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Experimental study on the relationship between the reflections from surrounding performers and acoustic properties

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ABSTRACT

Concert halls, which are ubiquitous in cities, provide a venue for live music performances that are beloved by the public. However, the global pandemic of COVID-19 has led to restrictions on live music performances in concert halls. One such restriction requires performers on stage to maintain a certain distance from one another. This is because the droplets that are emitted by performers when performing musical instruments have been identified as a potential source of COVID-19 infection. To minimize the risk of infection, it has been recommended that wind instrument performers maintain a distance of at least 2 meters from one another, and that string instrument performers maintain a distance of 1.5 meters. However, adhering to these distances can make it challenging for performers to play their instruments. Previous studies have suggested that such challenges may affect the ability of performers to hear themselves and others on stage, but the specific causes of these difficulties have yet to be fully elucidated. The purpose of this study is to clarify the effects of different distances between performers on acoustic properties and auditory perception. Specifically, a sound field was created in an anechoic chamber using acoustic panels that simulated performers, and the impulse responses and acoustic properties were measured by varying the distance between these panels. In addition, subjective evaluation experiments were conducted using the measurement results. The study found that changes in the distance between performers affect not only auditory perception but also the acoustic properties of the sound field. These effects arise from reflections from surrounding performers at different distances and the absorption of sound by performers. The findings of this study will contribute to the creation of a more comfortable environment for performers.

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1. Introduction

Concert halls, ubiquitous in cities, provide venues for live music performances beloved by the public. However, the global COVID-19 pandemic led to restrictions on live music performances in these venues. One such restriction required performers on stage to maintain a certain distance from one another due to the potential risk of COVID-19 transmission through droplets emitted while playing musical instruments. To minimize this risk, it was recommended that wind instrument performers maintain a distance of at least 2 meters from one another, and string instrument performers maintain a distance of 1.5 meters [1-2]. However, these distancing measures posed challenges for performers, making it difficult to hear the sounds made by surrounding musicians.

Previous studies by Gade et al. have identified that performers in bands and orchestras can experience difficulties when listening to their performances on stage, including hearing other performers or feeling discomfort from reflected sound [3-4]. Various researchers have conducted studies on stage performers from both subjective (performers' evaluations) and objective (acoustic parameters) perspectives, employing a variety of approaches [5]. The auditory perception of stage performers is influenced by complex factors such as the structure of the stage, the number of performers, the directivity of the instruments, and the arrangement of the performers. Consequently, the specific causes and the relationship between performers' subjective evaluations and corresponding objective parameters have not been fully elucidated.

We hypothesized that the difficulties performers experienced during the COVID-19 pandemic could provide insights into the environmental factors affecting performers on stage. Therefore, we studied the performers' experiences during the COVID-19 pandemic, with a particular focus on the relationship between the distance of performers, their sound-absorbing capacity, and their performance style.

An experiment conducted by Sato et al. conducted measurements in a reverberant room to determine the sound absorption capacity of humans. Their results indicated that in a room with a capacity of 160 people (reverberation time of 1.8 seconds), when 80 people were dispersed throughout the room, the sound absorption coefficient of humans was 0.42 in the frequency range of 300 Hz to 600 Hz [6-7]. The sound absorption coefficient of a 6mm plywood + 90mm air layer was 0.10 at 500 Hz [8]. Wind instruments exhibit varying frequency ranges. In orchestras and wind bands, each instrument plays a specific role in the melody, countermelody, bass, and other aspects, and instruments are organized into high, middle, and low registers. The 500 Hz frequency band falls within the midrange, making it a frequency that many instruments can produce. Therefore, since humans exhibit higher sound absorption than plywood, the sound of a performer's performance may still be absorbed by the surrounding performers, potentially affecting audibility.

The study by Dammerud and Barron suggested that the auditory perception of other performers' sounds on stage is altered by the presence of surrounding performers [9]. In large ensembles like symphony orchestras, the significant number of performers on stage means that the distance between some performers is large, with many other performers seated in between. This causes the performers and music stand to act as small barriers, obstructing the paths of direct sound and reflections from the floor. Dammerud and Barron's study investigated the sound pressure levels on stage with and without a large orchestra present, without a stage enclosure. They found that the sound diffracts and reflects around individual performers, and the shielding effect of the orchestra increases with higher frequencies. In the octave bands above 500 Hz, the orchestra's presence significantly attenuated the sound propagating within the orchestra. Skålevik's study, which conducted Maximum Length Sequence (MLS) measurements on sound transmission through a symphony orchestra, also demonstrated that sound transmission within the orchestra is significantly attenuated above 500 Hz [10]. While these studies are related to the audibility of other performers' sounds, we believe that the reflections from surrounding performers could similarly affect the audibility of one's performance.

Although not conducted in a concert hall, Fujii's research examined the average sound pressure level in a room when the positional relationship between the sound source and the sound-absorbing surface in the room was altered [11]. Experiments using omnidirectional speakers demonstrated that sound reduction became more effective when the sound-absorbing surface was closer to the sound source. Additionally, the difference between the sound absorption coefficient and the average room sound absorption coefficient increased. These findings suggest that sound reduction is more effective when the sound-absorbing surface is sharply directional.

Given that musical instruments have directivity [12-14], we can hypothesize that the distance between performers and the auditory perception of one's performance are related. This study aims to investigate how the distance between performers on stage influences the ease of playing musical instruments. Specifically, we analyze the sound absorption capacity of performers on stage and its impact on acoustic properties. We also examine whether differences in the distance between surrounding performers affect the auditory perception of one's performance.

2. Methodology

2.1 Measurement of Impulse Responses

The goal of this study was to examine the potential influence of performers' distances on acoustic properties. To this end, we set up a sound field in an anechoic chamber that simulates a partial arrangement of a wind ensemble or orchestra and measured the impulse responses. The acoustic properties were derived from the impulse response measurements.

Impulse responses are generally obtained by outputting an impulse and simultaneously capturing its response. However, the energy of the impulse itself is small, making it difficult to generate a large impulse and, consequently, challenging to achieve a sufficient signal-to-noise ratio (SNR) during measurement. To ensure a satisfactory SNR for the measurements, the impulse response was measured by outputting a time-stretched pulse (TSP) from a speaker placed within the sound field [15-16].

2.2 Equipment Used in the Experiment

The following equipment was utilized to measure impulse responses:

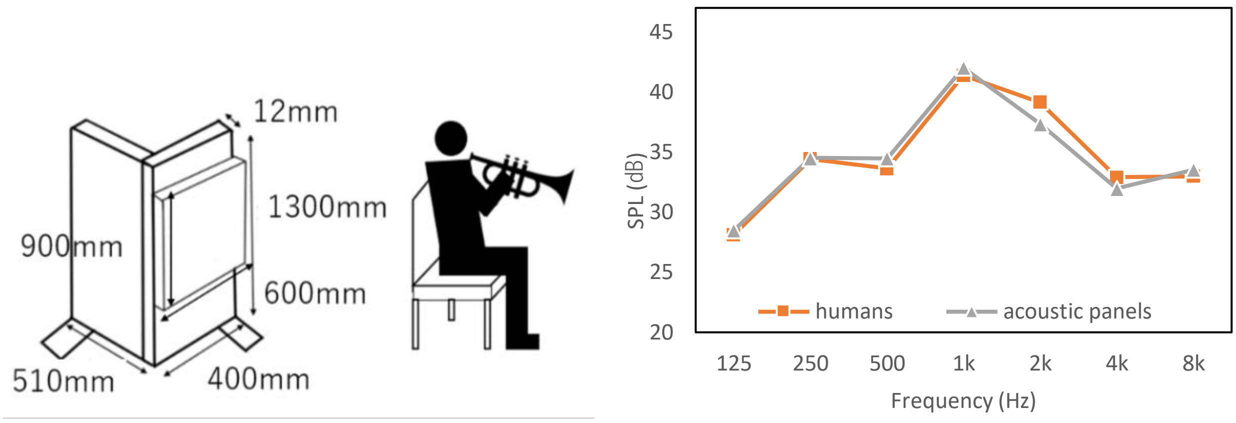
Speaker: YAMAHA POWERED MONITOR SPEAKER MODEL HS50M
Binaural Microphone: Adphox BME-200
Microphone Amp: audio-technica MICROPHONE AMPLIFIER AT-MA2
Audio Interface: RolandUSB Audio Interface Rubix24
Acoustic Panels that imitated performers

A near-omnidirectional source is commonly used to measure the impulse responses [17]. However, this study utilized a directional speaker to evaluate the performer's auditory perception when playing a directional instrument. To approximate the performer's auditory perception, binaural microphones were used, with one attached to each ear.

2.3 Acoustic Panels that Imitate Performers

While using human subjects to measure impulse responses in the sound field would have been ideal for investigating the impact of the distance between performers on acoustic characteristics, we conducted experiments using panels that simulate seated performers as a foundational study. This setup, referred to as the "acoustic panel" shown in Figure 1(a), comprised panels with attached sound-absorbing material. The sound-absorbing material was attached to a unit consisting of two panels made from 12mm thick plywood standardized by the Japanese Agricultural Standard (JAS). One panel measured 1300mm in height and 510mm in width, while the other measured 1300mm in height and 400mm in width. The dimensions of these panels were based on the seated height and shoulder width of a person, assuming that each acoustic panel represents a seated performer. The sound-absorbing material used for this experiment had a sound absorption coefficient of 0.43 at 500 Hz, which is similar to that of an average person [18].

A preliminary study was conducted to investigate whether the acoustic properties of the performer and the acoustic panel setup are similar, by measuring the sound pressure level (SPL) for both humans and the acoustic panels using the sound field Type B6 shown in Figure 2(c). The results, shown in Figure 1(b), revealed similarities between the acoustic panels and human characteristics. Therefore, we decided to use the acoustic panels for subsequent experiments.



(a) Acoustic panel (b) Type B6

Fig. 1. Acoustic Panel (a) Detail of the acoustic panel (b) Comparison of relative sound pressure levels between persons and acoustic panel in sound field Type B6

3. Experiment 1: Effects of Surrounding Performers on the Acoustical Properties

3.1 Measurement of the Acoustical Properties

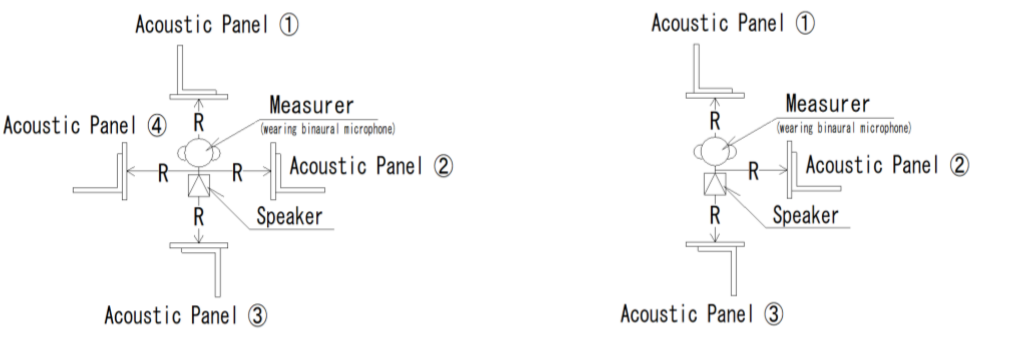
In an orchestra or brass band, performers are typically surrounded by other musicians positioned in four directions: front, back, left, and right, or arranged diagonally to enable the audience to see their faces. To recreate a simplified version of an orchestra or wind ensemble arrangement, we used an anechoic chamber to create five different types of sound fields. Figure 2 depicts the specifications of these sound fields.

To replicate the acoustic characteristics that actual performers experience from surrounding musicians, we placed human subjects wearing binaural headphones at the center of each of the five types of sound fields as the receiving point. The surrounding performers were simulated using acoustic panels. This setup allowed the target performer to experience the actual absorption and reflection properties of a human, thereby approximating the sound that the target performer would perceive in their left and right ears.

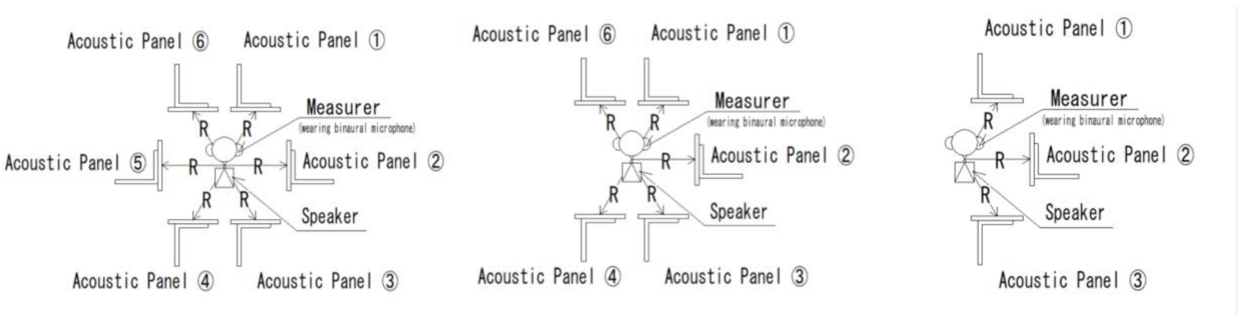
Type A represented a sound field with the target performer (human subject) in the middle, with the surrounding performers (acoustic panels) positioned in four directions. Type B represented a sound field with the surrounding performers seated in a diagonal direction. In this experiment, the changes in assumed performer positions were made depending on the number and placement of performers in the sound fields. The subjects in this experiment were assumed to be positioned in the middle (Type A4 and Type B6) or at the edge of a row (Type A3, Type B5, and Type B3) in an orchestra or brass band arrangement.

In the sound field, impulse responses were measured by varying the distance "R" between the sound source and the acoustic panels to 50 cm, 100 cm, 150 cm, and 200 cm. These distances were selected based on the limiting distances between the acoustic panels and the target performer, as well as between the acoustic panels and the side walls of the anechoic chamber. Gade recommended removing objects within a 2-meter radius around the transducer and maintaining a distance of at least 4 meters from the side walls when conducting stage acoustic measurements for orchestras [19]. This is an important consideration for capturing direct sound without interference from early reflections during analysis. However, Wenmaekers et al. pointed out that removing objects within these ranges would result in an unrealistic number of orchestra members being removed from the stage in an actual orchestral setting [20]. The objective of our study is to analyze the impact of the absorptive and reflective properties of performers on stage on acoustic characteristics. Therefore, considering the typical distances between performers in an actual orchestra, we conducted measurements even when the acoustic panels representing the target performer and surrounding performers were placed close.

The measurement conditions were denoted as "Type A or Type B amount of panels/distance R." For instance, when the distance "R" is 50 cm in sound field A4 shown in Figure 3(a), the condition was expressed as Type A4 / R=50 cm.



(a) Type A4 (b) Type A3



(c) Type B6 (d) Type B5 (e) Type B3

Fig. 2. Specifications of measurement sound fields

3.2 Result of the Acoustical Properties

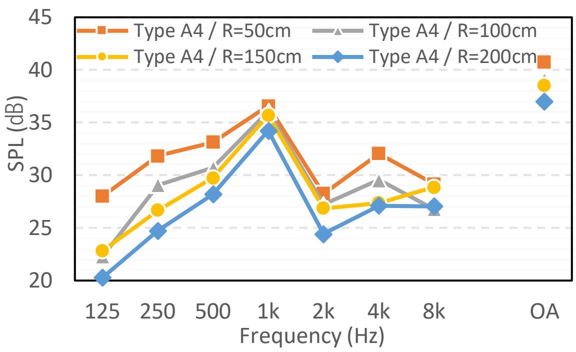
The measured impulse responses facilitated the acquisition of acoustic properties. This section presents the results of the sound pressure level (SPL) and the interaural cross-correlation (IACC), illustrating differences in acoustic properties under varying sound field conditions.

3.2.1 Result of the SPL

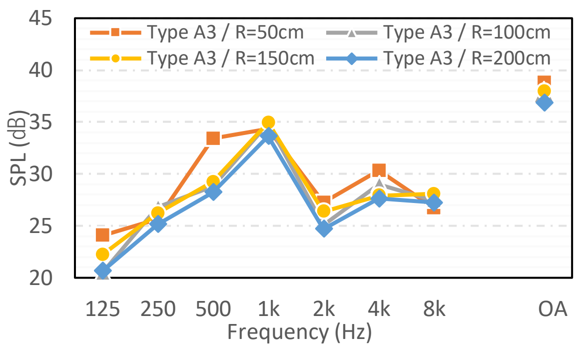
Figure 3 displays the SPL results at the right ear. Although the measurements were conducted binaurally, the experimental setup—including a symmetrical sound field and a sound field with an acoustic panel only on the left side of the target performer—resulted in the right ear having a more pronounced impact on the SPL.

As shown in Figure 3, the SPL decreased as the distance “R” between the sound source and the acoustic panels increased. Figures 3(a) and 3(c) illustrate that in the two symmetrical sound fields, Type A4 and Type B6, the difference in SPL at 500 Hz between R=50 cm and R=200 cm exceeded 5 dB. This difference in SPL is likely sufficient for performers to perceive a change in sound.

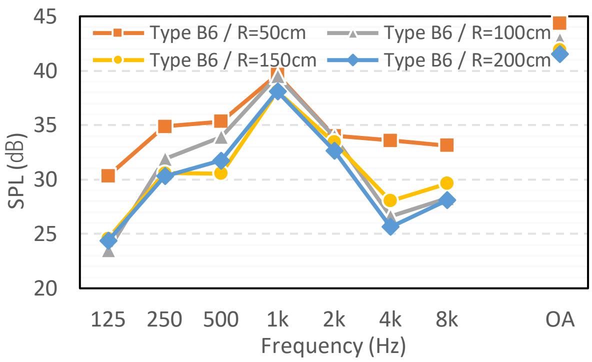
Furthermore, the frequency characteristics of the SPL varied between Type A4, Type A3, and Type B6, Type B5, and Type B3. In Type A, a significant dip was observed at 2 kHz, while in Type B, a notable dip occurred at 4 kHz. These differences were suggested to be due to the effects of sound diffraction and interference. In Type A, the acoustic panels were positioned in the direction of the speaker’s directivity, whereas in Type B, the front acoustic panels were placed 30° off from the direction of the speaker’s directivity. Consequently, the wavelengths most affected differed between the two types.



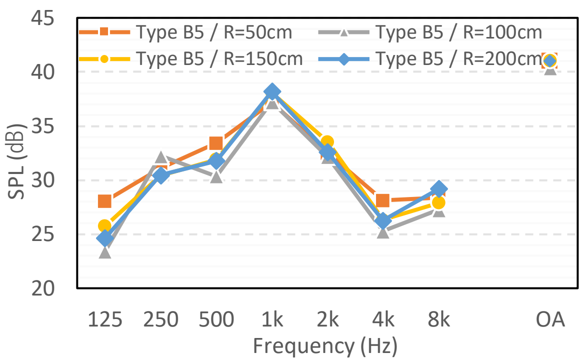
(a) Type A4



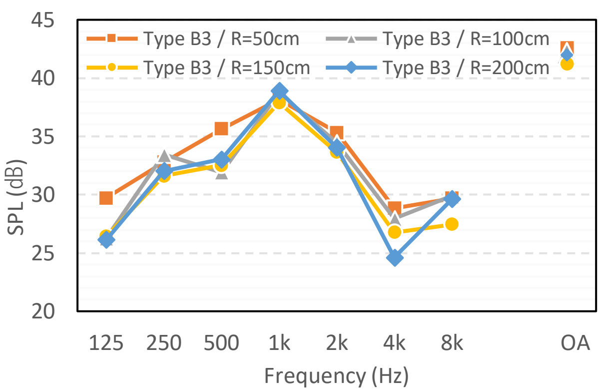
(b) Type A3



(c) Type B6



(d) Type B5



(e) Type B3

Fig. 3. Sound Pressure Level at the right ear versus the frequency octave band

Additionally, in the sound fields of Type A3, Type B5, and Type B3, the difference in SPL due to varying distances "R” between the sound source and the acoustic panels was minimal. This minimal difference was likely because Type A3, Type B5, and Type B3 were asymmetrical sound fields, and unlike the symmetrical sound fields (Type A4, Type B6), there were no panels on the right ear side. For the right ear SPL, in Type A3 at distances R=100 cm or more, and in Type B5 at distances R=150 cm or more, there was little difference across most frequency bands due to the varying distances between the sound source and the acoustic panels. In Type B3, there was little difference at distances R=150 cm or more, but a dip occurred in the frequency bands above 4 kHz. This dip could be attributed to the effects of sound diffraction and interference due to the speaker's directivity, although the exact cause was not determined.

In Experiment 1, given that the speaker used for the measurements had forward directivity, it was anticipated that reflections from the front acoustic panels would significantly affect the SPL. However, as shown in Figure 3, the small discrepancy in SPL in the asymmetrical sound field and the large discrepancy in the symmetrical sound field demonstrated that SPL is significantly influenced by other performers situated at the sides. This suggests that not only does the distance to the lateral performers affect the SPL, but it also impacts the auditory perception of the performers.

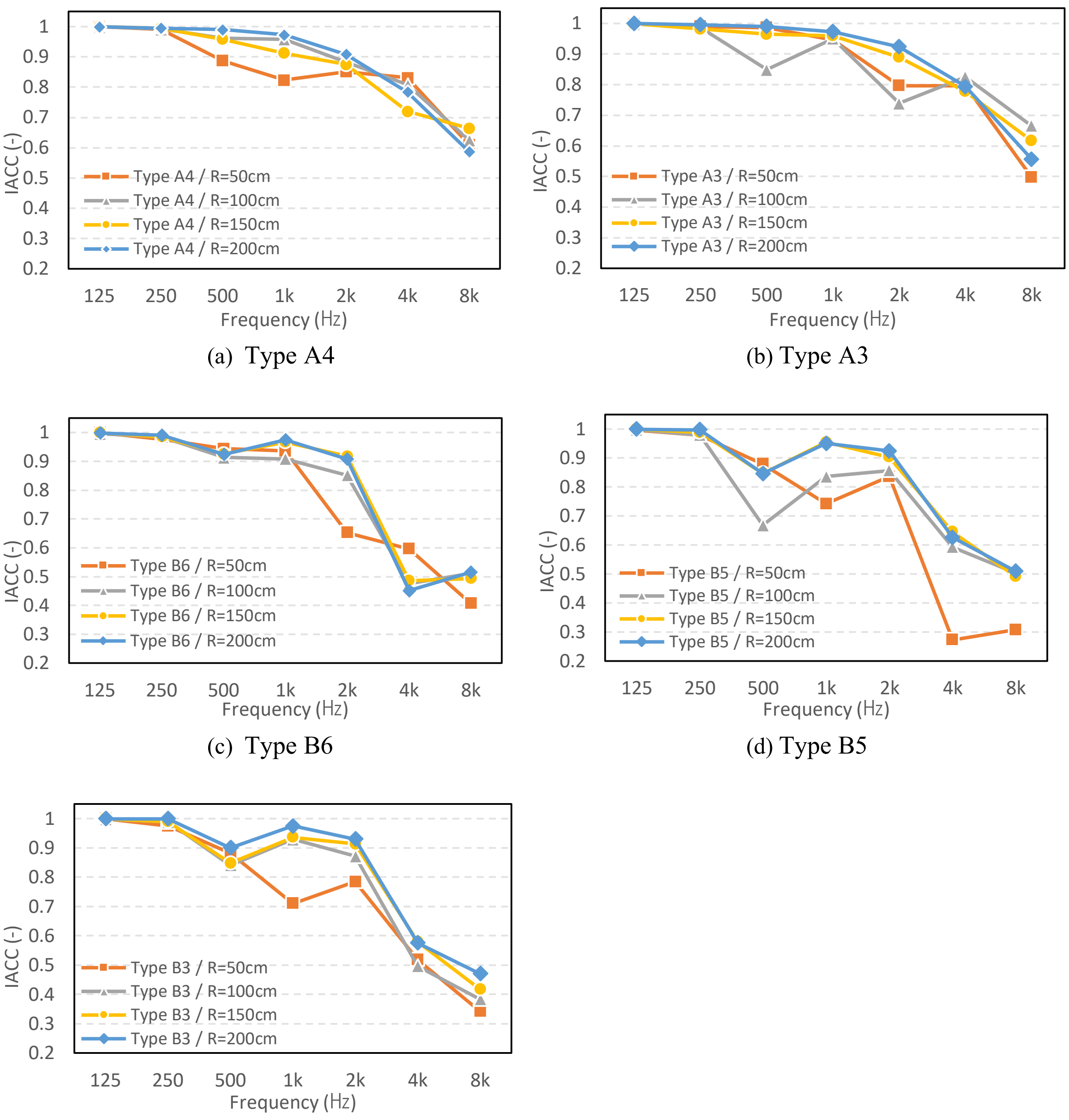
3.2.2 Result of the IACC

Figure 4 presents the results of the interaural cross-correlation (IACC). IACC measures the degree of signal discrepancy between sounds entering the two ears. A greater discrepancy in acoustic signals between the ears enhances the sense of spatial impression experienced by listeners.

The IACC value tended to decrease as the distance between the acoustic panels and the sound source decreased, with the highest value observed at R=200 cm. In Type A4 and Type B6, at R=50 cm, the IACC values at 4000 Hz exceeded those at other distances. Similarly, as shown in Figure 3, the SPL at R=50 cm was higher than at other distances, suggesting that at R=50 cm, the sound at 4000 Hz is significantly affected by diffraction and interference. Additionally, in Type A3, a significant dip was observed at 500 Hz and 2 kHz when R=100 cm, which can be attributed to similar reasons. Therefore, in other conditions, it can be said that the IACC generally decreased as the distance between the acoustic panels and the sound source decreased for frequencies above 2 kHz.

In the sound field Types A3, B5, and B3, shown in Figures 4(b), 4(d), and 4(e), effects appeared in the 500 Hz frequency band when the distance R was 100 cm. These exhibited a large reduction in IACC compared to the 250 Hz and 1000 Hz frequency bands. This indicates that in these sound fields, which are asymmetrical with no acoustic panel on the right side of the target performer, the diffraction of sound due to the distance between the sound source and the acoustic panels at R=100 cm was more pronounced compared to other distances. Sounds in the 500 Hz frequency band are present in various musical instruments, and the sound absorption coefficient of the acoustic panel at 500 Hz was close to that of a human, approximately 0.4 [13]. Consequently, performers positioned at the edge of a row detected a difference in the sounds they heard from their right and left ears, potentially impacting their ability to perceive their sounds clearly.

For sound fields B6 and B5, the IACC values exhibited minimal fluctuations when the distance "R" was 150 cm or more, as shown in Figures 4(c) and 4(d). Additionally, Figures 3(c) and 3(d) indicated that the SPL changed slightly when the distance "R" from the performers increased to 150 cm or beyond. Thus, it can be inferred that the acoustic properties tended to stabilize at a constant value as the distance between the performers on the left, right, and diagonal sides increased. Essentially, if the distance between performers is too great, the auditory perception may not notice any significant changes.



(a) Type A4 (b) Type A3

(c) Type B6 (d) Type B5

(e) Type B3

Fig. 4. IACC versus the frequency octave band

3.3 Discussion of the Acoustical Properties

Experiment 1 aimed to investigate the relationship between the distance of the target performer and the surrounding performers and to examine the acoustic properties using sound fields with acoustic panels. The results showed that as the distance between the performers increased, the IACC values tended to increase, while the SPL values tended to decrease. It was also suggested that destructive interference occurs at specific distances and frequency bands. This characteristic varied depending on the arrangement of the surrounding performers. When lateral performers were present, the differences in acoustic properties due to varying distances between performers were significant, whereas these differences were minimal when lateral performers were absent. Therefore, it was found that lateral performers affect the acoustic characteristics. However, the observed changes in the acoustic properties suggest the need for a more in-depth analysis to determine how the distance of surrounding performers influences auditory perception.

4. Experiment 2: Effects of Surrounding Performers on the Auditory Perception

4.1 Subjective Evaluation Experiment of the Auditory Perception

Experiment 2 was conducted to investigate whether the distance between the performers can influence both auditory perception and acoustic properties, and to examine the relationship between these two factors. In this study, we evaluated the impact of different performer distances on auditory perception by comparing the typical distances before and after the spread of COVID-19 [1-2].

Four sound sources were utilized in the experiment, created by convolving the impulse responses of Type A4 / R=100 cm, Type A4 / R=200 cm, Type B6 / R=100 cm, and Type B6 / R=200 cm with a dry sound source. Here, R=100 cm represented the pre-COVID-19 distance, while R=200 cm represented the post-COVID-19 distance.

The dry sound source used for the convolution was “Spring Song (Songs Without Words, Op. 62, No. 6)” by Mendelssohn. The initial 30 seconds of the piece were used in the experiment. This sound source was chosen because it includes tones from E3 (165 Hz), which marks the beginning of the standard playing range of a trumpet, up to approximately 1200 Hz, covering its primary range [21]. The dry sound source was recorded using a trumpet in an anechoic chamber, as the trumpet is a forward-directed instrument similar to the speaker directivity used in Experiment 1. Additionally, the trumpet sound in this piece was characterized by frequencies in the 500 Hz band, which prominently reflected the effects of changes in acoustic characteristics due to varying distances between the target performer and the acoustic panels in Experiment 1.

This study involved eight subjects, four men and four women, each with over seven years of musical experience in amateur wind ensembles. The subjects entered a pre-room of an anechoic chamber with low background noise and listened to the created sound sources through headphones. They then evaluated four items related to the auditory perception of performers: brightness, spatial impression, clarity, and intensity [22]. Sheffe’s ANOVA on Paired Comparison (Nakaya Variation) was employed as the evaluation method [23]. This method involves having each participant compare all possible pairs of two different sound sources once, without considering the order of comparison [24]. The reason for choosing this evaluation method was to reduce the number of trials by not considering the order of comparison, thereby allowing the subjects to focus on listening to and comparing the two presented sound sources. The subjects rated which of the two presented sound sources better matched each evaluation item on a 5-point scale. The subjects were asked questions using a questionnaire written in Japanese for each evaluation item.

4.2 Result of the Auditory Perception

Figure 5 presents the results of the main effects obtained from evaluating the perception of “brightness,” “spatial impression,” “clarity,” and “intensity.” The perceived trend for each evaluation item increased with a higher value of the main effect.

The significance levels (P) for each evaluation item were calculated from the obtained main effects. The results indicate statistically significant differences for “brightness” and “intensity,” as their significance levels were less than 5%. For “spatial impression,” the significance level was between 5% and 10%, suggesting a high level of significance. However, the significance level for “clarity” exceeded 10%, indicating no statistically significant difference. Therefore, it was considered that there were perceptual differences in “brightness,” “intensity,” and “spatial impression” due to the different sound field conditions used in the experiment, while there were no perceptual differences in “clarity.”

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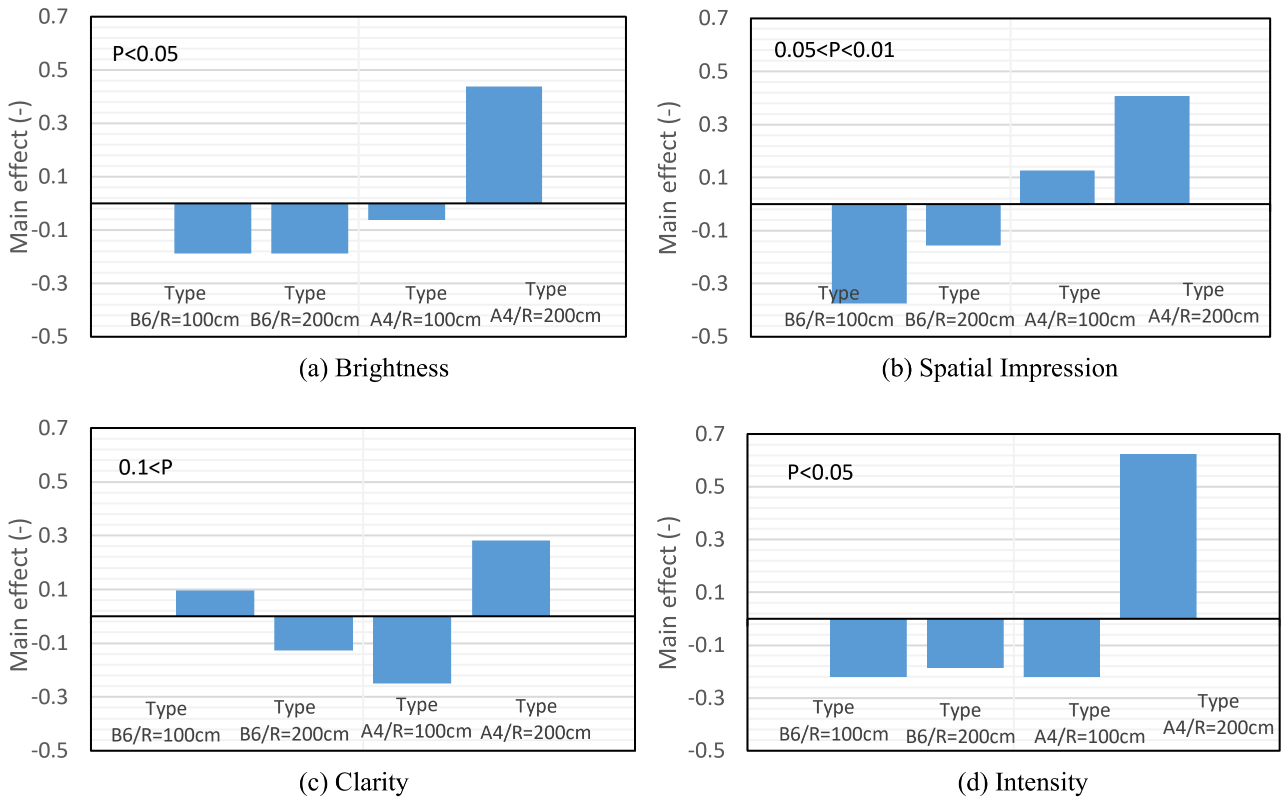


(a) Brightness

(b) Spatial Impression

(c) Clarity

(d) Intensity

Fig. 5. The main effects obtained from the evaluation

Figure 5 indicated that the subjects perceived a greater degree of “brightness,” “spatial impression,” and “intensity” with the Type A4 / R=200cm sound source compared to the Type A4 / R=100cm sound source. Subjects also reported experiencing a greater degree of “spatial impression” with the Type B6 / R=200cm sound source than with the Type B6 / R=100cm sound source. Notably, the difference in perceived “brightness” and “spatial impression” between the two distances was found to be more pronounced for the sound field Type A4 than for the sound field Type B6. This indicated that the presence of performers in front and behind has a greater impact on “brightness” and “spatial impression” due to differences in performer distances, compared to when performers are positioned at an angle.

Figure 5(d) further revealed that the participants experienced the highest degree of “intensity” from the Type A4 / R=200cm sound source, whereas the other sound sources did not elicit a similar response. This phenomenon was believed to be related to the SPL of the impulse response convolved with the sound source.

4.3 Relationship Between the Auditory Perception and the Acoustical Properties

4.3.1 " Intensity" and frequency spectrum

To investigate the correlation between the auditory perception of “intensity” and Sound Pressure Level (SPL), it was necessary to obtain a more detailed SPL measurement than the 1/1 octave band level. Therefore, Figure 6 presents the frequency spectrum calculated through Fast Fourier Transformation (FFT) analysis of the impulse response obtained from Experiment 1. The frequency spectrum primarily focused on the 165-1175 Hz range, which corresponds to the sound range of the trumpet used in Experiment 2.

Figure 6 illustrates that the SPL at approximately 400 Hz was lower in the sound field Type A4 / R=100 cm compared to the sound field Type A4 / R=200 cm. Furthermore, the SPL around 700 Hz was found to be lower in both Type B6 sound field conditions compared to Type A4 / R=200 cm.

Considering that the frequency range of the trumpet used as the sound source in Experiment 2 was 165 Hz to 1,175 Hz, the SPL at approximately 400 Hz and 700 Hz was significantly lower in conditions other than the sound field Type A4 / R=200 cm compared to the surrounding frequencies. Consequently, it was challenging for the subjects to perceive “intensity” due to certain sound regions being weaker than others in the sound sources. One possible reason for this is that sound field Type B6 had two more panels than sound field Type A4, creating an environment more conducive to sound absorption. As a result, specific frequencies might be attenuated in the sound field Type B6 compared to Type A4. Additionally, the reason why the sound field Type A4 / R=200 cm was perceived as having more “intensity” than Type A4 / R=100 cm could be attributed to the fact that the impulse responses used for the sound source were obtained in an anechoic chamber. Since the sound field Type A4 had only four acoustic panels, when these panels were placed further away, the sound field conditions became more similar to an anechoic environment compared to Type B6. Consequently, the impact of dips at specific frequencies was diminished, leading participants to perceive “clarity” as shown in Figure 5, and potentially causing confusion between the perception of “clarity” and “intensity.”

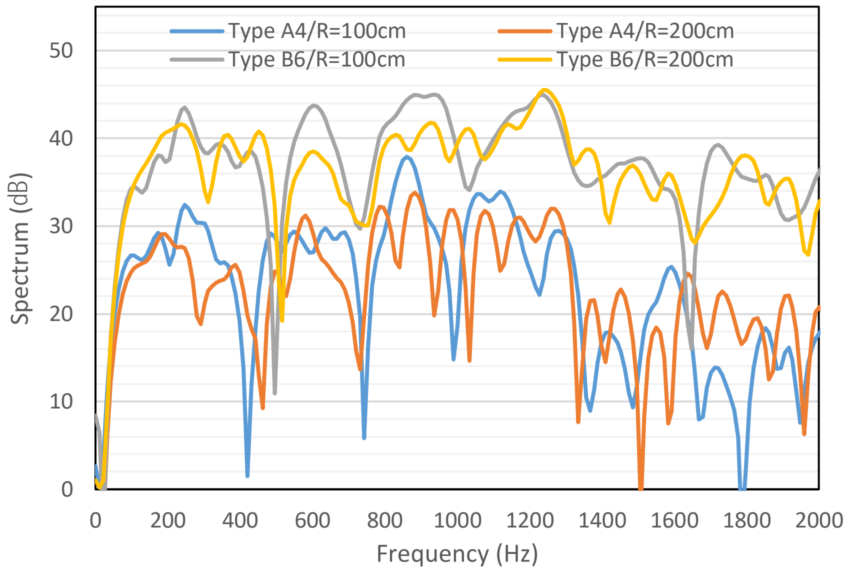


Fig. 6. Frequency spectrum at the right ear

4.3.2 Correlation coefficients between the main effects and the acoustical properties

The relationship between acoustic properties and auditory perception was investigated by calculating the correlation coefficients between the main effects and acoustic properties. Table 1 presents the correlation coefficients between the main effects and the interaural cross-correlation (IACC), while Table 2 displays the correlation coefficients between the main effects and Sound Pressure Level (SPL).

Notably, “clarity” did not show a significant correlation with either IACC or SPL. Even when the significance level was determined from the main effects of the subjects, no statistical significance was found. This indicated that there is no relationship between the sound field conditions and “clarity.” Other evaluation metrics demonstrated a positive correlation with IACC and the main effects, while showing a negative correlation with SPL and the main effects. It was observed that the correlation coefficient between “brightness” and SPL displayed a strong negative correlation of -0.8 or lower at frequencies below 2 kHz. “Spatial impression” exhibited a strong correlation with both IACC and SPL at frequencies below 500 Hz. The strong correlation at frequencies below 2 kHz was noted to be within the frequency range close to that of the trumpet, the sound source used in the experiment.

The strong correlation between IACC and SPL for “brightness” and “spatial impression” was confirmed in Tables 1 and 2. Therefore, Figures 7 and 8 illustrate these relationships. The frequency range of the acoustic properties in Figures 7 and 8 was in the 500 Hz band, which was also similar to the range of the trumpet.

Figure 7(a) indicated that the main effect of “brightness” was not significantly different between the sound fields Type B6 / R=100 cm and Type B6 / R=200 cm. Furthermore, the IACC values differed slightly between these sound fields. The result of Figure 8(a) found “brightness” to be strongly correlated with SPL, while the main effect and SPL values were not linear in sound field Type B6. Therefore, “brightness” was related to IACC rather than SPL.

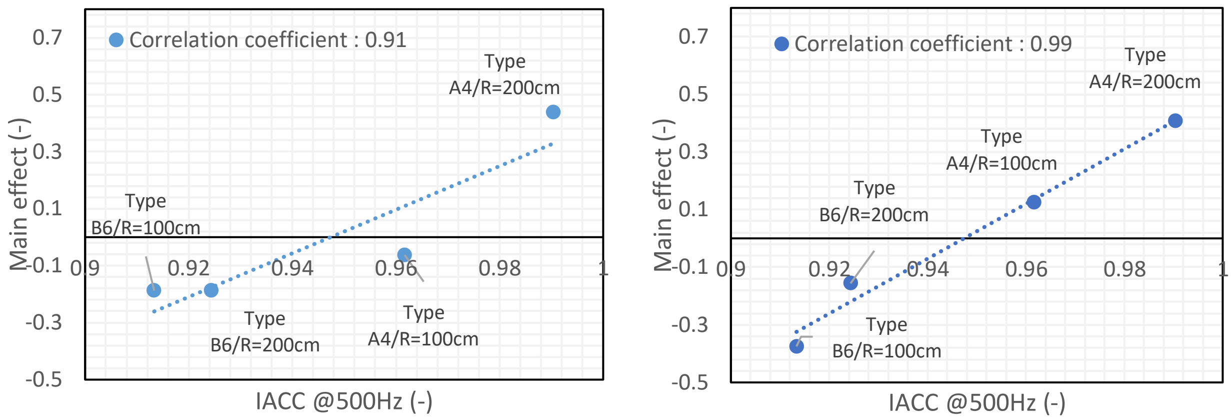
Figures 7(b) and 8(b) found a strong correlation between “spatial impression” and the main effects of both IACC and SPL, with both values being approximately linear. For Type A4 and Type B6, subjects reported a greater sense of “spatial impression” as the distance “R” between the sound source and the acoustic panels increased. It is generally believed that the stronger the “spatial impression” is perceived, the more non-identical the acoustic signals received by the right ear and the left ear become, making the IACC smaller. However, the results from Experiment 2 showed that subjects experienced a greater sense of “spatial impression” when the sound source had a larger IACC. This was considered to be due to the sounds being absorbed by the acoustic panels, reducing the likelihood of subjects experiencing a “spatial impression.” Conversely, when the number of acoustic panels was small or the distance “R” was large, the sound was absorbed not by the acoustic panels, but by the walls and floor of the anechoic chamber. In such cases, subjects were more likely to perceive the “spatial impression.”

Table 1
The correlation coefficient between Main effects and IACC.
Correlation coefficients at 500 Hz are presented in bold

Correlation coefficient	Brightness	Spatial Impression	Clarity	Intensity
125 (Hz)	0.67	0.93	-0.07	0.56
250 (Hz)	0.79	0.98	0.12	0.70
500 (Hz)	**0.91**	**0.99**	**0.33**	**0.80**
1k (Hz)	0.46	0.70	-0.12	0.44
2k (Hz)	0.53	0.67	0.07	0.55
4k (Hz)	0.69	0.87	0.05	0.52
8k (Hz)	0.51	0.78	-0.19	0.31

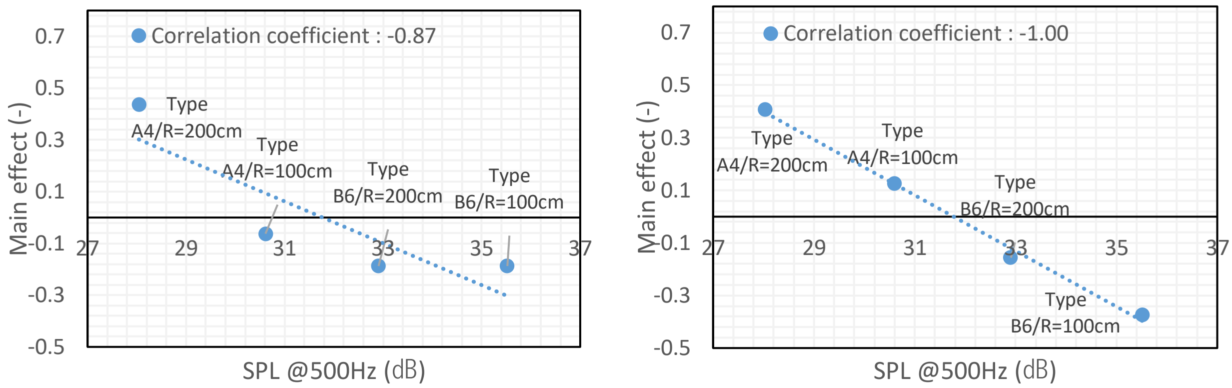
Table 2
The correlation coefficient between Main effects and SPL.
Correlation coefficients at 500 Hz are presented in bold

Correlation coefficient	Brightness	Spatial Impression	Clarity	Intensity
125 (Hz)	-0.90	-0.94	-0.39	-0.79
250 (Hz)	-0.94	-0.99	-0.40	-0.87
500 (Hz)	**-0.87**	**-1.00**	**-0.24**	**-0.77**
1k (Hz)	-0.85	-0.99	-0.20	-0.73
2k (Hz)	-0.85	-0.98	-0.22	-0.72
4k (Hz)	-0.42	-0.21	-0.59	-0.59
8k (Hz)	-0.67	-0.91	0.04	-0.51



(a) Brightness versus IACC (b) Spatial Impression versus IACC

Fig. 7. The correlation between Main effects and IACC in the 500 Hz band



(a) Brightness versus SPL (b) Spatial Impression versus SPL

Fig. 8. The correlation between Main effects and SPL in the 500 Hz band

5. Discussions

This paper shows the effect of the surrounding performers on the target performer from an experiment conducted in a sound field set up in an anechoic room. In Experiment 1, impulse responses were measured, and the acoustic properties were calculated by varying the distance between the performers in the sound field. In Experiment 2, subjective evaluation was conducted using the sound sources convolved with the impulse responses obtained in Experiment 1.

Regarding acoustic characteristics, it was observed that as the distance from the sound source to the acoustic panels increased, the IACC tended to increase while the SPL tended to decrease. Additionally, the position of surrounding performers also resulted in various outcomes in acoustic characteristics, and the manner of this influence varied across different frequency bands. The positions of the surrounding performers used in the experiment included in front of, behind, to the left of, to the right of, and diagonally relative to the target performer. The surrounding performers were positioned either asymmetrically on one side or symmetrically on both sides relative to the target performer, and this had a significant impact on the acoustic characteristics. The various acoustic outcomes in sound fields with different configurations suggest that both the IACC and SPL are influenced not only by performers positioned directly in front of the directional instrument but also by reflections from performers positioned to the sides and at angles.

As for the results of auditory perception, it indicated that the influence of audibility varied depending on the sound field conditions, such as the distance and position of the surrounding performers. There was a specific distance and frequency band between the sound source and the acoustic panels that tended to have an effect on SPL. This suggests that the subjects perceived the sounds of certain frequencies emitted from the sound source as relatively weaker than the sounds of other frequencies, making it difficult for them to perceive the auditory "intensity" of the sound. From these results, it can be concluded that in real wind bands and orchestras, there are sound ranges that are challenging for performers to hear because of the distance and positional relationships with surrounding performers.

The experimental results indicated that the perception of "brightness" and "spatial impression" tended to increase as the distance between the sound source and the acoustic panels increased. Correlations were also observed between the main effects of these evaluation items and the Interaural Cross-Correlation (IACC). However, contrary to the generally accepted correlation between IACC and "spatial impression," this experiment found that higher IACC was associated with a greater perception of "spatial impression."

In this study, it is possible that the impulse response of the sound field in the anechoic chamber was convolved with the sound source, resulting in a different outcome compared to a room with natural reverberation, such as concert halls. However, since this effect appeared in an experiment conducted in an anechoic chamber—an environment without external factors such as wall or floor reflections—the possibility of an increased change in IACC due to the difference in distance between performers and its effect on auditory perception cannot be denied when the same experiment is conducted in a reverberant environment like a concert hall. On the other hand, the relationship between acoustic characteristics and auditory perception needs to be compared with results obtained in environments other than an anechoic chamber.

6. Conclusions and Future Works

In this study, the effects of reflections and sound absorption by performers on acoustic properties were investigated by conducting experiments using acoustic panels (a setup that resembles a seated performer) and five different sound fields set up in an anechoic chamber. Additionally, the impact of the performers' positions and the changes in distance between performers on auditory perception and acoustic properties were examined.

The results of this study indicate that varying the distance and position of surrounding performers changes the impact of reflections and absorption experienced by the target performer. This not only affects the acoustic characteristics but also potentially leads to differences in auditory perception. Therefore, for actual orchestra and wind ensemble performers, differences in performer distances may result in varying levels of ease in performance. To further support this conclusion, future research should be conducted not only in anechoic chambers but also in concert halls or other environments with reverberation, using real performers instead of the acoustic panels utilized in this study.

This research investigated the relationship between acoustic properties and the auditory perception of performers on a concert hall stage, as well as examining the optimal distance between performers. Further investigation is planned to analyze the effects on auditory perception from varied distances between performers. These findings will be the subject of future research and will contribute to providing a comfortable performing environment for instrument performers.

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