L (s)	−3.49	−7.95	5.12	−1.98	4.17	−2.19	−0.72
	RT_R (s)	−3.06	−2.77	−3.97	−3.79	−3.58	5.39	3.87
	$IACC_{0,+}$	5.39	6.50	8.46	8.93	4.85	3.09	3.97
	$IACC_{0,80}$	1.55	2.40	8.18	7.59	3.71	1.09	3.03
	$IACC_{80,+}$	5.62	8.57	10.41	7.91	−0.06	2.39	1.81
	BR			−4.74		—	—	—
S3	$C_{80,L}$ (dB)	−5.22	−2.38	−0.24	1.74	0.45	1.89	−1.04
	$C_{80,R}$ (dB)	−5.85	−2.95	2.69	1.35	−0.09	1.44	0.63
	$D_{50,L}$	−2.99	−3.62	1.31	2.22	1.94	2.50	2.32
	$D_{50,R}$	−4.99	−4.55	1.75	1.50	0.45	1.63	−0.16
	EDT_L (s)	−3.31	−1.54	1.08	0.11	−1.63	−3.00	0.24
	EDT_R (s)	−0.57	−2.52	0.55	4.40	−0.91	−1.26	−0.23
	RT_L (s)	−1.13	−7.57	3.65	0.38	2.73	−1.46	0.39
	RT_R (s)	−0.59	−2.26	−2.37	−5.40	−3.32	1.73	2.03
	$IACC_{0,+}$	2.50	3.32	7.47	5.21	3.52	2.42	1.23
	$IACC_{0,80}$	−2.98	1.15	5.03	2.53	1.72	−1.15	−0.52
	$IACC_{80,+}$	3.77	4.18	7.38	4.19	0.15	1.85	2.06
	BR			−2.87		—	—	—
S4	$C_{80,L}$ (dB)	−0.90	0.46	−0.31	2.33	0.31	0.36	−0.48
	$C_{80,R}$ (dB)	−3.07	−2.02	0.51	2.76	0.43	1.09	1.82
	$D_{50,L}$	−0.40	1.14	−1.09	3.90	0.42	0.37	0.56
	$D_{50,R}$	−1.62	−0.56	1.34	2.23	−0.64	0.88	−2.43
	EDT_L (s)	−3.28	−0.38	1.25	−2.99	−0.77	−1.04	3.47
	EDT_R (s)	−0.51	−2.40	−0.38	2.56	−0.88	−0.24	0.71
	RT_L (s)	2.50	−2.31	1.97	0.01	−0.87	−0.60	0.60
	RT_R (s)	−2.66	0.27	−0.18	−1.42	0.02	2.62	−1.01
	$IACC_{0,+}$	3.44	2.49	2.53	4.90	−0.65	0.66	0.95
	$IACC_{0,80}$	0.10	2.30	1.30	3.22	−1.21	0.04	−2.77
	$IACC_{80,+}$	3.10	0.09	1.48	−0.32	1.52	0.39	2.34
	BR			−1.27		—	—	—

of the measured mid-frequency early hall spaciousness $IACC_{0,80}$ [Fig. 7(f)].

Concerning the point-to-point comparison, one can observe from Table V again that the scheme performance is improved in general when the number of training data is increased. S1 is not good even for the BR. Together with the results shown in Table III and Fig. 7, the prediction from S4 for the $IACC_{0,80}$ is remarkable, but S3 is not bad at all when the $IACC_{0,80}$, C_{80}, and EDT are concerned together. This makes S3 an important alternative as it requires 40% less training data than S4 does.

It can be concluded that S3 and S4 are acceptable schemes for the acoustical parameter predictions for both the concert hall and proscenium settings of Hall A. The prediction of reverberance parameters appears to be more difficult than the spaciousness parameters overall. The weaker reverberation under the proscenium setting results in less uniform spatial acoustical parameter distribution, resulting in a less significant point-to-point deviation between simulations and measurements statistically. However, the actual differences can be larger under the proscenium setting than under the concert hall setting.

B. Hall B

Hall B is considerably smaller than Hall A. Its seating plan and stage curvature are also different from those of Hall A. The acoustic shell of Hall B follows the curvature of the seating plan and is convex toward the audience. The corresponding diffusion has resulted in a higher uniformity of acoustical parameters related to reverberance under the concert setting than under the proscenium one in general, while the spaciousness parameters are not so affected [Table II(b)]. Again, the main focus in this section is on the performances of the four neural networking schemes inside this much smaller performance hall having a layout very different from that of Hall A. It should be noted that the comparison between the acoustical properties of Hall A and Hall B is not the intention of the present investigation. The upper stall in Hall B refers to the area under the balcony (starting from

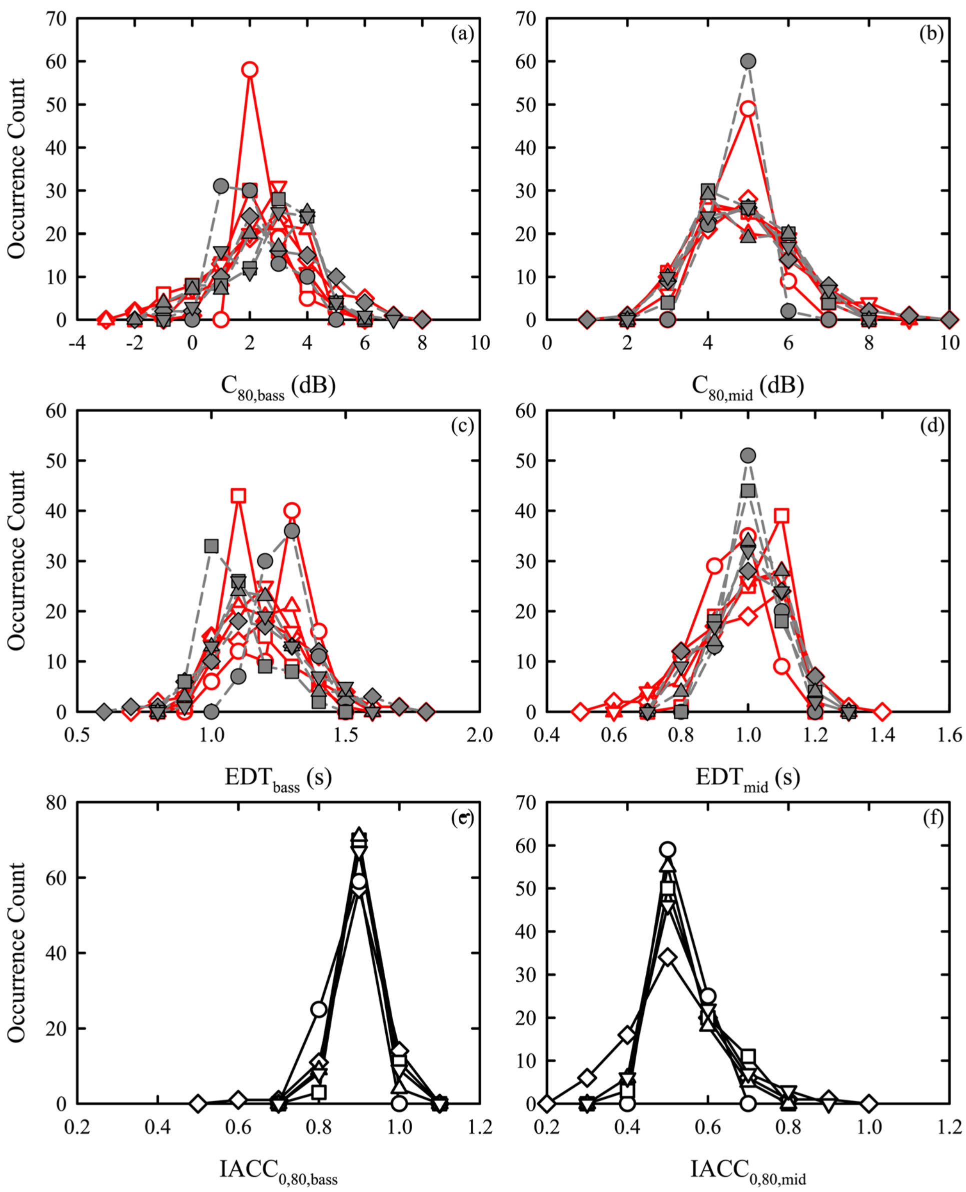

FIG. 10. (Color online) Statistical distributions of acoustical parameters under proscenium setting of Hall B. (a) $C_{80,bass}$; (b) $C_{80,mid}$; (c) EDT_{bass}; (d) EDT_{mid}; (e) $IACC_{0,80,bass}$; (f) $IACC_{0,80,mid}$. Legends: Same as those for Fig. 6.

row S). The measurement points and the training points for Hall B can be found in Fig. 2. It should be noted that no measurement has been done in the first three seating rows as they were removed during the present survey due to some hall functions.

1. Concert setting

Figure 8 illustrates the predicted $IACC_{0,80}$ in comparison with the measured data for Hall B. Certainly, an increase in the number of training data improves the performance of the prediction scheme, but one can observe from Fig. 8 that S3 and S4 give a similar performance. It appears that these schemes, except S2, perform better in Hall B than in Hall A. Similar phenomenon can be observed basically for the other parameters and thus the corresponding data are not presented.

The root-mean-square differences between simulations and measurements for Hall B are presented in Table VI. Similar to the conclusions for Hall A, the prediction of the reverberance parameters becomes better as the number of training data increases in general, while that of the spacious ones are less affected by such an increase. S2 even performs a bit weaker than S1 in the prediction of spaciousness parameters. This is also observed briefly in the analysis for Hall A (Table III). All four schemes give a similar accuracy on the overall predictions of BR. The predictions using S3 are comparable to those using S4. Given the relatively large number of training points used in S4, S3 should be an attractive option.

Figure 9 illustrates the statistical distributions of predicted C_{80}, EDT, and $IACC_{0,80}$ within the bass and mid-frequency range for Hall B under the concert setting. Those of the measured data are also included for comparison. S1 appears as a failure for the prediction of $C_{80,bass}$ while the other three schemes give similar performances [Fig. 9(a)]. However, all four schemes are performing similarly in the prediction of C_{80} in the mid-frequency range, with the distributions obtained using S3 and S4 closer to the measured ones [Fig. 9(b)]. One can observe similar phenomenon for the EDTs in Figs. 9(c) and 9(d), but S1 is not so bad this time although it produces distributions with kurtosis considerably higher than those of the measurements, especially for EDT_{mid}. Similar to the case of Hall A, the low frequency early hall spaciousness $IACC_{0,80,bass}$ varies over a narrow range. S2, S3, and S4 give nearly the same predictions and all the schemes correctly predict the mode of the statistical distribution. For $IACC_{0,80,mid}$, S2 is a failure and S1 is the second worst. S3 and S4 give a similar performance, but none of them predict accurately the shape of the statistical distribution, despite the large number of training data points used in S4.

Concerning the point-by-point differences between predictions and measurements, one can observe from Tables VI and VII that the performance of S2 is the worst, while S1 and S3 give a comparable performance. S4 is the best scheme overall, but its prediction of the mid-frequency reverberance parameters is not as good as S3. S4 is only marginally better than S3 in the prediction of hall spaciousness. It can be concluded together with results shown in Table V and Fig. 9 that S1 and S2 are less desirable, while S3 and S4 are comparable in performance but the fewer training points required by the former makes it slightly more preferable for the present application. This is in-line with the results obtained in Hall A.

TABLE VIII. Paired *t*-test statistics for vanishing differences between simulations and measurements under a proscenium setting of Hall B (95% confidence level).

		Octave band center frequency (Hz)						
Scheme	Parameter	125	250	500	1000	2000	4000	8000
S1	$C_{80,L}$ (dB)	−1.72	−2.03	0.95	−2.16	−0.14	0.62	0.25
	$C_{80,R}$ (dB)	**−7.03**	−1.78	−1.10	**−3.79**	0.58	**−3.25**	−3.27
	$D_{50,L}$	−0.67	**−3.18**	−1.24	**−2.68**	1.83	1.34	−1.19
	$D_{50,R}$	**−4.51**	**−3.24**	−2.08	**−3.09**	0.07	−0.54	−1.20
	EDT_L (s)	1.53	**3.37**	**−4.92**	−1.31	−1.57	−0.21	0.53
	EDT_R (s)	1.39	**3.53**	**2.67**	−0.04	−0.17	**4.40**	3.94
	RT_L (s)	−1.68	0.99	**−2.54**	**−7.07**	0.95	**−4.15**	−0.95
	RT_R (s)	**2.49**	1.09	0.63	1.88	**2.56**	−2.25	−3.81
	$IACC_{0,+}$	**−6.47**	−0.40	**3.02**	**−2.98**	−0.26	−1.44	0.67
	$IACC_{0,80}$	**−9.40**	−1.54	1.48	−0.52	1.11	−0.26	−0.89
	$IACC_{80,+}$	−0.94	**2.93**	**6.42**	−1.21	−0.60	0.36	−1.72
	BR			−2.10		—	—	—
S2	$C_{80,L}$ (dB)	**−4.28**	**−4.22**	**−4.19**	1.27	**−3.59**	−0.73	−1.37
	$C_{80,R}$ (dB)	−0.37	−1.10	−0.77	**3.10**	−1.69	0.57	2.08
	$D_{50,L}$	**−5.10**	**−3.67**	**−7.11**	**3.84**	−0.89	−1.62	0.74
	$D_{50,R}$	−2.14	**−5.00**	**−4.61**	**2.84**	−0.24	2.16	0.06
	EDT_L (s)	**−3.67**	0.65	2.07	0.46	**5.80**	**5.05**	0.38
	EDT_R (s)	**−5.42**	**−3.41**	−1.00	0.41	**2.95**	**3.21**	−0.37
	RT_L (s)	**−3.58**	−2.21	−1.82	−0.79	0.92	−0.64	−0.22
	RT_R (s)	1.27	0.75	**−6.71**	**−3.01**	0.16	−2.02	0.21
	$IACC_{0,+}$	**3.98**	**3.13**	**2.70**	**3.29**	**2.78**	**2.73**	1.56
	$IACC_{0,80}$	1.49	**2.54**	1.56	2.08	2.12	**2.52**	1.32
	$IACC_{80,+}$	**6.54**	**4.29**	**3.27**	1.65	0.73	−0.64	1.12
	BR			**−6.26**		—	—	—
S3	$C_{80,L}$ (dB)	−2.13	**−3.33**	−1.29	−0.10	−0.55	−0.79	0.21
	$C_{80,R}$ (dB)	−1.19	**−2.79**	**−2.38**	−0.62	−1.06	−0.85	0.33
	$D_{50,L}$	**−3.83**	**−5.02**	**−5.43**	1.99	0.88	−0.02	1.11
	$D_{50,R}$	**−3.47**	**−4.56**	**−4.58**	−1.64	−0.51	0.44	−0.34
	EDT_L (s)	**−3.22**	2.12	−0.21	−0.12	0.95	**3.11**	−0.97
	EDT_R (s)	**−3.16**	0.98	0.62	1.16	**3.46**	**4.49**	1.19
	RT_L (s)	**−2.68**	−0.73	−1.86	**−3.23**	1.09	**−3.38**	−1.59
	RT_R (s)	1.73	1.08	**−3.79**	−0.60	1.08	**−2.96**	**−2.96**
	$IACC_{0,+}$	0.73	2.07	**2.89**	0.60	**2.58**	1.53	**2.29**
	$IACC_{0,80}$	−2.08	0.56	0.61	0.55	1.19	1.47	0.03
	$IACC_{80,+}$	**3.44**	**3.76**	**4.87**	1.25	0.64	0.37	−0.68
	BR			**−3.08**		—	—	—
S4	$C_{80,L}$ (dB)	−2.27	**−2.74**	−0.84	0.78	**2.56**	**2.74**	1.25
	$C_{80,R}$ (dB)	−1.13	−0.60	−0.59	−1.76	−0.62	0.03	−0.99
	$D_{50,L}$	**−2.50**	**−2.91**	−1.92	0.95	1.34	**2.56**	1.07
	$D_{50,R}$	**−3.06**	**−2.68**	−1.77	−2.21	0.39	−0.16	−0.47
	EDT_L (s)	−1.63	−0.11	−0.76	−0.44	−1.66	−0.81	−0.32
	EDT_R (s)	−2.12	1.49	0.39	−0.66	−0.26	−0.13	−0.36
	RT_L (s)	1.36	0.61	1.26	−0.56	0.58	−1.83	0.34
	RT_R (s)	**2.57**	−0.07	−0.71	−0.75	0.64	−0.38	−0.33
	$IACC_{0,+}$	1.86	1.86	**4.14**	**2.56**	**3.01**	0.96	0.09
	$IACC_{0,80}$	−0.10	1.72	**3.37**	**2.50**	**2.94**	**3.27**	2.25
	$IACC_{80,+}$	2.24	1.66	**2.63**	−0.87	−0.37	−1.78	−0.49
	BR			−1.18		—	—	—

2. Proscenium setting

The spatial variations of the acoustical properties inside Hall B become larger in the absence of the acoustic shell [Table II(b)]. The weaker reverberation enhances the clarities and definition, but reduces the spaciousness feeling. In term of the root-mean-square difference between prediction and measurement, S4 is the best performer and the performance is reduced as the number of training points decreases (Table VI). Although this is rather expected, one can notice that the differences between S3 and S4 are very small.

S1 cannot reproduce the statistical distributions of the C_{80} in the bass and mid-frequency range as shown in Figs. 10(a) and 10(b). Schemes S2, S3, and S4 can basically predict the distributions, but it appears that S3 and S4 perform slightly better for $C_{80,bass}$ and $C_{80,mid}$, respectively. The EDT_{bass} distributions predicted by using S1 and S2 are not satisfactory, while those obtained by adopting S3 and S4 are basically the same and can satisfactorily follow the shapes of the measured statistical distributions [Fig. 10(c)]. In the mid-frequency range [Fig. 10(d)], S1 is again the worst performer. S2 predicts the right EDT_{mid} distribution skewness but with a larger kurtosis. Again, S3 and S4 give more accurate predictions and their performances are similar. Results shown in Figs. 10(e) and 10(f) indicate that all four schemes predict the distribution mode accurately. They also give similar $IACC_{0,80}$ statistical distribution predictions and that of S1 in the bass frequency range is not bad at all despite the small number of training points involved in the scheme.

The point-by-point paired-*t* test results give more details on the deviations of the neural network simulations from the measurements, and those for Hall B under the proscenium setting are presented in Table VIII. One can observe again that the accuracy of the neural network prediction for the parameters related to reverberance is higher when more training data are involved. However, the results obtained using S4 do not appear to be the best overall as they fail marginally the paired-*t* test for the early hall spaciousness. On the contrary, S3 produces reasonable estimations of these $IACC_{0,80}$'s as can be concluded from Tables VI and VIII and Fig. 10. Also, its predictions for the mid-frequency reverberance parameters are acceptable, although its results for the 500 Hz D_{50} are not so good. Together with the overall root-mean-square difference results shown in Table VI, S3 is a more preferable scheme for Hall B under the proscenium setting. Schemes S1 and S2 are not performing so well in the paired *t*-test, but their predictions of the $IACC_{0,80,mid}$ are still acceptable, confirming once again that the neural network prediction for the hall spaciousness does not require a large amount of training data.

V. CONCLUSIONS

A detailed binaural measurement has been carried out inside two multi-purpose performance halls in the present study. Both of them have a balcony, but they are of different seating capacities and designs. One of them has a total seating capacity of 1372 and a rectangular seating layout, while the other can house a maximum of 919 people and has a fan shape seating plan. The seating area of each hall was divided into three specific sub-areas, namely the stall, the upper stall, and a balcony in the present study. About 10% of the seating locations evenly distributed in each hall were surveyed. The effectiveness of using neural network in the prediction of the acoustical properties inside these halls was examined in terms of point-by-point deviations from measurements and overall statistical distributions of acoustical parameters. Four schemes with a different number of data sets were introduced to train up the neural network. The first one consisted of three training data sets obtained from the two ends and the middle part of the middle row of each specific hall sub-area. The second one used six training data sets obtained from the near and far boundary of each sub-area relative to the stage (three from each boundary), while the third one was a combination of the first two schemes. The final one was basically the third one but with a finer span-wise resolution. For simplicity, the spherical coordinates of the measurement points were used as the inputs to the neural network algorithm. Both the concert and proscenium settings were included in the present study. A relatively simple neural network prediction algorithm was adopted.

A general observation from the present result is that regardless of the stage setting and hall design, the neural network training scheme which includes only training data from the middle region or from the boundaries of each specific hall area fails to give acceptable predictions. The more reverberant condition under the concert stage setting results in less spatial variations of acoustical parameters than under the proscenium setting, such that the difference between performances of the four neural network training schemes are a bit less remarkable.

Regardless of the hall settings and designs, the neural network scheme with more input training data gives the better performance in terms of the overall root-mean-square deviation from measurements, statistical distribution matching, and point-to-point statistical deviations in general. The one including nine uniformly distributed data points within each hall area (the third scheme) appears to be the best choice regardless of the hall setting and design as an about 70% further increase in the number of training data can only yield insignificant improvement on the prediction accuracy, while the differences of its predictions from measurements are acceptable. It is also found that the prediction of hall spaciousness in general requires less of an amount of training data than that of the reverberance parameters, regardless of the hall setting and design.

As the two performance halls selected in the present study were of very different designs and layouts, it is believed that the present findings are relevant to other multi-purpose performance halls. A simple framework for the evaluation of performance hall acoustics is established, at least for halls with a similar level of reverberance.

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