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Acoustic characterization of on-stage performers in performing spaces

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ABSTRACT

The influence of on-stage performers on the acoustic characteristics of performing spaces is significant because the musicians are absorptive and close to the sound source. However, the acoustic information of the musicians and their effect on absorption, scattering, and diffusion remain unclear. The acoustic characteristics of musicians were measured in a reverberation chamber and a semi-anechoic chamber while varying the type of clothes, the instruments, and seating density. The clothing worn showed a larger impact on the absorption per person, whereas the addition of cellos resulted in low-frequency absorption per person. The addition of cellos also increased the scattering and diffusion characteristics. Finally, the total absorption by the musicians under various conditions was analyzed in a concert hall using the simple Sabine equation where the influence of the musician's instruments resulted in reverberation time of more than 0.1 s decrease with about 90 musicians on stage. However, the influences of additional musical instruments resulted in no significant difference in the reverberation time compared to the people alone. In addition, scattering due to the various conditions of orchestra such as the seating density and the addition of musical instrument was not a significant predictor of reverberation time.

1. Introduction

Measurements of the room acoustics of performing spaces have been obtained for a venue in the vacant state, but the actual playing environment is fully occupied by both the audience and musicians on stage. Musicians on a performing stage are the sound source and absorbing materials at the same time. For accurate prediction of the sound field of the space, it is necessary to understand the acoustic characteristics of the musicians, including their clothes, musical instruments, and furniture. The sound pressure levels with the spaces occupied by the instruments and chairs decrease in the audience compared to an empty stage [1]. The early sound level can be interfered with by the musicians on stage [2]. The absorption characteristics of musicians were quantified with real and 1:10 scale models in a reverberation chamber [3]. The equivalent absorption area of musicians in different-sized orchestras have been presented and absorption was utilized to predict the reverberation of fully occupied states [4]. However, the absorption and diffusion characteristics of the musicians can vary depending on conditions related to the musicians.

Computer simulations in buildings are diversely used to predict the acoustic conditions [5–7], and the acoustic properties of the building elements are required for the accurate estimations [8,9]. Because people in buildings are also affecting the room acoustics, researches have been conducted to quantify the sound absorption characteristics of people and furniture for the prediction of room acoustics in various spaces. Traditionally, there have been many studies of the method used to measure the reverberation chamber to quantify the absorption properties of the audience and chairs in a concert hall. Kath and Kuhl [10] suggested placing the chairs in the corner of the reverberation chamber. Bradley [11] proposed to measure the various perimeter to area ratio of seating arrangements and predict the larger block of the auditorium seats by calculation of linear regression of the absorption according to the ratio. The major concern of these studies was to evaluate the edge effects of the audience in the reverberation chamber. Martellotta et al. [12,13] evaluated the absorption characteristics of occupied pews in a reverberation chamber. Based on the evaluation results, a method was proposed using simple prediction and computer simulations for the acoustic conditions in a church which has a large volume and long reverberation time [14]. Church seats are normally less absorptive and have a higher density than chairs in an auditorium. Moreover, Martellotta et al. considered a standing audience and their absorption with larger exposed surfaces than a seated audience. In the case of a class or lecture room with people and furniture, Vitale [15] measured the scattering coefficient and diffusion coefficient of tables and chairs in various shapes and arrays to understand the acoustic properties of the objects and to use the data for predictions. Thus, discrete objects including

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humans and furniture significantly affect room acoustics and it is necessary to consider them for each prediction method for a particular space. Musicians on stage, compared to the general audience, are placed at certain intervals and have instruments and chairs. Therefore, it is expected that the absorption, scattering and diffusion characteristics of the performance space depend on the conditions of musicians. However, no quantified cases based on measurements have been published.

Therefore, various measurements were carried out to evaluate the absorption characteristics of the types of clothing, musical instruments, and the area occupied by the musician in the reverberation chamber. In addition, the scattering and diffusion coefficients were quantified by ISO methods [16–18] using a 1:10 scale model [9,19,20]. Based on the measurement results, a simple prediction method is discussed based on the use of the Sabine equation for the variation of reverberation time (RT) based on musician conditions and scattering coefficients were applied in a computer simulation.

2. Preliminary investigations on orchestra arrangements

An orchestra is an instrumental ensemble consisting of string, woodwind, brass, and percussion sections ranging from about 15 musicians in a small chamber orchestra to 100 musicians in a full-size orchestra (symphony or philharmonic orchestra). The size of the orchestra is determined according to the venue size and the music genre, and can be influenced by the era of the musical piece. A Baroque to modern orchestra typically has 34–110 musicians; the typical instrument configuration of the modern orchestra of 90–110 musicians [21] is shown in Table 1.

For the design of the stage floor area, the orchestra size and the orchestra instrument type should be considered. Beranek [22] determined that a musician occupies an area of 1.9 m^2. Harwood and Burd [3] measured the equivalent sound absorption area (absorption per person) assuming a seated person area of 2.3 m^2. Barron [23] pointed out that these values were too generous, instead suggesting areas for various instruments of 1.25 m^2 for the violin and wind instruments, 1.5 m^2 for the cello and larger wind instruments, 1.8 m^2 for the double bass, 10 m^2 for the timpani, and 20 m^2 or more for other percussion members. According to the typical orchestra containing 90–110 musicians, the net covered areas were calculated to be 151.5–179.2 m^2.

As a case study, an arrangement of the orchestra was surveyed in a concert hall. The layout was manually measured with tape lines during the break time of the rehearsal. The total stage area was about 270 m^2 and the net covered area in this layout was 168.5 m^2 with 100 orchestra members. The calculation of the layout based on Barron's approximation was 156 m^2. The difference was caused by the strings, which occupied a larger space of 1.6 m^2/person due to the larger stage area. On a larger stage, musicians tend to spread out to available areas [23], so the acoustic characteristics of the musician seating density need to be investigated. From case studies, Barron's approximation of the net area per musician was confirmed, and the orchestra density depends on the stage size of the concert hall as well as the orchestra size according to the instrument components.

Table 1
Arrangements of a modern orchestra containing 90–110 members. The covered area is calculated based on Barron's area per musician [23].

Instrument	Small	Large	Area per musician	Covered area (small)	Covered area (large)
Woodwinds					
Piccolo	1	1	1.25	1.25	1.25
Flutes	2	4	1.25	2.50	5.00
Oboes	2	4	1.25	2.50	5.00
Cor anglais (English horn)	1	1	1.25	1.25	1.25
Bass clarinet	1	1	1.25	1.25	1.25
Clarinets	2	4	1.25	2.50	5.00
Bassoons	2	4	1.25	2.50	5.00
Contrabassoon	1	1	1.25	1.25	1.25
Brass					
Horns	4	8	1.25	5.00	10.00
Trumpets	3	6	1.25	3.75	7.50
Trombones (1–2 bass trombones)	3	6	1.80	5.40	10.80
Tuba	1	2	1.80	1.80	3.60
Percussion					
Timpani	1	1	10.00	10.00	10.00
Drums, Cymbals	1	1	20.00	20.00	20.00
Mallet percussions (Glockenspiel, Xylophone, Vibraphone, Marimba)	1	1			
Triangle, Tambourine	1	1			
Keyboards					
Piano	1	1	5.00	5.00	5.00
Celesta or pipe organ	1	1	1.80	1.80	1.80
Harp	1	2	1.80	1.80	3.60
Strings					
1st Violins	16	16	1.25	20.00	20.00
2nd Violins	14	14	1.25	17.50	17.50
Violas	12	12	1.25	15.00	15.00
Cellos	10	10	1.50	15.00	15.00
Double basses	8	8	1.80	14.40	14.40
Total	90	110		151.5	179.2

3. Methods

3.1. Absorption characteristics

3.1.1. Measurement setup

The absorption per person of the musicians were measured in real and 1:10 scale-model reverberation chambers according to the ISO 354 guidelines [16]. The volumes of the reverberation chambers were 325 m^3 and 0.253 m^3, respectively. Two omnidirectional speakers (B&K Type 4296, Denmark) were employed at two positions in the real reverberation chamber, and a high-voltage electrical spark source was employed at two positions in the scale model. Impulse responses were recorded three times at six receiver positions using 1/2″ microphones (G.R.A.S Type 26CA, Denmark) and 1/8″ microphones (B&K Type 4138, Denmark). A total of 36 impulse responses were obtained for the RT measurements in the 1/3-octave bands from 100 Hz to 5 kHz for the real scale and from 1 to 50 kHz for the 1:10 scale. Absorption per person were calculated from the RTs, with and without musicians. Absorption per person from 125 Hz to 4 kHz were obtained as octave values, derived by averaging the center frequencies of the 1/3-octave bands. The real and scale-model chambers were maintained at temperatures of 20.0 ± 0.2 °C and 27.4 ± 0.9 °C and relative humidity of 67.7 ± 0.6% and 57.0 ± 3.5%, respectively.

3.1.2. Measurements on the real scale

The absorption per person of orchestra musicians on stage were measured to quantify the acoustic characteristics depending on the performance clothing, the type of instruments, and seating density in a reverberation chamber, as shown in Fig. 1. The musicians were located at the center of the floor without an edge screen. In the real reverberation chamber, nine seated people in performance dress including jackets were spaced at a density of 2.3 m^2 per person. In addition, the absorption per person were measured for nine seated people with instruments, including nine violins each, nine cellos each, and six violins and three cellos mixed. The woodwind