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Validation and application of three-dimensional auralisation during concert hall renovation

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Abstract

During the renovation of auditoria and concert halls, the acoustic quality is normally evaluated from measurements of impulse responses. One possibility for evaluating the acoustic quality from the measurements (the simulations) consists of convolving anechoic music with the measured (or simulated) impulse responses. In this way, a psycho-acoustic test is achieved using a virtual sound field representation. The listening room 'Arlecchino' at the University of Bologna includes ambisonics (up to fifth order) and stereo-dipole playback for virtual reproduction of sound in rooms. In this article, the effectiveness of the listening room 'Arlecchino' is first analysed, comparing acoustic parameters obtained from binaural impulse responses measured in some opera houses (in Italy) and auditorium (in Japan) with those virtually measured after the virtual reconstruction obtained in the listening rooms. The similarity between real and virtual sound fields, has been evaluated by comparing different acoustic parameters calculated by real and virtual sound fields, in four halls in different configurations, by means of the stereo-dipole method. In the second part of the article, the listening room was used to analyse the variation in interaural cross-correlation measurements in rooms obtained considering different anechoic sound signals convolved with the binaural impulse responses, to quantify the variation of the interaural cross correlation with different motifs. For this purpose, two different musical instrument digital interface musical motifs, very different from each other for their music characteristics, have been considered. Moreover, for each musical motif, different sound characteristics (i.e. different musical instruments) were considered, to consider both the rhythmic and timbre aspect.

Keywords

Three-dimensional auralisation, room acoustics, binaural impulse response, interaural cross-correlation function, stereo-dipole validation

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Introduction

The acoustics of historical theatres and concert halls is considered of primary importance since 18th century,[1] and it requires proper measurement techniques capable of determining and reproducing the characteristics of the spatial propagation of the sound field.

In general, the overall indoor quality in buildings includes high level of sound insulation from external and internal noise,[2,3] high level of thermal comfort especially without any specific heating system, also balancing costs and performance,[4,5] high levels of air quality and light distribution.[6] These aspects are particularly relevant for theatres and opera houses, where the overall subjective evaluation depends not only on sound propagation but also on other aspects.

The stereo-dipole method, obtained using binaural impulse responses (BIRs) measured in theatres, permits the reconstruction of a virtual sound field with very high precision, including also binaural effects, such as spatial impression of the sound, localisation of the source and timbre. The virtual sound field is reproduced in a listening room where it is also possible to simulate variations of shapes, dimension and sound absorption of surfaces, and listen to the effect that these changes produce. Therefore, it is possible to compare the acoustic quality of theatre during the design process.

Validation of three-dimensional auralisation

The virtual sound field reconstruction consents reproducing in a properly equipped listening room the original sound distribution measured (or simulated) in a room. In other words, it enables to reach the target of the designed acoustic quality allowing to test different technological solutions during the design process, giving immediate sound renderings.

Nevertheless, to evaluate the similarity between virtual sound field (obtained with stereo-dipole technique) and real sound field, different acoustic parameters should be compared from real (measured) and virtual (played back) acoustics. One of the most important methods which could be utilised for virtual playback, and here considered, is the stereo-dipole technique. This technology was first implemented in the Arlecchino listening room in 2005. The accuracy of the playback was analysed, comparing the acoustic parameters in the original BIRs with those calculated from the BIRs virtually obtained with the stereo-dipole method.[7] Moreover, the subjective evaluations of real and virtual rooms have been studied and validated in other papers.[8]

Real IRs

In this article, the validation proceed of the listening room (named Arlecchino) was achieved considering the impulse responses measured in four different acoustic spaces by means of microphone arrays which included also a dummy head and a B-Format Microphone.[9] Two Italian theatres (Teatro Nuovo in Spoleto and Teatro Alighieri in Ravenna) and two Japanese concert halls (Kirishima International Musical Hall in Kagoshima and the Tsuyama Musical Cultural Hall in Okayama) are shown in Figure 1.

The Teatro Nuovo in Spoleto was opened in 1864. It was in a typical horseshoe shape, which characterises the classical Italian opera houses. The boxes in the theatre are divided into four levels which face to the stalls. The theatre could host 800 persons. In 1914, the Teatro Nuovo has been refurbished and the most striking change was the reduction of the stage to enlarge the orchestra pit. Such a modification has probably compromised the good balancing between singer on the stage and orchestra in the pit. In addition, in 1933 all the original floor has been replaced. Moreover, in 1950 the orchestra pit was extended to ensure a larger orchestra, which was necessary for the new

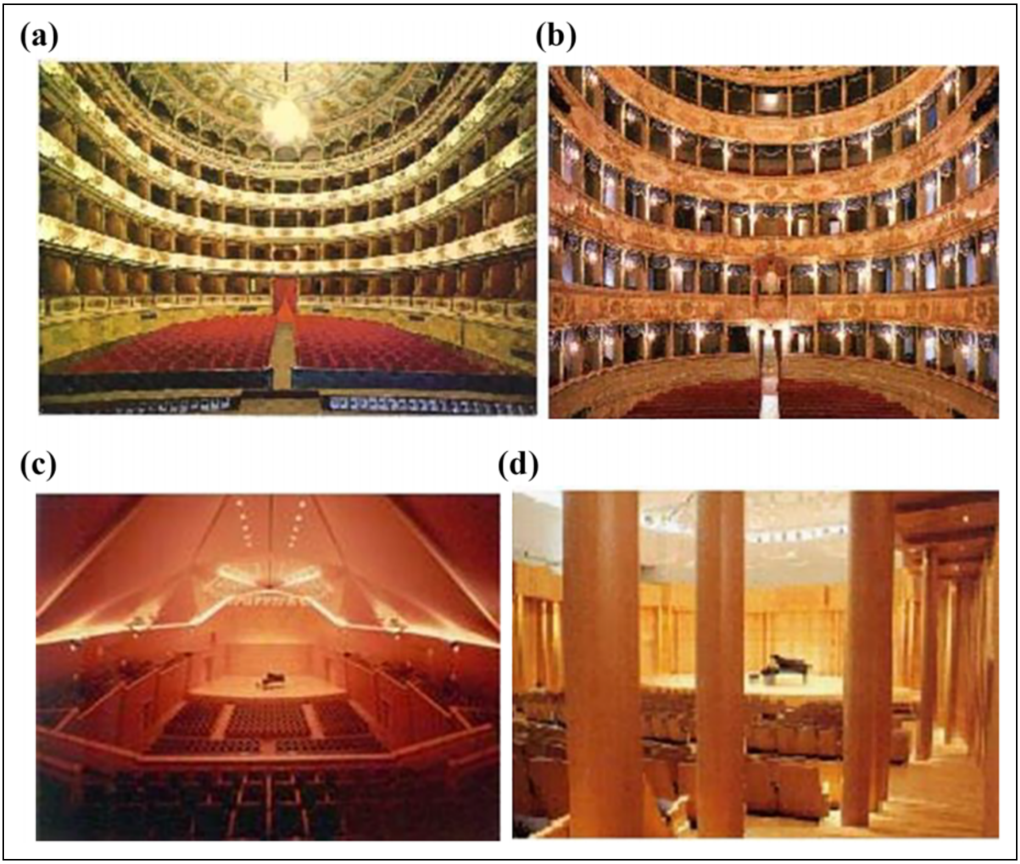

Figure 1. (a) Teatro Nuovo in Spoleto (Italy), (b) Teatro Alighieri in Ravenna (Italy), (c) Kirishima International Musical Hall in Kagoshima (Japan) and (d) Tsuyama Musical Cultural Hall in Okayama (Japan).

music festivals. Finally, in 2005 the regional authorities approved further restoration works aiming also to improve the acoustics especially for musicians located in the orchestra pit.

The Teatro Alighieri in Ravenna was designed by two Venetian architects, Tomaso and Giovan Battista Meduna and was opened in 1852. They proposed a theatre not very different from the Venetian Teatro la Fenice, well known for its acoustics,[10] that they had designed few years earlier. In 1929, the gallery substituted the balcony in the fourth order, and also the stage was remodelled, enlarging the stalls. The number of seats is 334 for the stalls and 463 for boxes and galleries. One of the most relevant factors of the theatre is the cavity located below the orchestra pit. It is one of the few cavities not dismantled in other Italian styled opera houses during the 20th century, and it was recognised as responsible of a certain modification in strength and reverberation time during recent acoustic measurements. These effects were also considered during the emulation of sound characteristics of musical instruments[11–13] which influenced the sound perception of music motifs.[14]

The Kirishima International Musical Hall was opened in Kagoshima (Japan) in 1994. Its shape recalls the shoe-box style. The audience area is covered by the ceiling that recalls the bottom of a ship. This particular shape allows a well-diffused sound distribution among all the stalls. The hall could host 518 people in the stalls and 252 in the gallery.

Table 1. List of the measured impulse responses.

Auditorium	Source	Receiver	Name
Teatro Nuovo di Spoleto	Stage	Stalls	SPO_ss
	Pit	Stalls	SPO_ps
	Stage	Box	SPO_sb
	Pit	Box	SPO_pb
Teatro Alighieri di Ravenna	Stage	Stalls	RAV_ss
	Stage	box1	RAV_sb1
	Stage	box2	RAV_sb2
Kirishima musical hall	Stage	Stalls	KIR_ss
Tsuyama musical hall	Stage	Stalls	TSU_ss

The Tsuyama Musical Cultural Hall was opened in Okayama (Japan) in 1999. Following the principal acoustic concept 'forest', a lot of pillars are arranged in rows in front of the lateral walls. The diffused sounds at the pillars reach the listeners, and they would experience the same resonance effect like in the forest. On the ceiling, there are floating reflective boards which are hung by wire ropes. The number of seats is 600.

All the acoustic measurements of IRs were taken by employing an omnidirectional, pre-equalised loudspeaker (Look Line), a dummy head (Neumann™ KU100), and a B-Format Microphone (Soundfield™ MKV). However, for the purposes of this article, only the BIRs have been considered, recorded using dummy head. The height of the source was 1.4 m when the loudspeaker was located on the stage, and 1.2 m when the loudspeaker was located on the orchestra. The height of microphones was always 1.1 m from the floor to the ear. The direction of the dummy head was adjusted to the source position in each measurement. To obtain the impulse responses, an exponential sine-swept (ESS) signal was generated by a personal computer (PC).[15] The signal ranged from 40 to 20 kHz for a duration ranging from 20 s (in the opera houses) to 30 s (in the concert halls).

Table 1 explains the arrangements of sources and receivers, and the impulse response recorded in the theatres and concert halls. The measured impulse responses analysed in this article are, respectively, as follows: four positions for the Teatro Nuovo di Spoleto, three positions for Teatro Alighieri di Ravenna, one position for Kirishima musical hall and one position for Tsuyama musical hall.

Measurement in Arlecchino listening room

The single and dual stereo-dipole representations were carried out in the Arlecchino listening room in Bologna (Italy), to perform psychoacoustic tests following Ando's theory.[16] In the listening room, two loudspeakers (Montarbo W400A) were located in front of a dummy head (Neumann) and the other two loudspeakers (Montarbo W400A) were located in the rear of it as shown in Figures 2 and 3.

An ESS signal was generated by Adobe Audition and was played by the four loudspeakers to obtain BIRs in the listening room. In Table 2, the characteristics of the swept sine generated by PC are reported.

The BIR of the listening room can be obtained for the front and rear loudspeakers, after deconvolution of the signals recorded by the dummy head. The envelopes of impulse responses were windowed to remove extra reflections to obtain only the direct sound from each loudspeaker.

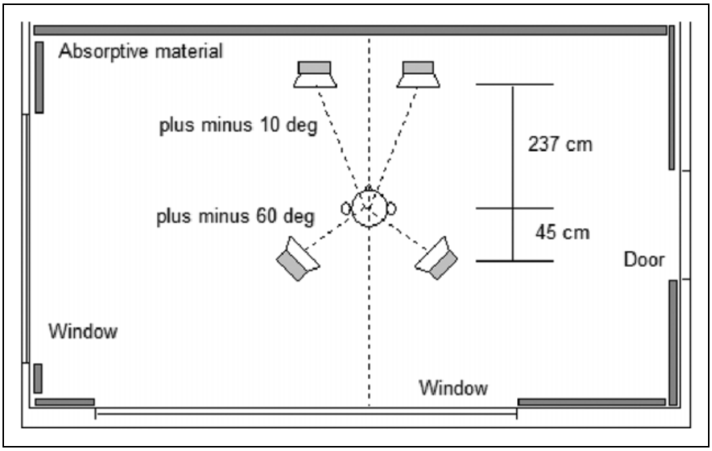

Figure 2. Plan of Arlecchino listening room with dual stereo-dipole: front (above) and back (below).

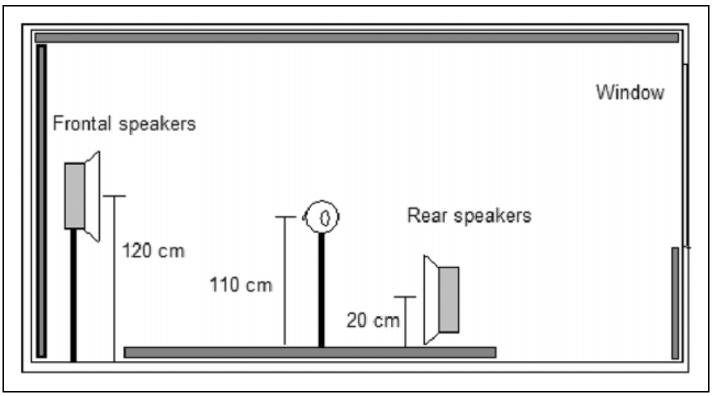

Figure 3. Section of Arlecchino listening room.

Table 2. Properties of swept sine signal.

Variable	Value
Start frequency (Hz)	50
End frequency (Hz)	20,000
Duration (s)	30
Amplitude	8192
Sampling (Hz)	48,100
Resolution	32-bit

Generation of cross-talk cancelling filter

The IR was processed with the cross-talk cancelling filter using the plug-in of 'Invert Kirkeby'[17] in Adobe Audition. Therefore, two different cancelling filters were generated for the frontal loudspeakers and for the rear loudspeakers. Table 3 reports the properties of the Invert Kirkeby plug-in.

Table 3. Properties of Invert Kirkeby plug-in for frontal and rear cancelling filters.

Variable	Value
Filter length (sample)	2048
Lower cut frequency (Hz)	80
IN-band parameter	1
High cut frequency (Hz)	16,000
OUT-band parameter	10
Width	0.33

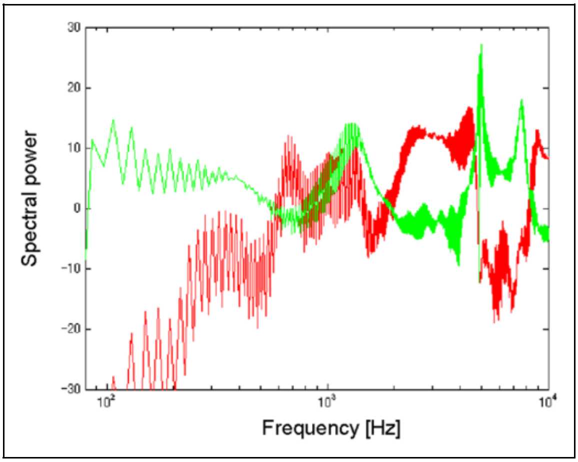

Figure 4. Spectral powers of front cancelling filter (red) and rear cancelling filter (green).

Since the Arlecchino listening room is not a perfect anechoic space, the cross-talk cancelling filters have non-linear frequency responses, as shown in Figure 4.

Virtual IR

The original ('anechoic') sweep-sine signal was convoluted with the impulse responses of the theatres and concert halls. The obtained ('echoic') sweep-sine signals were convoluted again by the cross-talk cancelling filters for the two pair of loudspeakers. The resulting signals were presented by the frontal and rear loudspeakers at the same time, and the sounds were recorded by the dummy head.

Finally, by deconvoluting the recorded signal, an impulse response was obtained. In this study, it is called 'virtual IR', which means the IR obtained in the listening room after having processed the ESS, to distinguish the 'real IR' that was measured in the theatres.[18,19]

Results

To confirm the accuracy of sound field representation by the stereo-dipole technique, in this article the real IR and virtual IR were compared in terms of acoustic parameters: SPL (sound pressure level) and EDT (early decay time). The values are the average of SPL and EDT calculated from the left and right impulse responses. The virtual IR by single stereo-dipole was obtained using only the

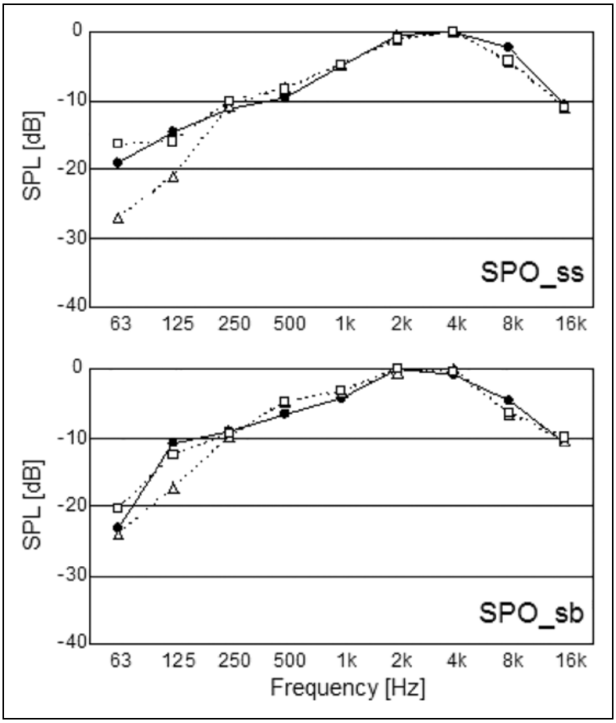

Figure 5. SPL: real IR (●), virtual IR by single stereo-dipole (△) and virtual IR by dual stereo-dipole (□), Spoleto 1/2.

frontal loudspeakers. Figures 5–10 show the SPLs calculated from the real IR and the virtual IR by single and dual stereo-dipoles.[20,21]

In all case, the SPL of the virtual IR is close to the SPL of the real IR. However, in the low-frequency range, the SPL of the virtual IR by single stereo-dipole tends to be lower than the SPL of real IR. The gap of SPL is improved by carrying out the dual stereo-dipole. For the concert hall, the single stereo-dipole shows better performances than the dual stereo-dipole.

Figures 11–16 show the results of EDT. From these results, it can be found that the stereo-dipole technique in the Arlecchino listening room works for the sound field representation with high correlation. However, like the results of SPL, EDT of the real IR in the low-frequency range is difficult to be expressed by the single stereo-dipole.

The results suggest that the stereo-dipole technique has a good accuracy of the sound field appearance. Thus, virtual sound field reproduced in the listening room with stereo-dipole technique has high correlation with the acoustic quality of theatres and concert halls.

Application of three-dimensional auralisation

In this section, the Arlecchino listening room was used to analyse the values of interaural cross correlation (IACC) calculated by 'echoic music' and 'virtual echoic music'. This parameter is very important for retrofitting design because allows evaluate spatial impression of sound in a hall.

Normally, IACC is calculated only from BIRs. However, IACC changes when we consider that music motif is played in the room, since the motif modify changes the spectral aspects of the BIRs, in accordance with the kind of musical motif, and the presence/absence of low frequencies which

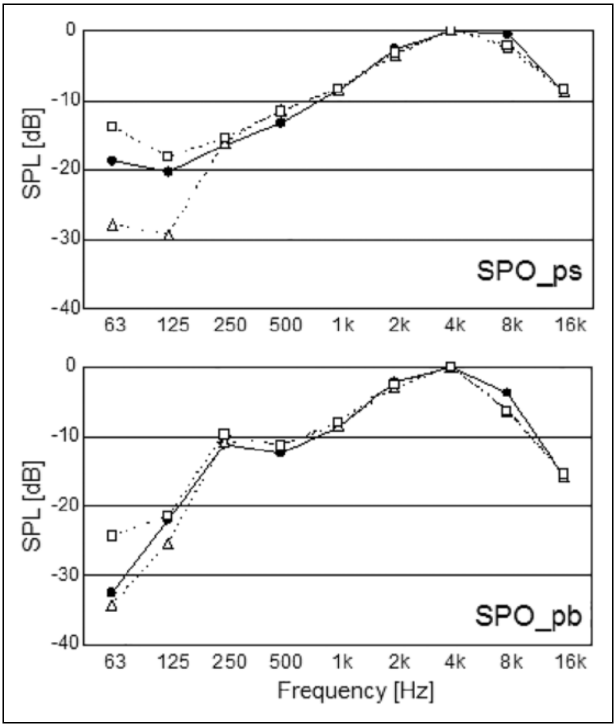

Figure 6. SPL as a function of band frequency: real IR (●), virtual IR by single stereo-dipole (△) and virtual IR by dual stereo-dipole (□), Spoleto 2/2.

could influence the sound quality. In this article, using musical instrument digital interface (MIDI), anechoic musical signals convolved with the BIRs, are composed by changing two kinds of melody and three kinds of musical instrument.

IACC and normalised autocorrelation function

Sound propagated from sound source is received at left and right ears by different pathways. Interaural cross-correlation function (IACF) is defined by the correlation between the signals at the left $p_l\,(t)$, and right, $p_r\,(t)$, ears as function of delay time τ. IACC is the maximum peak amplitude of IACF, and is defined by

$$IACC = \left| \frac{\int_{-T}^{T} p_l(t)p_r(t-\tau)dt}{\sqrt{\int_{-T}^{T} p_l^2(t)dt \int_{-T}^{T} p_r^2(t)dt}} \right|_{\max} \qquad |\tau| < 1(\text{ms}) \tag{1}$$

where $2T$ is the integral interval, τ is time delay, and $p_l\,(t)$ and $p_r\,(t)$ correspond to impulse responses recorded at left and right ears of a dummy head. A large IACC makes listener perceive the well-defined direction of the incoming sound. A small IACC corresponds to subjectively diffused sound, and listener has no impression of clear direction of the sound.

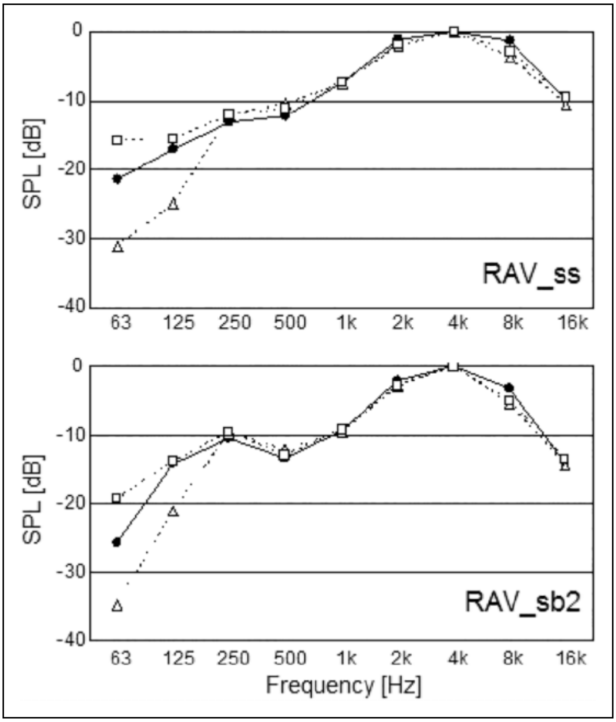

Figure 7. SPL as a function of band frequency: real IR (●), virtual IR by single stereo-dipole (△) and virtual IR by dual stereo-dipole (□), Ravenna 1/2.

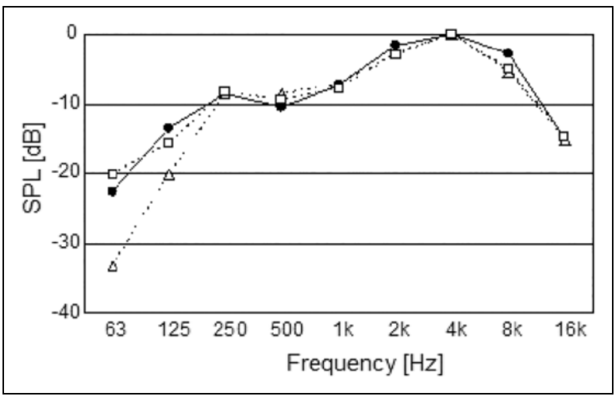

Figure 8. SPL as a function of band frequency: real IR (●), virtual IR by single stereo-dipole (△) and virtual IR by dual stereo-dipole (□), Ravenna 2/2.

During a performance of music, the acoustic characteristics (e.g. pitch and tempo) were varied as a function of time. Running normalised autocorrelation function (ACF) is necessary to observe the fluctuation of these characteristics, which could be influenced by the performance of walls and floors especially at low frequencies. For the blending of sound field and performance, Ando proposed τ_1 and τ_e to determine temporal acoustic characteristics of musical performances. The τ_1 and τ_e are factors of ACF as shown in

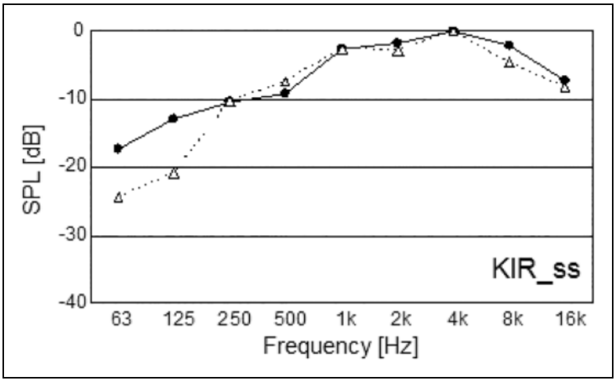

Figure 9. SPL as a function of band frequency: real IR (●) and virtual IR by single stereo-dipole, Kagoshima.

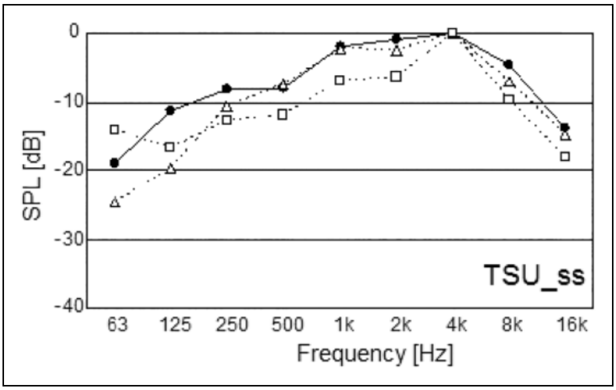

Figure 10. SPL as a function of band frequency: real IR (●), virtual IR by single stereo-dipole (△) and virtual IR by dual stereo-dipole (□), Okayama.

$$\phi(\tau) = \frac{\Phi(\tau)}{\Phi(0)} \tag{2}$$

where

$$\Phi(\tau) = \frac{1}{2T} \int_{-T}^{T} p'(t) p'(t + \tau) dt \tag{3}$$

and $2T$ is the integral interval that slides along the duration of music, τ is time delay, and $p'(t)$ is an original acoustic signal after passing through the A-weighting filter. The ACF factors are τ_1 is a delay time of the maximum peak, and τ_e is an effective duration of ACF, defined by the delay time at which the envelope of the normalised ACF becomes and then remains smaller than 0.1 as shown in Figure 17.

Value of τ_1 indicates pitch of the signal, and value of τ_e is repetitive feature that corresponds to kinds of musical instrument, tempo of the motif and pattern of playing like legato or staccato.

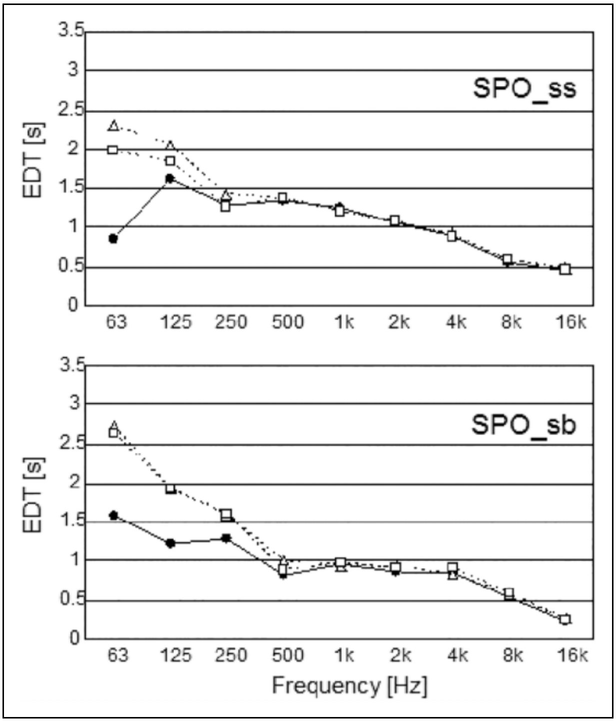

Figure 11. EDT: real IR (●), virtual IR by single stereo-dipole (△) and virtual IR by dual stereo-dipole (□), Spoleto 1/2.

BIRs of Teatro Nuovo in Spoleto

In the following study, we analyse only two kinds of BIRs (namely 'BIRn1' and 'BIRn2') measured in Teatro Nuovo in Spoleto. The BIRs were recorded using omnidirectional pre-equalised loudspeaker (Look Line) and dummy head (Neumann KU100). The loudspeaker was located on two positions of the stage; near (BIRn1) and far (BIRn2) from the frontal edge of the stage, and the dummy head was located in the middle of the stalls. IACC for all-passed octave band from 125 Hz to 4 kHz BIRn1 and BIRn2 resulted, respectively, 0.339 and 0.26. Figure 18 illustrates the spectral characteristics of IACC in these BIRs.

Anechoic musical motifs

Four kinds of an anechoic musical motif generated by MIDI are used, 'Melody A by trumpet', 'Melody A by piano', 'Melody B by piano', and 'Melody B by organ'. The scores of Melody A and Melody B are shown in Figure 19. The duration of the musical motif is 30 s.

To observe the acoustic characteristics of these anechoic musical signals, we calculated the running ACF using $2T$ of 1 s with 0.1 s sliding steps (Figure 20).

The results show that τ_1 is affected by the difference of musical instruments (trumpet, piano, or organ) and τ_e is mainly affected by the difference of melody (Melody A or Melody B). It is not easy to determine a unique representative value to express the difference between Melody A and Melody B, because ACF factors change dynamically along the signal duration. In particular, the values of τ_e increase to extensively high value, so that the mean value of τ_e is meaningless.

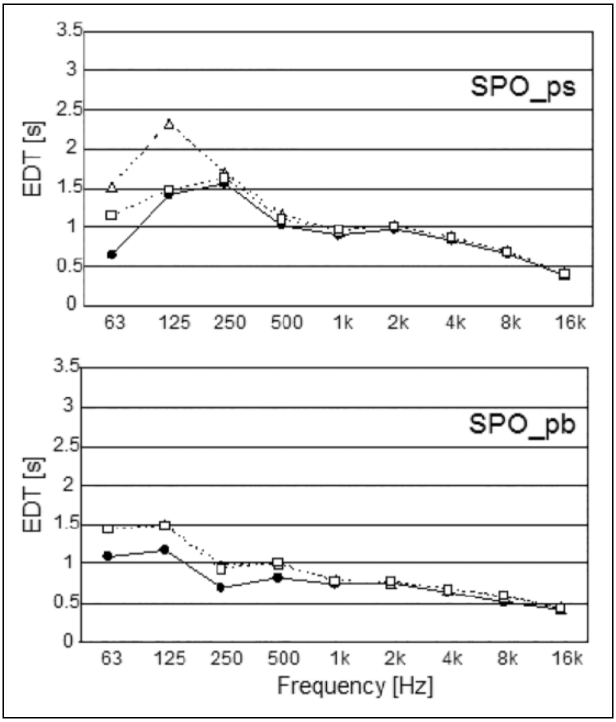

Figure 12. EDT as function of band frequency: real IR (●), virtual IR by single stereo-dipole (△) and virtual IR by dual stereo-dipole (□), Spoleto 2/2.

In this study, the 300 values obtained by running ACF in a rate of 0.1 s along the duration of 30 s were converted into the histogram, and the representative values were determined by the 50% probability of cumulative frequency. These values are termed 'τ_1 (50%)' and 'τ_e (50%)', and they are listed in Table 4.

Procedure of stereo-dipole

The single stereo-dipole representations were carried out in the Arlecchino listening room. The experimental setup is the same as shown in Figures 2 and 3. Using Adobe Audition, we generated log swept-sine signal that was presented by two loudspeakers alternately.

After deconvolution of signals, the Invert Kirkeby method described in section 'Generation of cross-talk cancelling filter' was adopted and the cross-talk filter was generated from impulse response.[15–17]

The 'anechoic music motifs' were convoluted with the impulse responses of Teatro Nuovo in Spoleto and the 'echoic music' obtained was convoluted again by the cross-talk cancelling filters. The convoluted music was presented by the two loudspeakers at the same time and recorded by the dummy head. The recorded musical motifs are defined by 'virtual echoic music'.

Results

The temporal fluctuations of IACC in cases of the echoic music (thick line) and the virtual echoic music (thin line) are compared in Figure 21 (Melody B by piano was not employed in the stereo-dipole examination). Analysing Figure 21, the following conclusion could be obtained.

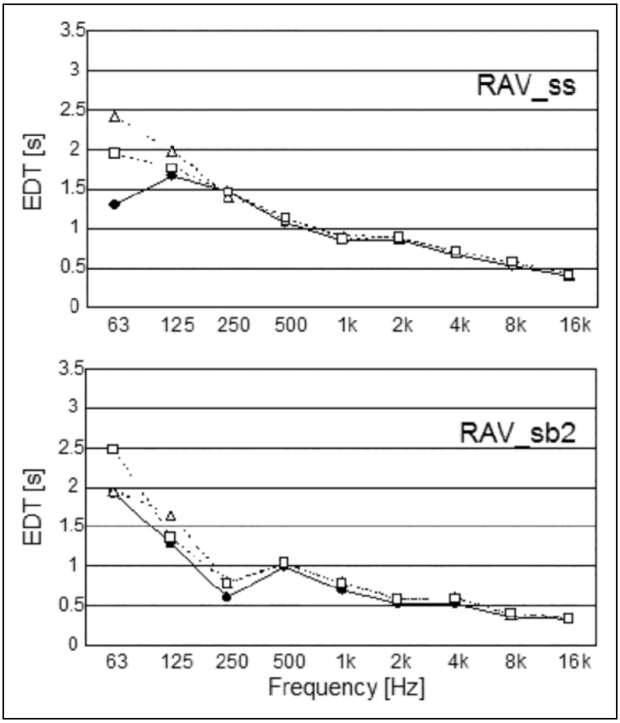

Figure 13. EDT as a function of band frequency: real IR (●), virtual IR by single stereo-dipole (△) and virtual IR by dual stereo-dipole (□), Ravenna 1/2.

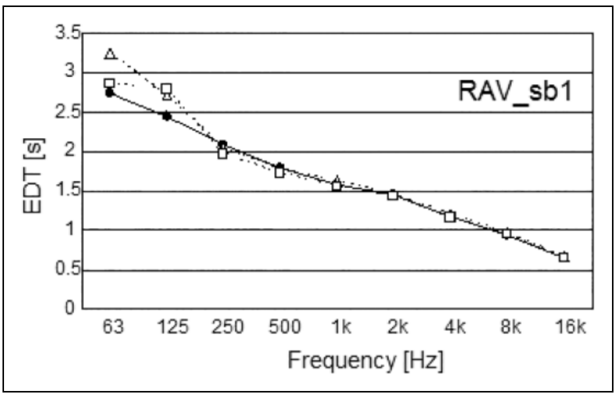

Figure 14. EDT as a function of band frequency: real IR (●), virtual IR by single stereo-dipole (△) and virtual IR by dual stereo-dipole (□), Ravenna 2/2.

First of all, the steady state value of IACC normally obtained from the BIRs, is really different from the running value of IACC obtained convolving the BIRs with the anechoic music. This means that what listeners experience in a real performance could vary considerably in terms of IACC from the single BIR.

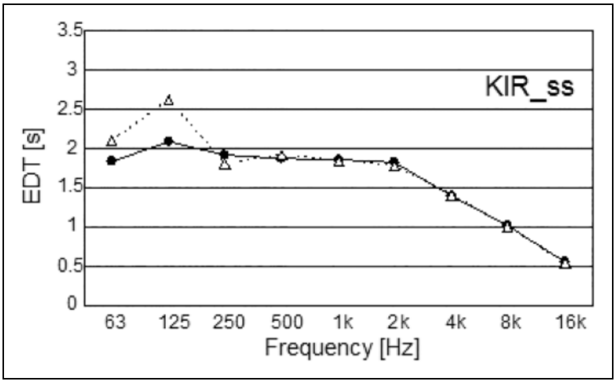

Figure 15. EDT as a function of band frequency: real IR (●) and virtual IR by single stereo-dipole (△), Kagoshima.

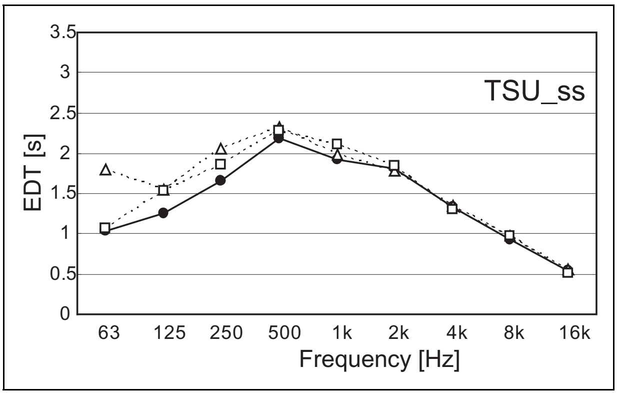

Figure 16. EDT as a function of band frequency: real IR (●), virtual IR by single stereo-dipole (△) and virtual IR by dual stereo-dipole (□), Okayama.

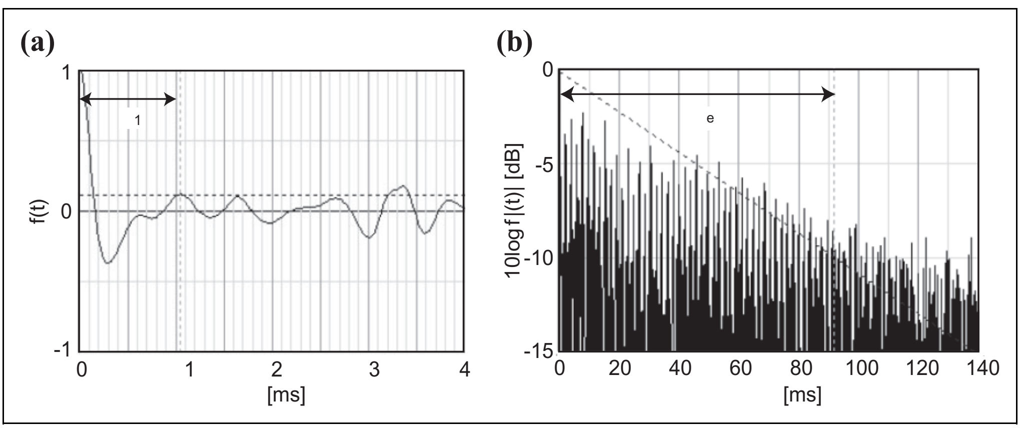

Figure 17. Definition of ACF factors: (a) τ_1 and (b) τ_e.

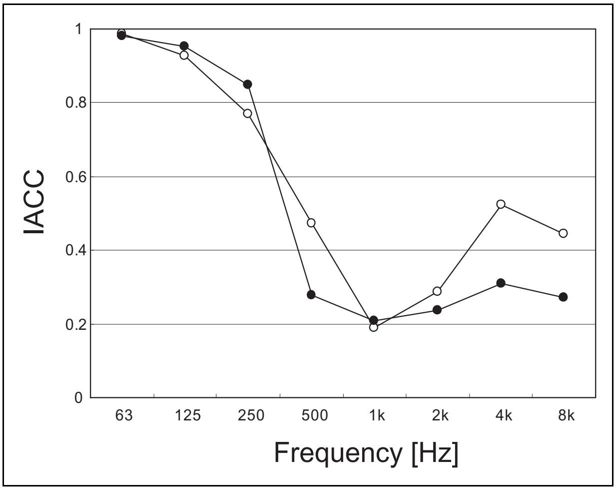

Figure 18. IACC of BIRn1 (○) and BIRn2 (●) as a function of frequency band.

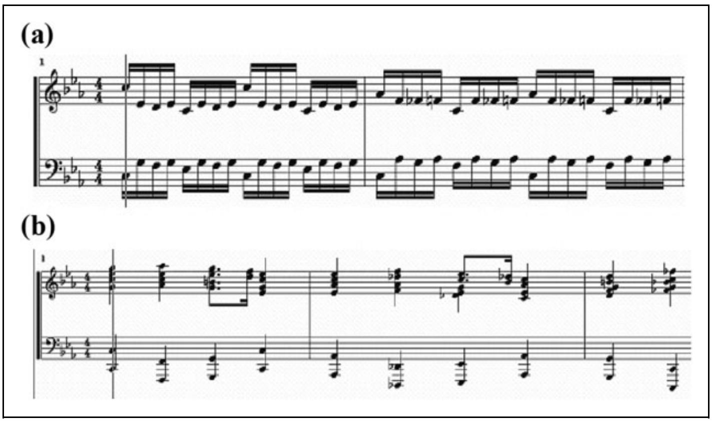

Figure 19. (a) Scores of Melody A and (b) scores of Melody B.

Considering the different music motifs and timbre of different musical instruments, we could see that in case of Melody A by piano, the values of IACC are similar among the echoic and virtual echoic music. For Melody A by trumpet, the values of IACC for echoic and virtual echoic music are very different from each other. This means that the timbre characteristics could considerably influence the running value of IACC. For Melody B by organ, IACCs simultaneously fluctuate between the echoic and virtual echoic music, and at some moments are quite different from each other. In case of BIRn2, the running value of IACC (convolved with Melody B by organ) has an offset of 0.2 if compared with the IACC obtained from the BIR.

Moreover, different distribution of IACC between the echoic and virtual echoic music is compared. The running IACC arranged a long time is converted into a histogram, and the cumulative frequency is rearranged along IACC (Figure 22). The distributions of IACC are so close when the sound source is Melody B by organ. On the contrary, in the case of Melody A by trumpet, the distributions of IACC for echoic music and virtual echoic music are different from

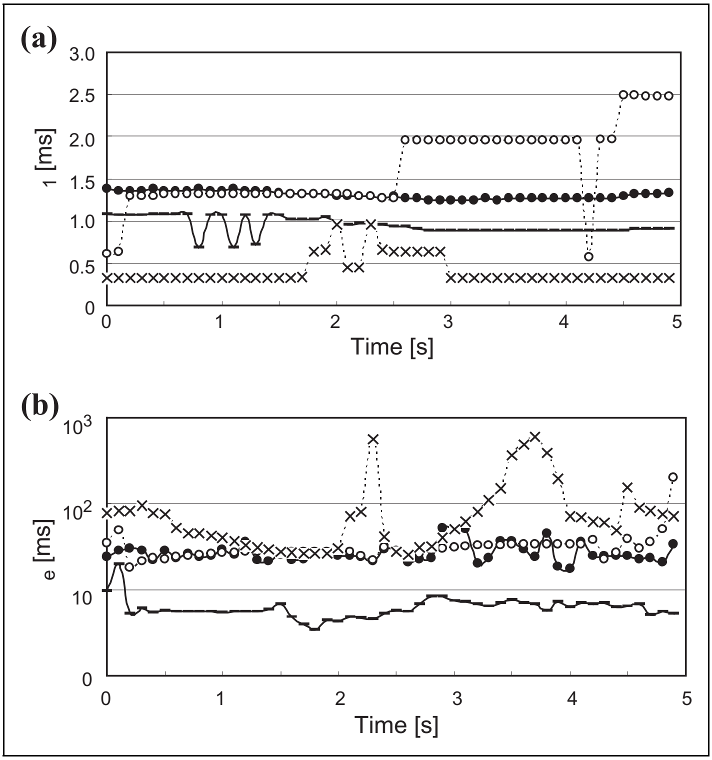

Figure 20. Different symbols indicate different musical motifs: (–) Melody A by trumpet; (●) Melody A by piano; (×) Melody B by organ; (○) Melody B by piano. (a) ACF factor $\tau_1$for 5 s and (b) ACF factor τ_e for 5 s.

Table 4. Anechoic musical motifs and their τ_1 (50%) and τ_e (50%).

Musical motif	τ_1 (50%) (ms)	τ_e (50%) (ms)
Melody A by piano	1.33	246.5
Melody A by trumpet	0.88	54.9
Melody B by organ	0.46	526.7
Melody B by piano	1.94	308.8

each other. Moreover, the case of BIRn2 improves the accuracy of virtual echoic music compared to the case of BIRn1.

The difference of IACC between the echoic and virtual echoic music could be calculated as following

$$Error = \int_{1}^{100} |IACC_{echoic}(x) - IACC_{vechoic}(x)|dx \tag{4}$$

where $IACC_{echoic}$ (x) and $IACC_{vechoic}$ (x) are the values of IACC calculated from the echoic music and the virtual echoic music in the probability x%, and the results are shown in Table 5.

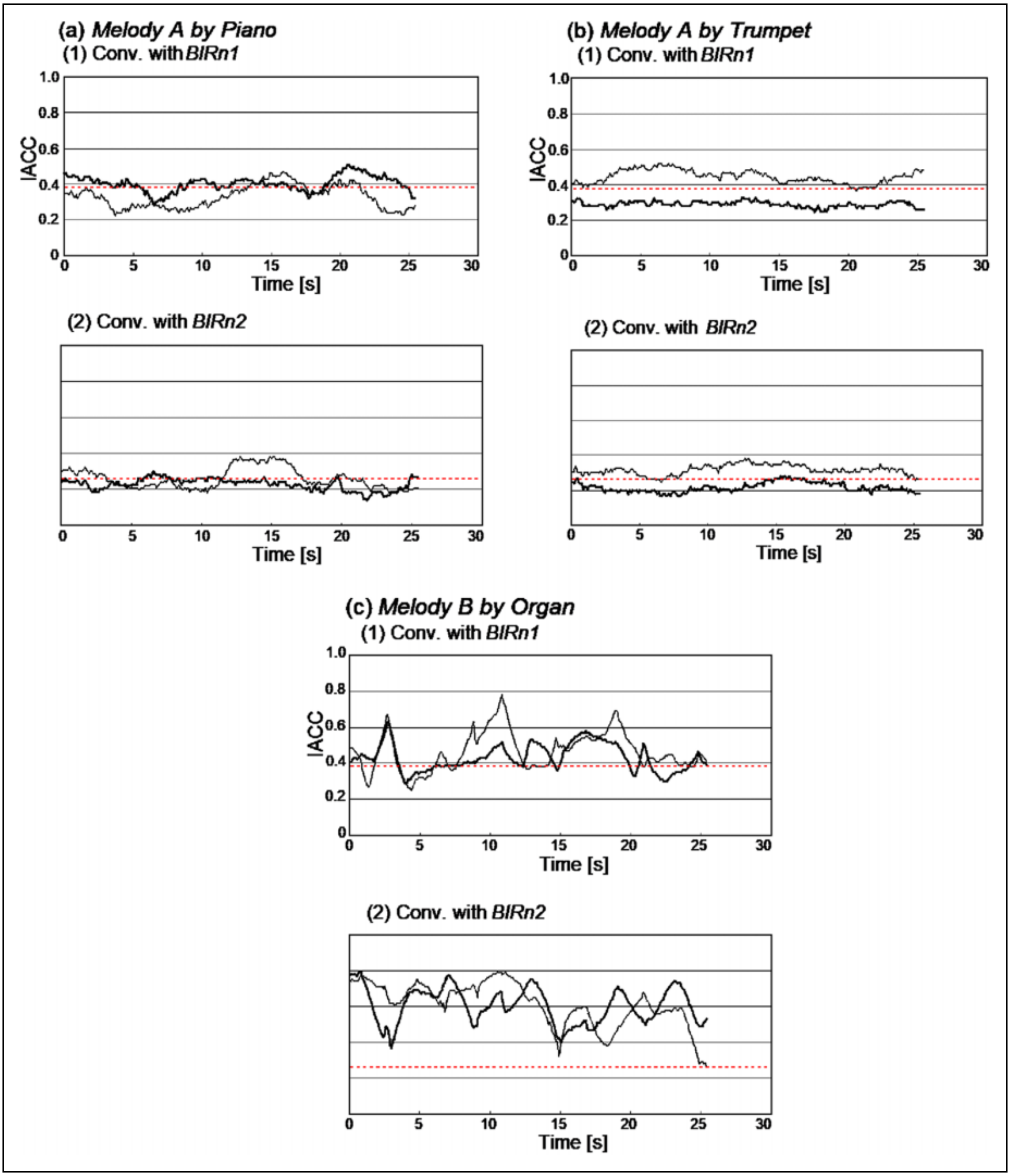

Figure 21. Running IACF as a function of time. The thick lines indicate echoic music and thin lines indicate virtual echoic music. The red dotted line indicates the values of IACC calculated from the all-passed BIRs.

The accuracy of the stereo-dipole technique depends not only on the characteristics of each BIR, but even more on the musical motif. Although the music motif is the same, there are differences due to the timbre characteristics of musical instruments. In other words, the errors of Melody A by piano and Melody A by trumpet are different. Even though the number of different motifs is not enough to support the statistical significance, having considered only two melodies, the error values have a good correlation with τ_e (50%) extracted from anechoic musical motifs.

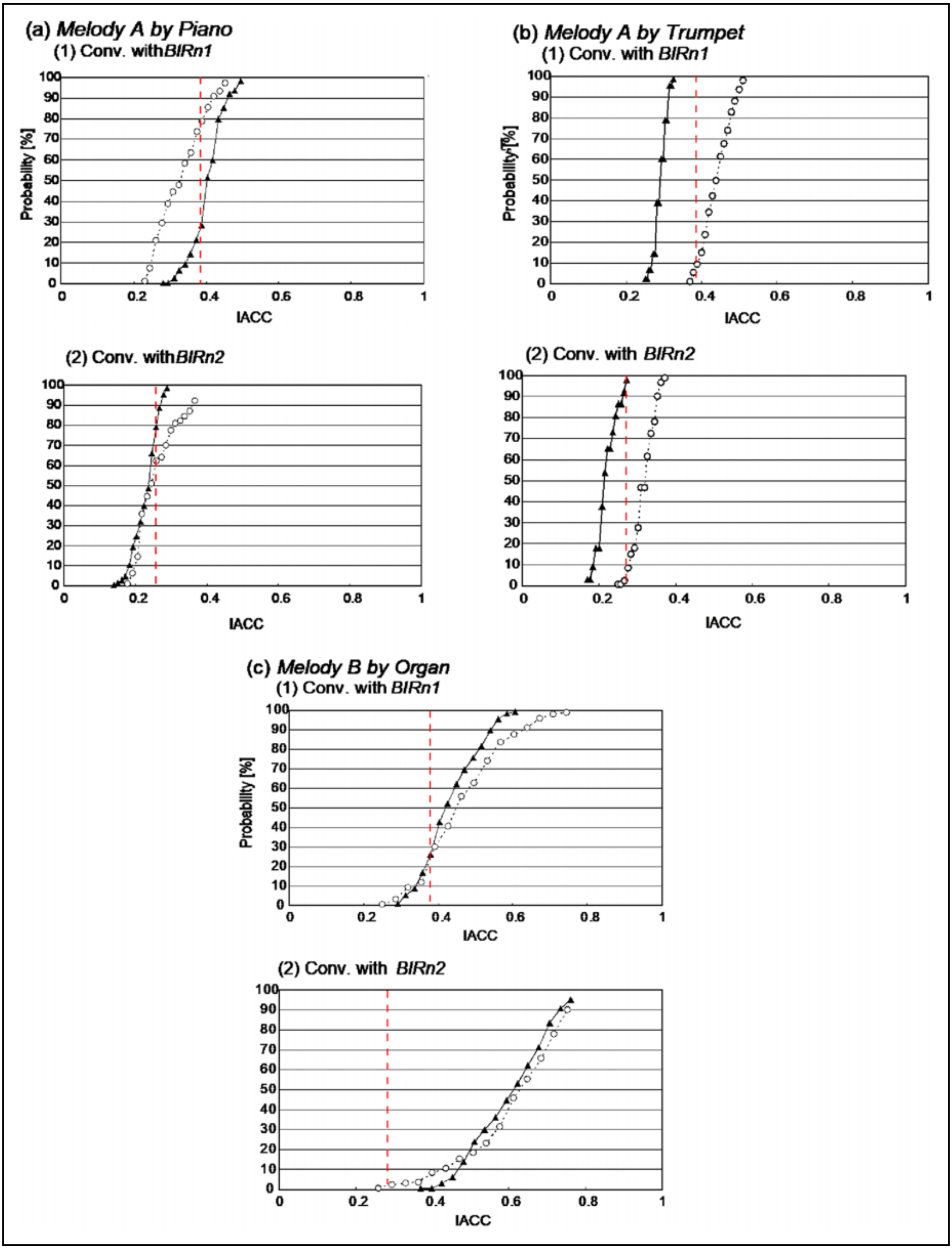

Figure 22. Cumulative frequencies as a function of IACC of the echoic music (▲) and the virtual echoic music (○). The red dot line indicates the values of IACC calculated from the all-passed BIRs.

Table 5. Errors of IACC arranged in terms of BIR and musical motif.

Musical motif	BIRn1	BIRn2
Melody A by piano	0.07	0.03
Melody A by trumpet	0.16	0.10
Melody B by organ	0.04	0.03

Conclusion

The first part of this study was focused on the effectiveness of the stereo-dipole playback system, employed in the listening room 'Arlecchino'. To validate the virtual sound field, the acoustic parameters calculated from BIRs measured in two Italian opera houses and two Japanese auditorium have been compared with those virtually measured by means of the same dummy head after the virtual reconstruction obtained in the listening rooms. The results showed that the values of SPL and EDT of the virtual BIRs are close to the real BIRs especially in the high-frequency range. Moreover, the gap between real BIRs and virtual BIRs for these acoustic parameters has been reduced by carrying out the dual stereo-dipole technique. Therefore, the stereo-dipole technique employed in the Arlecchino listening room has been successfully verified and it can be used for psychoacoustic experiments, including three-dimensional (3D) auralisation for checking new technological solutions during the acoustic design process.

In the second part of this study, 'echoic' music (sound convolved with real BIRs) and 'virtual echoic' music (sound convolved with virtual BIRs) obtained considering three music anechoic motifs and BIRs measured in Teatro Nuovo in Spoleto, were considered to check the variation of the binaural acoustic parameters with different signals. The error of IACC comes to the range from 0.03 to 0.16 and this result confirms that the stereo-dipole technique can reproduce the virtual sound field of the Italian opera house with high correlation. The accuracy dependents both on the kinds of BIR and on the kinds of the musical motif. Moreover, the experiments pointed out that running IACC could depend also on the timbre of the musical instrument employed for the experiment. It is interesting to notice that the anechoic musical signal with longer τ_e improves the accuracy of stereo-dipole representation. In subsequent studies, acoustic quality of theatres like the Teatro Nuovo in Spoleto should be evaluated from the measurements of BIRs to check acoustic improvement proposed during design process.

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