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Experimental study on auditory impression of sounds produced by flutes in a concert hall

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ABSTRACT

The auditory impression of sounds produced by musical instruments differs depending on the distance at which they are perceived. In this study, we investigated the auditory impression of a musical performance of flutes in a concert hall, focusing on how the flute sounds reverberates in the hall we call this phenomenon "sonority." We conducted an experiment in which sounds produced by eight flutes were recorded at the stage and audience areas of a concert hall; these were presented to thirteen participants using a three-dimensional sound field reproduction system. They were asked to evaluate the sonority of each flute. After the listening session, we interviewed them regarding their definitions of sonority, and the perceived characteristics of their individual evaluations. The results demonstrated that the participants were divided into two groups based on their responses: one group focused on the difference in sound between the stage and audience area and the other group did not. It was also found that the hearing impression of general impression, loudness, transmission, and expression were related to the evaluation of sonority. From the acoustic analysis, results of the sound pressure level and dynamics of SPLs had moderate agreement with the subjective evaluation of sonority.

Keywords: Concert hall acoustics, Auditory impression, Sonority, 3-D sound reproduction.

1. INTRODUCTION

The auditory impression of sounds produced by musical instruments differs depending on the distance at which they are perceived. When an instrument is played in a concert hall, it is important for it to be heard by the audience while retaining the performer's musical expression. Furthermore, it is important for the performing musicians to review the characteristics of their musical instruments as to how they sound in a concert hall to give optimal performances.

One of the main phenomena related to the sound of the musical instruments in a concert hall is "sonority", we call "TOHNARI, SOBANARI" in Japanese. In general, "SOBANARI" is defined as a sound that is loud when listener is close to the instrument, but it is softer at a distance. "TOHNARI" is a sound that retains its quality even at large distances [1]".

Thus far, "TOHNARI" and "SOBANARI" have not been systematically studied, and the fundamental matters remain unclear, such as whether performers agree on the definition and evaluation of TOHNARI and SOBANARI. In this study, we used a high-definition sound field reproduction system to perform a listening experiment that presented performance sounds recorded simultaneously at two different points, onstage and in the audience area. Focusing on the TOHNARI and SOBANARI of each instrument, we conducted a listening experiment using the sound played by one flute player with eight instruments. In this paper, we introduce the main results from our previous study [2].

First, as a basic study on TOHNARI and SOBANARI, we examined the definitions of TOHNARI and SOBANARI given by the experimental participants and tried to grasp the outlines of their individual definitions. Second, the flute sounds were presented to the participants, and the evaluation of the degree of TOHNARI of each sound was examined. By analyzing the words that the participants commented, we investigated the hearing impression they associated the TOHNARI sounds with. Third, using the sound of the musical instruments, which were evaluated as TOHNARI and SOBANARI, the

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correspondence between subjective evaluation and the acoustical characteristics of the performed sound was examined.

2. EXPERIMENTAL SYSTEMS

2.1 3-D sound recording/reproduction system

In this study, we used the "Sound Cask" (Fig. 1, right) [3] to present acoustic virtual environments that are close to their real environments. The boundary surface control (BoSC) principle [4] was used to create the 3D sound field in the sound cask. The sound pressures at surface are reproduced at surface in the secondary sound field via an inverse filter matrix that is determined from the impulse responses of all possible combinations of loudspeakers and microphones. By combining the Kirchhoff-Helmholtz integral equation and the theory of inverse systems, the BoSC system can accurately reproduce a 3D sound field surrounded by a closed boundary surface [5-7].

The BoSC system comprises the BoSC microphone system (Fig. 1, left) and the reproduction room, namely, the sound cask (Fig. 1, right). First, the BoSC microphone system records the sound pressure on the surface of a volume defined by the BoSC microphone array. Next, the recorded signals are convolved with a set of inverse filters. Finally, the loudspeaker array in the sound cask accurately recreates the sound field in other locations by reproducing the convolved signals. In the BoSC system, the inverse filters are determined by an inverse system of a transfer function matrix measured for each loudspeaker and microphone pair.

The configuration of the BoSC microphone array is the same as that of a C80 fullerene. An omnidirectional microphone (DPA 4060BM) is at each of the 80 nodes of the fullerene. The diameter of the microphone array is approximately 46 cm. The area of the BoSC system to be reproduced is the region enclosed by the microphone array; thus, the system can reproduce a 3D sound field surrounding the head of a listener.

The sound cask (approximately 2 m x 2 m, H = 2.2 m) has a nonagonal horizontal cross section to avoid parallel surfaces, except for the floor and ceiling, and vertically its surfaces are set at three different angles. A porous sound absorbing material (100 mm) is attached to the inner wall; its 96-channel sound field reproduction system comprises 96 full-range loudspeakers (FOSTEX FE103EN) installed in every surface except the floor. The loudspeakers are installed in the walls in six rows, with 9 loudspeakers in the top and bottom rows, and 18 loudspeakers in each of the remaining four rows. Six loudspeakers are installed on the ceiling.

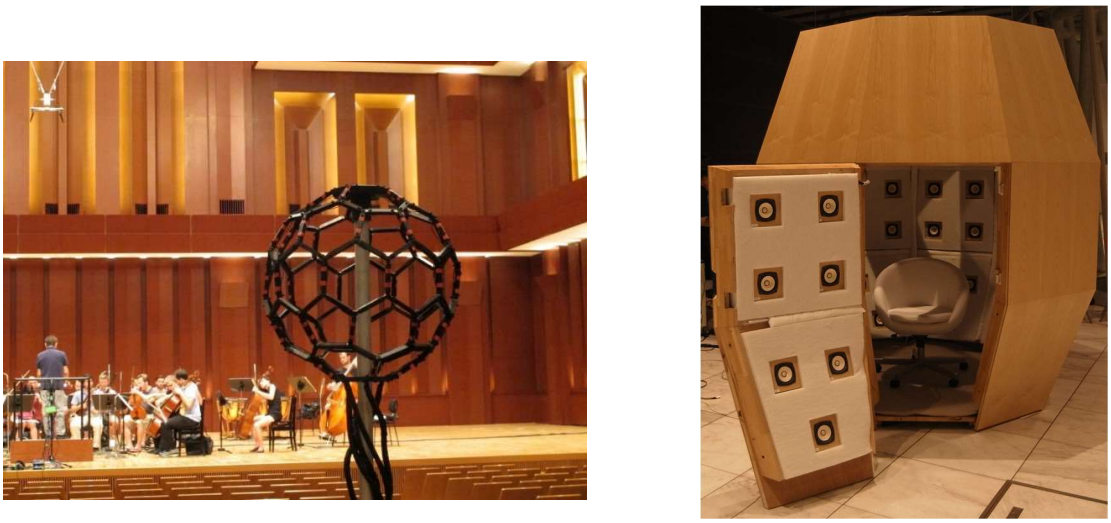

Figure 1 –BoSC system comprises BoSC microphone system (left) and sound cask (right)

2.2 Recordings of performed sound

The recording was conducted under concert conditions in a multipurpose concert hall with 1,200 seats (T_{30}=1.4 s). A 70-s phrase from Sonata f-moll by G. Ph. Telemann was performed without accompaniment and recorded both onstage and at a rear seat of the audience area (Figure 2). Eight flutes with various production ages and materials were played by a professional flutist with 34 years of experience. We asked the flutist to identify the individuality of each instrument while playing a style that makes use of this individuality.

Table 1 lists the flutes used in the experiment, their materials, countries of production origin, and

production dates. In addition, the characteristics of each instrument were described by the performer and the owner of the instrument in interviews.

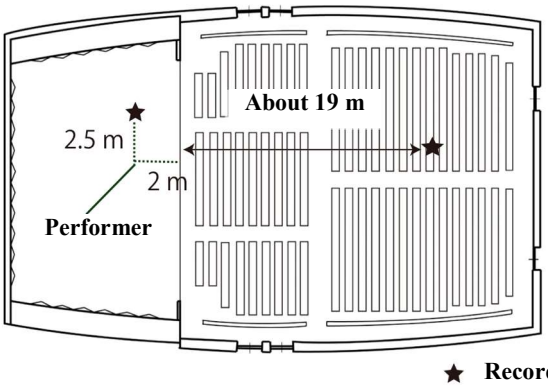

Figure 2 – Measurement points. Sound was recorded 2.5 m away from the performer on the stage. In the audience area, it was recorded 21 m away from the performer (19 m away from the stage edge).

Table 1 – Instruments tested in this study

Flute	Manufactured country	Materials	Manufactured age	Note by the owner and the performer
A	France	Nickel silver	late 19th C – early 20th C	Adjustment was insufficient.
B	France	Silver	late 19th C – early 20th C	Delicate and elegant tone.
C	USA	Silver	first half of 20th C	Sweet and elegant tone that shines at the concert.
D	France	Silver	middle of 20th C	Refined tone, it is liked by many even today, is said to be a masterpiece.
E	France	Silver	late 19th C– early 20th C	A tone common to D, manufactured by a craftsman at a D workshop.
F	Japan	14-karat Gold	1990s	Produced with emphasis on the feeling of wind playing.
G	Japan	18-karat Gold	2000s	The same manufacturer as F, the instrument that is daily used by the flutist performed for recordings in this study.
H	USA	19.5-karat Gold	2000s	Powerful and sharp tone.

3. LISTENING EXPERIMENT

3.1 Methods

In the listening test, the recorded sound sources were presented to thirteen participants — including nine professional flute players. A sound obtained by convolving the inverse filters of the BoSC reproduction room with the recorded sound of eight flutes was presented to the experiment participants as a test sound. The playback sound pressure level was set to be equal to the original sound field at the center of the reproduction area in the sound cask.

The participants sat at a chair in the sound cask, listened to the sounds of each instrument in the order of the stage and the audience, and wrote down their hearing impression for evaluation. The test sounds of the instruments were presented in a random order for each participant, without any prior knowledge provided on the instrument. The test sounds were presented repeatedly at the request of the participant.

After listening to all the sounds, the relative extent of the TOHNARI of each instrument was evaluated. In particular, the participants were shown a horizontal number line in which TOHNARI and SOBANARI were arranged at both poles, and then they were asked to place cards on this line corresponding to each instrument according to the degree of TOHNARI-SOBANARI perceived. They were asked to freely define the vertical number line to express the difference of characteristics of each instrument. Then, viewing the results of the placement of cards, we interviewed them on their definition of TOHNARI and SOBANARI and their hearing impressions related to their evaluations given per instrument.

3.2 Results and discussion

3.2.1 Definition of TOHNARI

From the interview surveys, although various vocabularies were used for the expression, there were common interpretations among participants, as follows. As for TOHNARI, it is "to be clearly at a large distance," and, for SOBANARI, "cannot be clearly heard at a large distance." TOHNARI and SOBANARI are opposites, and in this respect the results are in general agreement with the prevailing definitions.

It was found that the responses of participants could be divided into several groups depending on the focus of evaluation. For TOHNARI, there were some who defined only the sound from the audience (audience-focused group), and other participants who described the definition compared to the sound of the stage and the audience (comparison group). The audience-focused group defined the sound that can be clearly heard in the audience as TOHNARI and did not focus on how it sounded on the stage. Contrarily, in the comparison group, TOHNARI was defined as when sounds in the audience are heard as expected or better than expected by comparing the sound from the audience and the sound from the stage.

Regarding SOBANARI sounds, there were participants who focused only on the sound of the stage (stage-focused group) in addition to the above two groups. The stage-focused group defined the sound as SOBANARI when the sound was perceived as "loud on the stage," whereas in the audience-focused group and the comparison group, participants defined the sound as SOBANARI when it was not clearly heard in the audience. In the comparison group, they tended to decide "SOBANARI" when the sound was not clearly heard in the audience, compared with the sound on the stage.

3.2.2 Evaluation of each flute

Based on the psychological evaluation value where the experiment participant illustrated the degree of TOHNARI numerically, we ranked the instruments according to the extent of TOHNARI. As a result, the ranking of the instruments differed per participant, and there was no singular instrument that all participants agreed and described as "TOHNARI" or "SOBANARI". However, a common evaluation tendency was also found when the ranking was overviewed according to the above-mentioned definition groups for the focusing point. Figure 2 shows the percentages selected as top one and two rankings in the TOHNARI and SOBANARI evaluation respectively for each definition group. Here, for SOBANARI, the selection rate was displayed as one group of “non-comparison,” combining a stage-focused group and an audience-focused group.

TOHNARI: Looking at the selection rates by the definition groups, in the non-comparison (audience-focused) group, the selection rate of flute G was 80%. Whereas 70% of the comparison group selected flute H. Flute B had high selectivity, with 60% in the non-comparison group and 35% in the comparison group. Other instruments were not selected above the chance level at 25%. From these results, it was found that there are instruments such as B, which are evaluated as TOHNARI regardless of the focus of the participant, and instruments such as G and H, whose evaluation results changed depending on the focus of the participant.

SOBANARI: The difference in selection rates between the definition groups tended to be smaller than that of TOHNARI sounds. In terms of the selection rate of all participants, A was the highest at 54%, followed by F, E, and D.

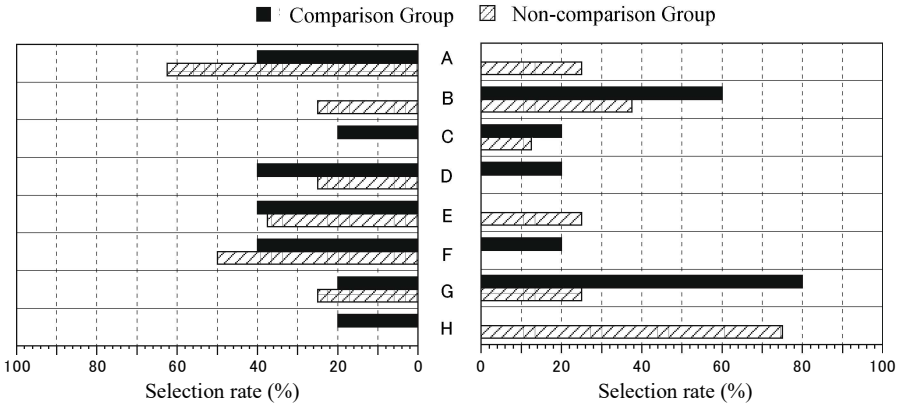

Figure 3 – Percentages selected as top one and two rankings in the evaluation of TOHNARI (right) and SOBANARI (left), as calculated for each participant group.

All the instruments were selected for the top two rankings, and high evaluations were not concentrated on a specific instrument. In the interview process, eleven out of thirteen participants commented that there are more flutes that had SOBANARI features among the commonly used instruments than the flutes presented in this experiment. In the experiment, few instruments can be evaluated as SONABARI; thus, the evaluation might be difficult.

Although there is a prevailing notion that the metal value of the material of the flute is related to the ringing in the hall, no clear relationship was confirmed between the material and the ranking results.

3.2.3 Hearing impressions that relate TOHNARI

In order to investigate hearing impressions that are related to the evaluation of TOHNARI, we analyzed the words for hearing impressions that participants remarked upon for the musical instruments whose rank of TOHNARI and SOBANARI were at least second.

The classification was conducted by two persons on the hearing impression phrase (for TOHNARI: 121 phrases, for SOBANARI: 96 phrases) for four musical instruments. As classification categories, referring to the previous research [8], seven categories were used as follows: loudness, sounding, timbre, transmission, expression, general impression, others. The classification results were determined when the category decided by two classifiers matched. As a result, the number of phrases was large for overall impression, loudness, sound transmission, sound timbre, and expression. Among them, the categories containing the phrases that were remarked upon by three or more participants are shown in Table 2. The results are summarized below.

Overall impression: It was found that the TOHNARI is often evaluated as a "good sound", and a preferable sound is likely to be evaluated as TOHNARI. Whereas with regard to SOBANARI, it was not considered a "bad sound", but rather considered a "not good and not bad" or "sound without features," neutral sound.

Loudness: There were a lot of comments that the "sound is loud" for the instrument that was evaluated as TOHNARI. In addition, there were many remarks upon the loudness differences perceived between the stage and the audience (attenuation level), but both responses of "low attenuation" and "high attenuation" were obtained. This indicates that it is not a simple correlation such as "it is TOHNARI if there is small difference in volume between the stage and the audience." Regarding SOBANARI, there were many comments that "it is softer in the audience seat, although the sound is loud on the stage" or "too loud." It was shown that the loudness was one of the main focus points, although no common view was found over the relationship between loudness and the TOHNARI sound.

Table 2 – Hearing impressions of the instruments characterized as TOHNARI and SOBANARI. The number in parentheses is the number of participants.

	TOHNARI		SOBANARI	
Category	Num.	Comments	Num.	Comments
Overall impression (53 in total)	32	Good sound (7), Good sound heard on stage reaches the audience as it is (5). Preferable sound (3), Sound that makes you want to hear for yourself (3).	21	Normal, no features, neither good nor bad (9). Impact on stage is strong (4).
Loudness (41 in total)	24	Sound level was high (13), large volume attenuation on stage and audience(5), low volume attenuation on stage and audience(3).	17	Although the sound is loud on the stage, the sound is small in the audience (6). Loud (4). Loud on the stage.
Transmission (39 in total)	24	The sound is spreading (3), ringing / spreading throughout the venue (5), flying to the audience (4).	15	It is ringing on the stage (far). (5) It does not fly to the audience unexpectedly (5).
Expression (29 in total)	20	The performances and expressions of the stage are transmitted to the audience(10), expressive(5).	9	Change in expression and nuance is not transmitted (5). It sounds like the same tone(4).
The other	5	There is a change in tone (3), can feel harmonics (3).	13	More resistance.

Transmission: As for the instruments that were evaluated as TOHNARI sounds, the impressions that "the whole venue was ringing, the sound was spreading" and "ringing nearby" were observed. As for SOBANARI, comments such as "it sounds far (over)" were provided. Regarding the expression of "fly" commented for the transmission, there were two types of imagery stated by multiple participants, "sounds that fly straight" and "sounds that spread across the entire venue and spread sideways." Among them, the latter was often described as "the image of TOHNARI".
Expression: Almost all the participants expressed the viewpoint that the wishes and expressions of the performers were transmitted to the audience. It is believed that if the expression on changes in volume, timbre, and intensity in the phrase is transmitted to the audience, it is judged to be TOHNARI; if it is not transmitted, it is judged to be SOBANARI.
The Other: Among the phrases that could not be classified into the above categories, there were many instances of harmonics. Throughout the interview process, eight out of thirteen participants mentioned the relationship between the harmonics and the TOHNARI and SOBANARI sounds, and many said that "the more harmonic there is, the more I feel like the sound is going far."

From the results above, it was found that the loudness, the manner of transmission, and the expression were the main hearing impressions that were related to the ultimate decision of TOHNARI or SOBANARI. In addition, many phrases related to the overall impression were observed; it can be concluded that the sound must achieve "a good sound that has reached the audience at a sufficient sound volume" to be considered TOHNARI. Although there were many comments on the timbre, the vocabulary used for explanation was diverse, and an expression captured on one evaluation axis relating to TOHNARI was not obtained.

4. ACOUSTIC ANALYSIS

Based on the hearing impressions analyzed in the previous section, we tried to analyze the physical characteristics in order to find out the acoustic factors that affect the evaluation of TOHNARI and SOBANARI. From the results of the listening experiment, we verified that three flutes (B, G, H) were evaluated as TOHNARI, and one flute A as SOBANARI. The values of the eight flutes were calculated as the average value.

For the acoustic analysis, the playback sound of each flute's performance was recorded with a free sound field microphone (Brüel & Kjær, 4189) placed at the center of the head in the sound cask (Fs: 48 kHz, 24 bits).

4.1 Average sound pressure level difference between the stage and the audience

As there were many comments regarding the loudness in the listening experiment, the average A-weighted sound pressure level (SPL) of each performance sound (about 70 sec.) was analyzed, and the difference between the stage and the audience area was calculated.

Figure 4 shows the SPL of the stage on the horizontal axis, and the SPL of the audience area on the vertical axis, generating the average SPL of each performance sound. The average attenuation value among all the instruments for the attenuation of the volume is shown by a broken line in Figure 4. As a result, the volume towards the audience was higher than the average for all B, G, and H flutes that were evaluated as TOHNARI sound. In addition, the amount of attenuation was smaller than the average for B and H. However, A, which was evaluated as SOBANARI, had a lower SPL in the audience area and the attenuation due to distance was larger than the average.

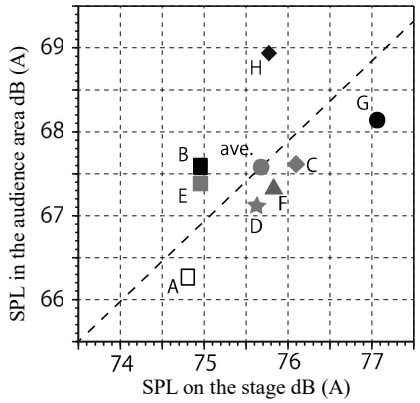

Figure 4 – SPLs of the performed sounds of the eight flutes, A to H, both on stage and in the audience area. The “ave.” shows the average SPL of 8 flutes. The broken line shows the average attenuation value.

Regarding the instruments evaluated as TOHNARI, it was confirmed that the sound pressure level was physically larger than the average, and the amount of attenuation by distance tended to be low — in agreement with the listening experiment. From these results, it is thought that the amount of attenuation of the SPL caused by the distance between performer and the audience seat is an important factor in distinguishing between TOHNARI and SOBANARI.

4.2 Dynamics of sound levels

As changes in the nuances such as volume and tone were noted in the listening experiment, changes of the SPL during the phrase were examined. As the index, the difference between the average SPL in the phrases p (piano), f (forte), and mp (meso piano), displayed on the score were calculated. The analysis target was two pairs in which the same melody was repeated by p and f, and one pair repeated by p and mp (meso piano), for a total of 3 pairs (6 short phrases). Using the average value of the SPL difference in the three pairs as the dynamics, this index was calculated for the stage and the audience sound.

Figure 5 shows the dynamics of the stage on the horizontal axis and the dynamics of the audience on the vertical axis. It was shown that B and G, which had a high evaluation of TOHNARI compared to the average, had large dynamics in both the stage and the audience, and that A, which was evaluated as SOBANARI, had small dynamics in both the stage and the audience.

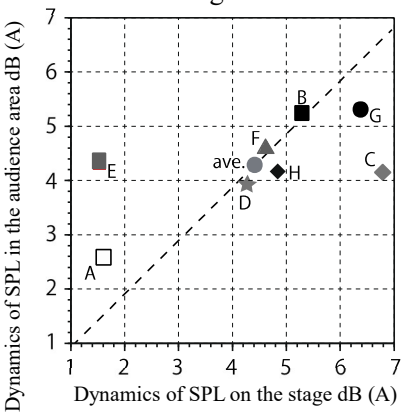

Figure 5 – The average dynamics of SPLs for the eight flutes, A to H, both on stage and in the audience area. The “ave.” shows the average SPL of all 8 flutes.

5. FINAL REMARKS

In this study, we investigated the auditory impression of a musical performance with flutes in a concert hall, focusing on how the flute sounds reverberates in the hall. Results indicated that the remarks upon perceptions of TOHNARI and SOBANARI had commonalities among participants and were in general agreement with the prevailing definitions. However, regarding the focus within the evaluation, the participants were divided into two groups: one focused on the differences in sound between the stage and audience area, and the other not focused on this. Besides, it was found that hearing impressions of overall impression, loudness, transmission, and expression are related to the evaluation of TOHNARI and SOBANARI. From the acoustic analysis of the tested sound signals, the results of the sound pressure level and dynamics of SPLs showed some agreement with the subjective evaluation of sonority. That is, a partial correspondence between the subjective evaluation and physical characteristics was confirmed.

The current research focuses on the combined effects of the instrument's personality and the acoustics of the hall that has not been sufficiently scientifically verified and explored thus far. However, it is important for any music performer to know how the sound is perceived in the rear seat of an audience area. In this study, we examined only the difference between instruments, however, the resounding of performance sound in a hall can be determined by musical instruments, technique of a performer, and concert hall acoustics. Further investigation on the relationship among these factors especially the contribution of concert hall acoustics, would be an interesting future work.

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