Glycative Stress Research

Online edition : ISSN 2188-3610
Print edition : ISSN 2188-3602
Received : March 23, 2019
Accepted : May 22, 2019
Published online : June 30, 2019
doi:10.24659/gsr.6.2_103

Original article: Case report

Characteristic and function of the newly developed articulatory panels (Aural Sonic).

Manabu Fukushima

Department of Media Technologies, School of Engineering, Nippon Bunri University, Oita, Japan

Abstract

In Japan, the number of people suffering from hearing impairment is increasing as the population composition continues to age, and various treatments and support devices are being developed to address this problem. The new articulatory panel (Aural Sonic™) was developed to adjust the propagation of acoustic signals inside rooms with the expectation that its use will improve listening and comprehension. A room where articulatory panels have been installed is characterized by a low attenuation factor for sound sources of 800 Hz frequency, reduction in the noise produced by peripheral wavelengths, and in particular, by the inclusion of a large number of harmonic overtones in the treble range. Its reflection characteristics is that sounds of frequencies in the vicinity of 500 Hz, 1.2 kHz and 2.9 kHz are reflected, while the other wavelengths are absorbed, reducing the reverberation time. The voiced vowels were emphasized using formant frequency distribution in which the frequencies important for vowel recognition while listening to languages are analyzed. In the case of two experimental collaborators for whom the three-syllable articulation test was conducted with a simultaneous measurement of brain waves, the α/β wave ratio increased due to the use of the new articulatory panels, and the brain was in a relaxed state, showing that the switching of the brain between the standby (resting) and arousal (activity) states in response to the test was smooth, from which it was inferred that a high thinking ability was sustained. We plan to continue the research on these articulatory panels that are likely to contribute towards the improvement of study rooms for maintaining concentration and provide assistance in the auditory cognitive function of the elderly with hearing loss, and also sleep quality.

***KEY WORDS*:** brain wave measurement, articulation material, wireless electroencephalograph, concentration

Introduction

Hearing impairment is one of the degenerative changes associated with aging. As people age, their hearing threshold in the treble range increases, which not only hinders their listening and comprehension of words and music but also impacts life in general and leads to a decline in the quality of life (QOL)[1]. Around one-third of the world population, aged 65 and above are considered to be suffering from hearing loss, and in the super-aging society of Japan too, the number of patients with hearing loss is undoubtedly expected to further increase in the future[2]. Mild hearing loss occurs in 30% of people in their sixties, and the percentage increases to over 80% for people in their eighties. As one gets older, there is a decrease in not only the average hearing ability checked by pure tone audiometry, but also in discrimination ability checked by speech audiometry[3, 4], and it is necessary to pay attention to the treatment as a decrease in word recognition[5] may develop into auditory agnosia.

If hearing impairment is not treated, it often aggravates the deterioration in the communication ability and cognitive function in the elderly, and appropriate intervention is necessary from an early stage. It has been pointed out that many diabetes patients are likely to have hearing impairment[6-12], which is suspected to be linked to glycation stress. Only drug therapy and hearing aids are used as a symptomatic treatment, and treatment for hearing loss has not been sufficiently established.

Construction members that change the sound environment of a room are used extensively. Sound absorbing materials, which is a construction member, is used to prevent modes of the room. However, for the complete acoustic absorption of sound energy, it is essential that the incident sound energy is converted internally, for example, into thermal energy, and

Corresponding to: Manabu Fukushima, PhD
Department of Media Technologies, School of Engineering, Nippon Bunri University
1727 Ichigi, Oita, 870-0397 Japan
TEL: +81-97-524-2748 FAX: +81-97-592-0911
EMAIL: fukushima@nbu.ac.jp

not reflected by the members. For this reason, it is necessary that the length and material of the sound absorbing material should correspond to the assumed wavelength of the acoustic signal. This means that sound energy which is not absorbed remains in the room. Soundproofing materials and sound insulation materials are members mainly to suppress the propagation of sound energy between adjacent rooms and are not necessarily meant to adjust the sound environment inside a room. For this reason, even if these construction members have been used, the sound environment inside a room may not be as desired.

In this situation, we are introducing an articulatory panel (Aural Sonic™: Tokyo Steel Industrial Co., Ltd., Kita-ku, Tokyo, Japan) [13] that was developed to adjust the sound environment inside rooms.

Acoustic Characteristics

Principle of Articulatory Panels

The articulatory panel was developed to adjust the propagation of acoustic signals inside rooms with the expectation that its use will improve listening and comprehension. However, the time averaging method generally used by current measurements cannot measure the characteristics of the panels appropriately, and a method for measuring acoustic events that occur in a short time is required. The authors have proposed a time-frequency analysis method for short-time events [14]. The proposed method uses Different Length Rectangular time window (effective sample preparation) (DLR) method [15,16] as the basic algorithm, and since this method exhibits excellent properties with the number of time averages less than the conventional method, analysis can be performed in a short time, and consequently, time tracking suitable for analysis of short-time events has been achieved.

The articulatory panel was designed such that the "primary reflected sound striking the wall returns a weak reflected sound such that it does not interfere with the direct sound" (*Fig. 1*). Also, by delaying the weak reflected sound, wider space, and sound field than the actual area are created acoustically.

According to the results of the surveys conducted so far on the acoustic properties of the articulatory panel, it was evident that even in the sound environment, the panel preserves the reflection characteristics at the frequency bands and timings that are important for listening and comprehension of words, and also with the three-syllable articulation test that is prescribed as the standard articulation test, has shown an improvement by approximately 30% (from 28/50 to 43/50) in articulation [13]. This value obtained by adjusting the sound environment using the articulatory panel significantly surpasses the values expected with physical improvement. It is considered that the articulatory panel brought the improvement in articulation, not only in terms of acoustic physics but also by some other effect, indicating that this panel will likely have an impact on sleep environment, learning environment, as well as the work environment.

Articulation is a test in which a person writes the syllables heard through sound stimulus that is presented and is used to examine intelligibility. In general, intelligibility is highest when the emitted acoustic signals are completely reproduced on the tympanic membrane. However, even if the sound stimulus is the same on the tympanic membrane, in reality, the perceived signal need not be recognized as an appropriate word depending on the fatigue level and subjective impression. Therefore, in the subjective evaluation experiment, conditions such as the fatigue level of the experimental collaborators have to be maintained at the same level. This is because not only acoustic physics but also brain activity, such as sound recognition function, contributes to the hearing ability.

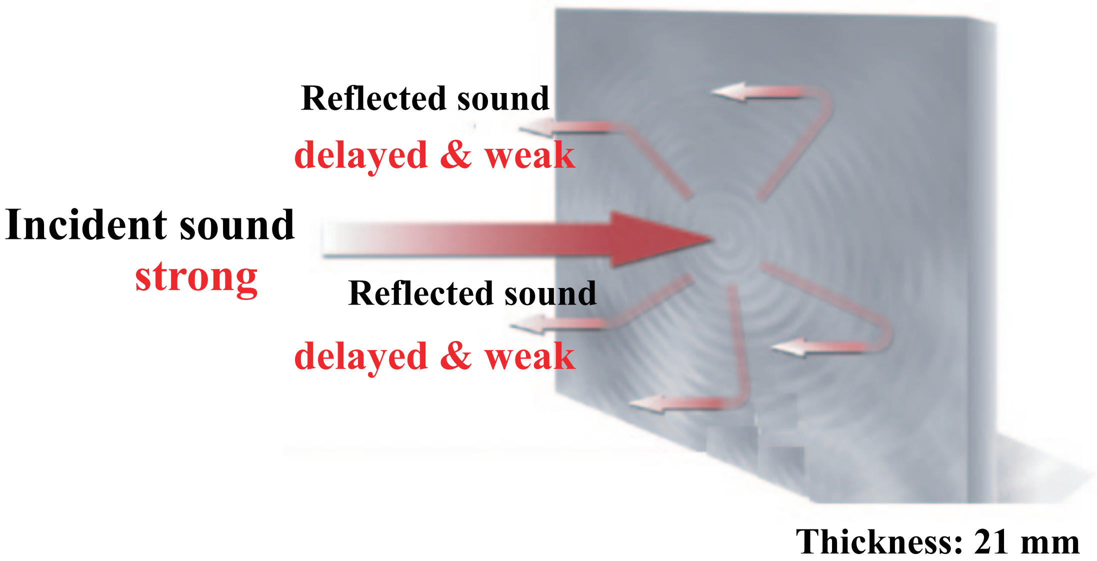

Fig. 1. **Principle of the articulatory panel.**

Impact on the Sound Waves Emitted by a Sound Source

Sound waves of 800 Hz, 120 dB (measured in an anechoic room) emitted by the front speakers were measured at the listening point of a home theatre system before (without using articulatory panels) and after using the articulatory panels, and when the panels were installed facing the speaker, and the results were compared (*Fig. 2*).

When the panels were not used, for sound waves of 800 Hz, more than 104 dB could not be reproduced due to the interference of the reflected waves generated in the room (red circle A). In the treble range (1.2 to 30 kHz), the reflection of sound was high with marked noise and dull sound (blue circle A).

On the other hand, after using the articulatory panels, interference between the sound waves was eliminated, and consequently, sound up to 116 dB could be reproduced which was close to the generated sound (120 dB) (red circle B). Even in the treble range, noise reduced, and harmonic overtones, which are elements that determine the tone remained clear, and the original sound could be detected reliably (blue circle B). Even at frequency bands in the bass range (500 to 800 Hz), the noise had reduced (yellow circle C). Acoustically, this sound range is very important, and noise elimination in this range is generally considered to be complicated.

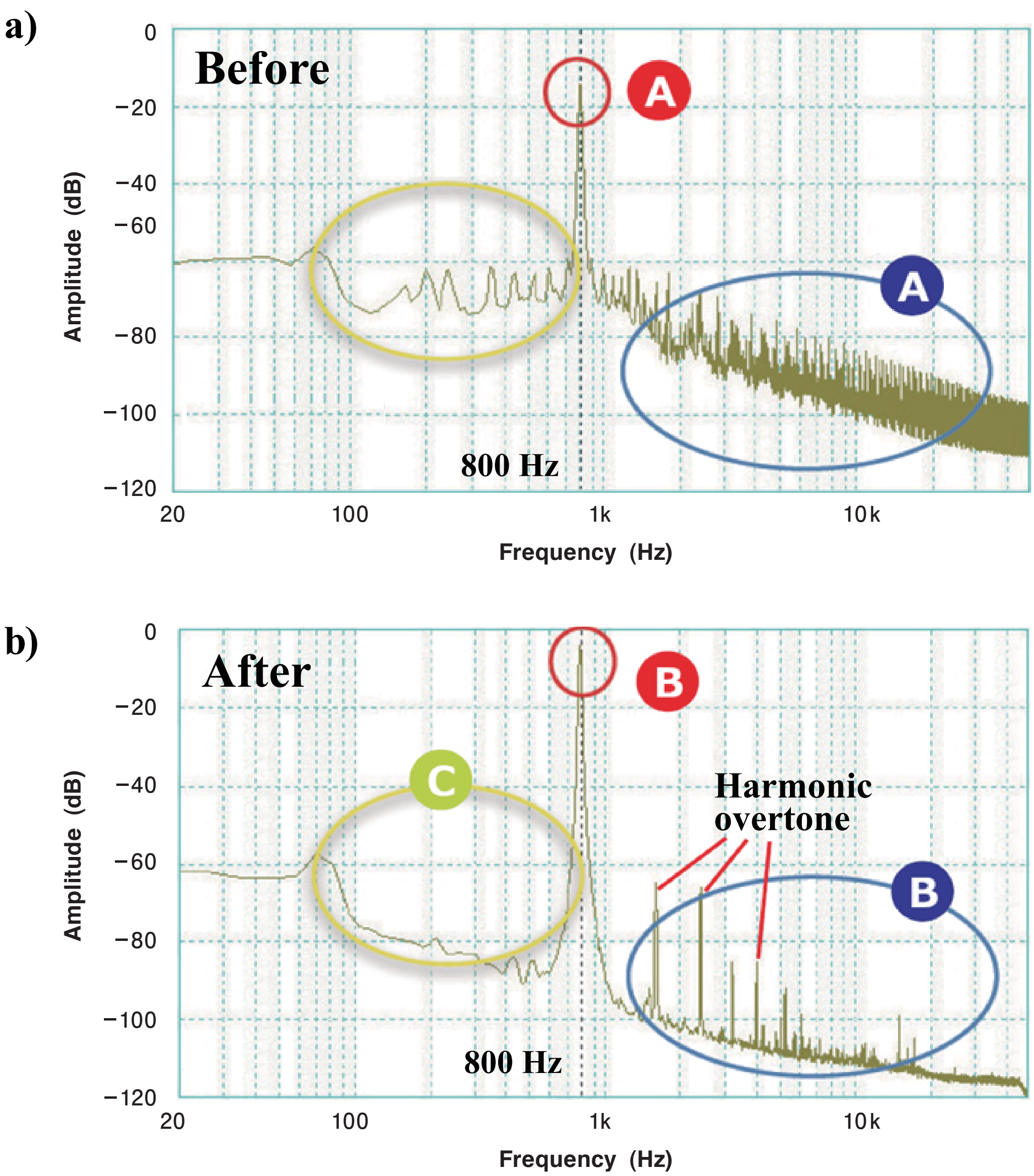

Fig. 2. **Interference and noise on generated sound.**

a) Before using the articulatory panels, the sound wave (800 Hz) attenuates from 120 dB to 104 dB (red circle). Note the marked noise generation in treble range (1.2～30 kHz; blue circle). **b)** After using the articulatory panels, the sound attenuation becomes small from 120 dB to 116 dB (red circle) and the noise markedly reduces with harmonic overtone generation (blue circle). Noise reduction is also observed in bass range (500～800 Hz; yellow circle).

Changes in Reverberation Characteristics

Reverberation characteristics were measured when using the articulatory panels. The experimental conditions are shown below (***Fig. 3***).

Depth 4.28 m
Width 2.55 m
Height 2.5 m
Floor area 10.914 m^2 (six tatami mats 10.9443 m^2)
Room volume 27.285 m^3

The theoretical reverberation time calculated from the room size was 0.451 sec. The calculation formula is given below.

Reverberation time = 0.161 V/(α x s) = 0.161 x 27.285/(0.174 x 55.978) = 0.451 sec
Floor area 4.28 x 2.55 = 10.914 m^2
V = Room volume 4.28 x 2.55 x 2.5 = 27.285 m^3
s = Surface area of the room ((4.28 x 2.55) + (2.55 x 2.5) + (4.28 x 2.5)) x 2 = 55.978 m^2
α = Average sound absorption coefficient, 0.174

The results of the measurement are as follows (***Fig. 4***). A speaker was installed in a room of approximately six tatami mats size, and the reverberation time was calculated by measuring the impulse response.

0 panels: Reverberation time 0.444 sec (almost the same as the theoretical value)
2 panels: Reverberation time 0.396 sec (89.19% → About 10% shorter)

The reverberation time reduced by about 10% with the installation of articulator panels (300 mm x 400 mm). Although sound quality improved by increasing the number of panels, reverberation time could not be assessed as the sound left a pleasant resonant tone. This is because of change in “sound quality” with “sound absorption and reflection” when articulatory panels are used, unlike sound absorbing materials.

In sensory evaluation, the sound became “clear” as the use of articulatory panels reduced the cause of "unclear" sound. Also, the high-frequency reverberation remained, facilitating a feeling that the sound was “easy to listen and comprehend”. Since the “sound quality” changes depending on the installation position, it is better to decide the placement based on one’s “preference”.

Reflection Characteristics and Vowel Recognition

Sense of hearing of humans is different depending on the frequency. To know “which sound frequency will be reflected to what extent”, it is important to know the reflection characteristics. The reflection characteristics of the articulatory panel were evaluated by enclosing a space with the articulatory panels on three sides. As a result, it was shown that the sounds of frequencies in the vicinity of 500 Hz, 1.2 kHz and 2.9 kHz are well reflected (***Fig. 5***). Next, this effect was confirmed using formant distribution (***Fig. 6***). Formant distribution is a representation of two frequencies important for vowels in spoken languages. It was shown that voiced vowels are emphasized by the use of the articulatory panels. These findings suggest that the installation of the articulatory panels may improve the ease of listening and comprehension.

Sound Stimulus Presentation Time and Measurement of Brain Waves

The impact on brain waves during the listening and comprehension test will be explained. A three-syllable articulation test [17-21] was conducted as a listening and comprehension test with a 22-year-old male as the experimental collaborator. In this test, three meaningless syllables are used as one spoken word and 50 such spoken words are played to the experimental collaborator who writes the answers on a paper. After the spoken word is played, the experimental collaborator is provided with adequate time to write down on the answer sheet, and the test is carried out such that there are no omissions while hearing or when writing in the answering section by using “line numbers” after every five spoken words are played. By adding narration to explain the test at the beginning, consideration was given to ensure that the experimental collaborator understands the articulation test before playing the spoken words. In this study, phonetic signs No. 1 was used out of the six types of phonetic signs (Table on which 50 spoken word patterns is defined) and the stimulus signal of an NHK male announcer (1982 version, Sound Engineers and Artists Society of Japan) was used as the speaker.

The experimental arrangement was as follows. The sound stimulus was played from an acoustic player installed in front of the experimental collaborator who was seated at the dummy head (pseudo-head microphone) position to hear the sound. The experimental collaborator identified the sounds heard and wrote them on the answer sheet. A response table was prepared with measures taken not to affect the sound propagation between the sound stimulus presentation device and the experimental collaborator. In the experiment, the stimulus of spoken words was presented, and the differences in the effect on the brain waves based on the placement conditions of the articulatory panel were compared.

Brain waves were measured at a sampling frequency fs = 512 (Hz) using a wireless method [13]. Brain waves were divided, as shown in ***Table 1***, according to the frequency bands.

Brain waves were measured at the place corresponding to the electrode arrangement FP1 given in the international 10-20 method by the simple induction method with the reference electrode attached to the earlobe. It is known that changes to the sound stimulus appear more frequently in this region for brain waves of the frontal lobe [22]. A wireless electroencephalograph was connected to a personal computer by Bluetooth and fixed to the head using a hair band, and the measuring instrument was not visible to the experimental collaborator, who was not aware of the electroencephalograph measuring device during the experiment and impact on the measured value was reduced to the maximum possible extent.

Frequency analysis of the time waveform measured by the electroencephalograph was carried out. The number of samples was selected as n = 512 for setting the frequency resolution to 1 (Hz), and the power spectrum was derived from the distortion-free autocorrelation function determined by the DLR method [15, 16]. Time tracking was set to 0.5 seconds, corresponding to the time resolution, by adjusting the overlap number to distinguish between the sound stimulus

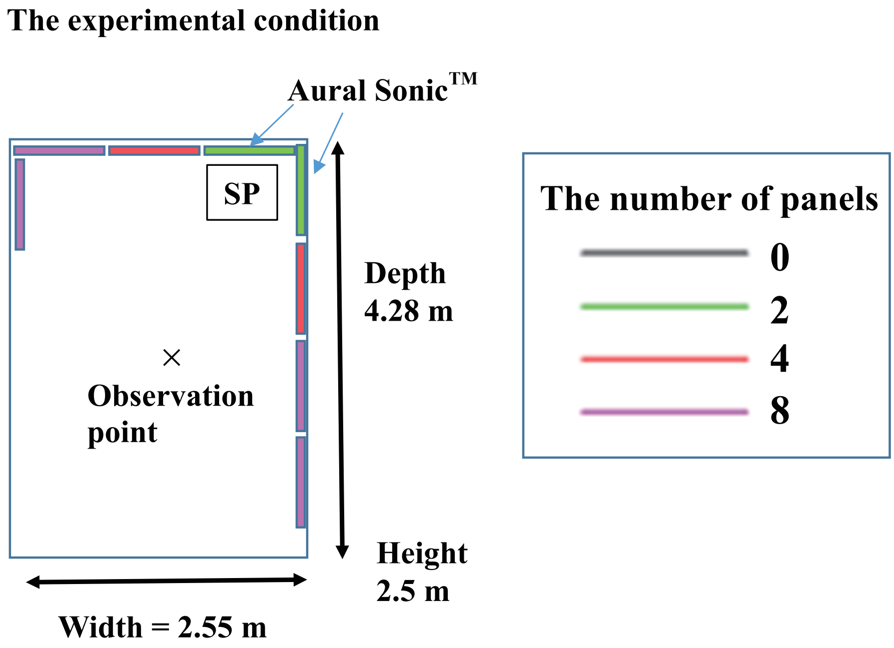

Fig. 3. **The experimental condition for reverberation measurement.**
SP, a loud speaker.

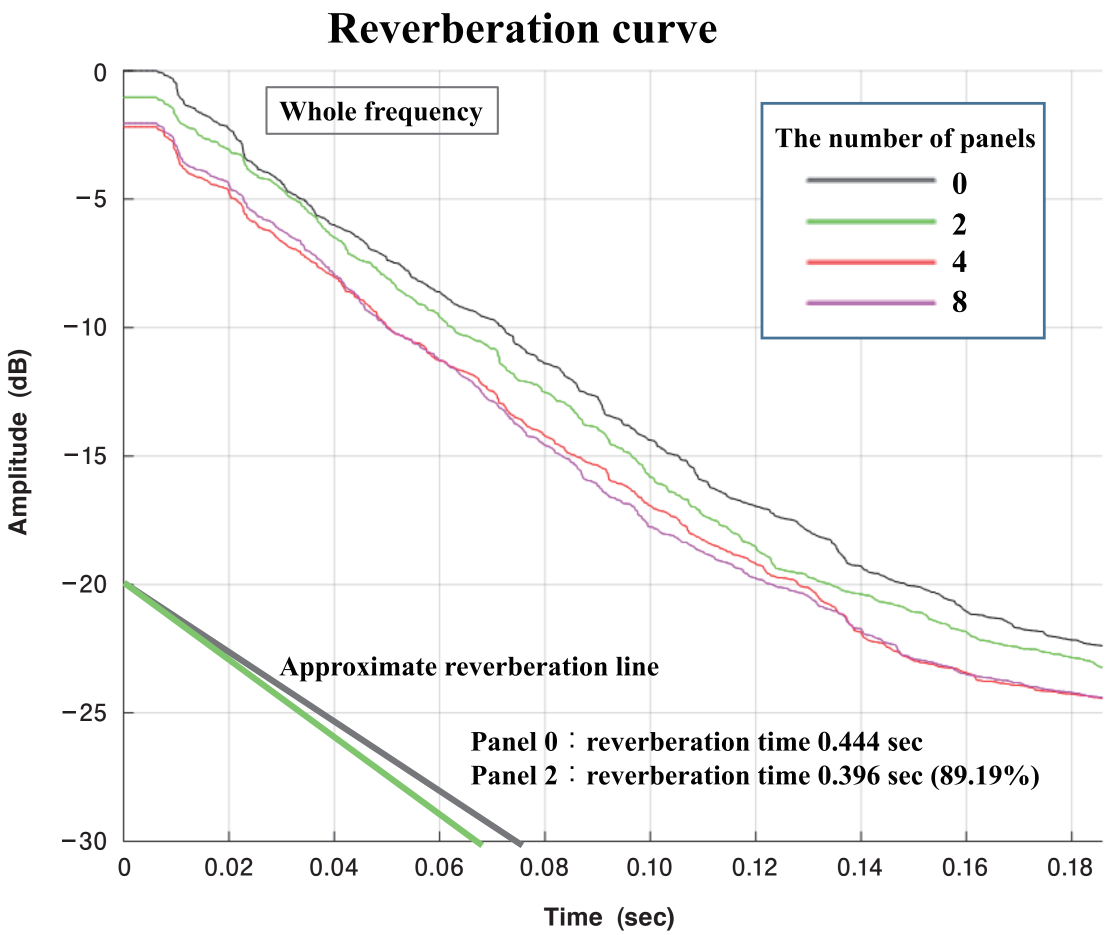

Fig. 4. **Comparison of reverberation curves between conditions with or without articulatory panels.**

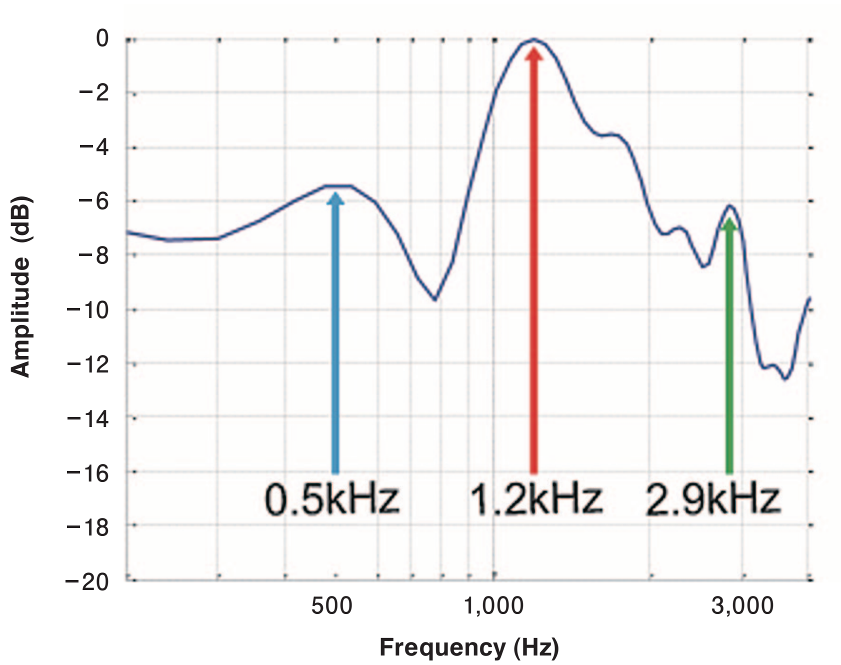

***Fig. 5.* Reflection characteristics of the articulatory panel.**

Sound reflection is preserved at the frequency area of 500 Hz, 1.2 kHz and 2.9 kHz.

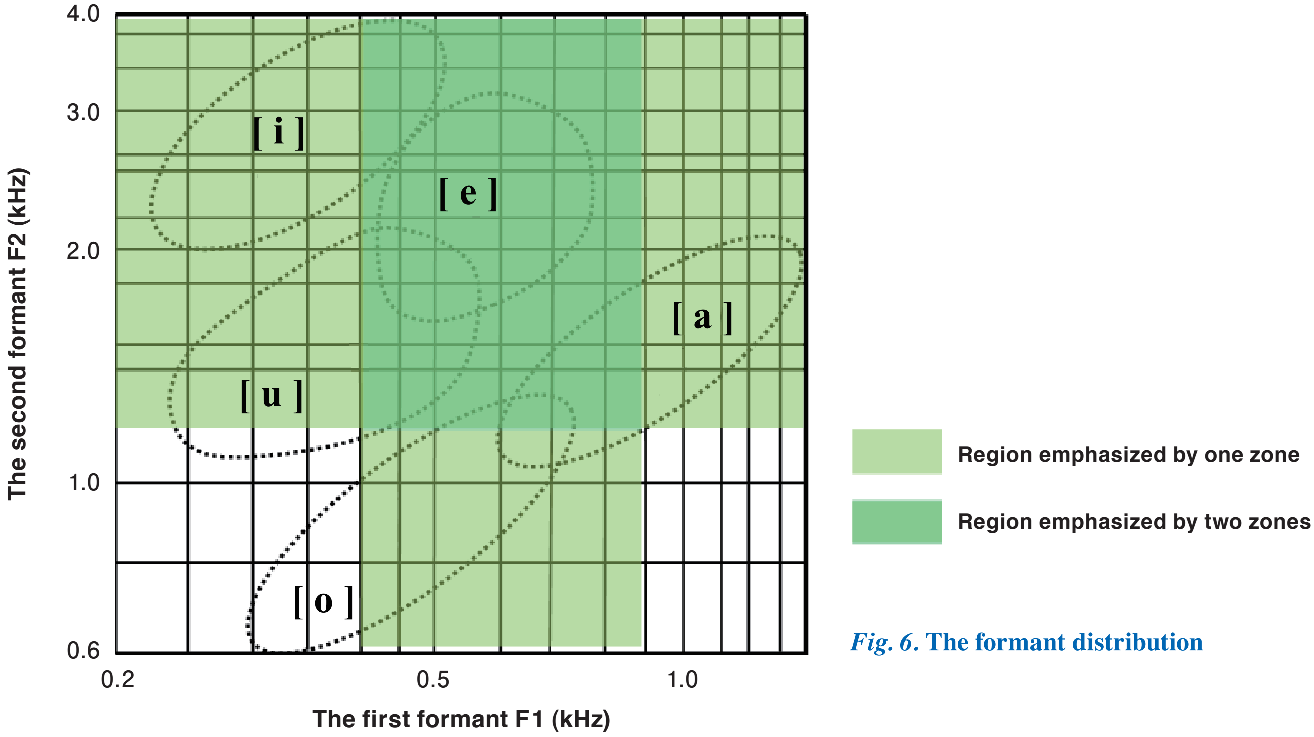

***Fig. 6.* The formant distribution**

Table 1. Characteristic of each frequency band.

Name	Brain-wave frequencies (Hz)	Characteristics
Delta (δ) wave	1 ~ 3	Associated with the deepest levels of relaxation, restorative and sleep.
Theta (θ) wave	4 ~ 7	Associated with deep meditation state, sleepy state and conscious exercise state.
Alfa (α) wave	8 ~ 12	Prominent in daydreaming, inability to focus, and being very relaxed.
Beta (β) wave	12 ~ 30	Involved in conscious thought and logical thinking, and excited state.
Gamma (γ) wave	30 ~	Responsible for cognitive functioning, learning, memory, and information processing.

and silent intervals. The tests were carried out with two experimental collaborators **Case 1** (*Fig. 7*) and **Case 2** (*Fig. 8*) for two conditions of the articulatory panel, (1) Without the panel, (2) With panel installed behind the head. Consent was obtained from the experimental collaborators in advance for participation in these tests, and to present the information in conferences and papers.

The change in the power spectrum of brain waves over time is indicated logarithmically with frequency along the horizontal direction, the magnitude of the power spectrum in dB along the vertical direction and time along the depth direction (starting point is at the back) (*Fig. 7, 8-a, c*). As a result, the frequency at which the magnitude of the power spectrum increases and the frequency at which the magnitude decreases due to sound stimulus changes with time.

Although it is shown that the electroencephalograph used in this experiment detected the changes caused by the sound stimulus, the smaller part of the power spectrum is concealed by the larger part making it difficult to observe. Therefore, a contour display (*Fig. 7, 8-b, d*) was prepared from the top view of (*Fig. 7, 8-a, c*). The X-axis indicates the frequency, and the Y-axis indicates time. The yellow power spectrum is high, indicating that the brain is excited. The green power spectrum is low, indicating that the brain is in standby and a state of rest.

Case 1 (22 years, male), before the articulatory panels were used for this experimental collaborator, green color during which the brain is at rest was less and yellow color which indicates that the brain excited was observed continuously, even after the determination of listening and comprehension was completed (*Fig. 7-a, b*). The brain can easily get tired as it is not relaxed when at rest, and mistakes can easily occur during the listening and comprehension judgment. The score was low at 28/50. When the articulatory panels were used, the brain switches smoothly between excitement (yellow) and rest (green) (*Fig. 7-c, d*). Since the brain is at rest for a long time, the ability to excite the brain can be sustained to be used when required. It was possible to sustain concentration during the study, and as a result, there was a 30% increase in the score (43/50).

There are individual differences in the responsiveness to the sound stimulus. **Case 2** (48 years, male), for this experimental collaborator, a shift was observed between the yellow and green areas even before the articulatory panels

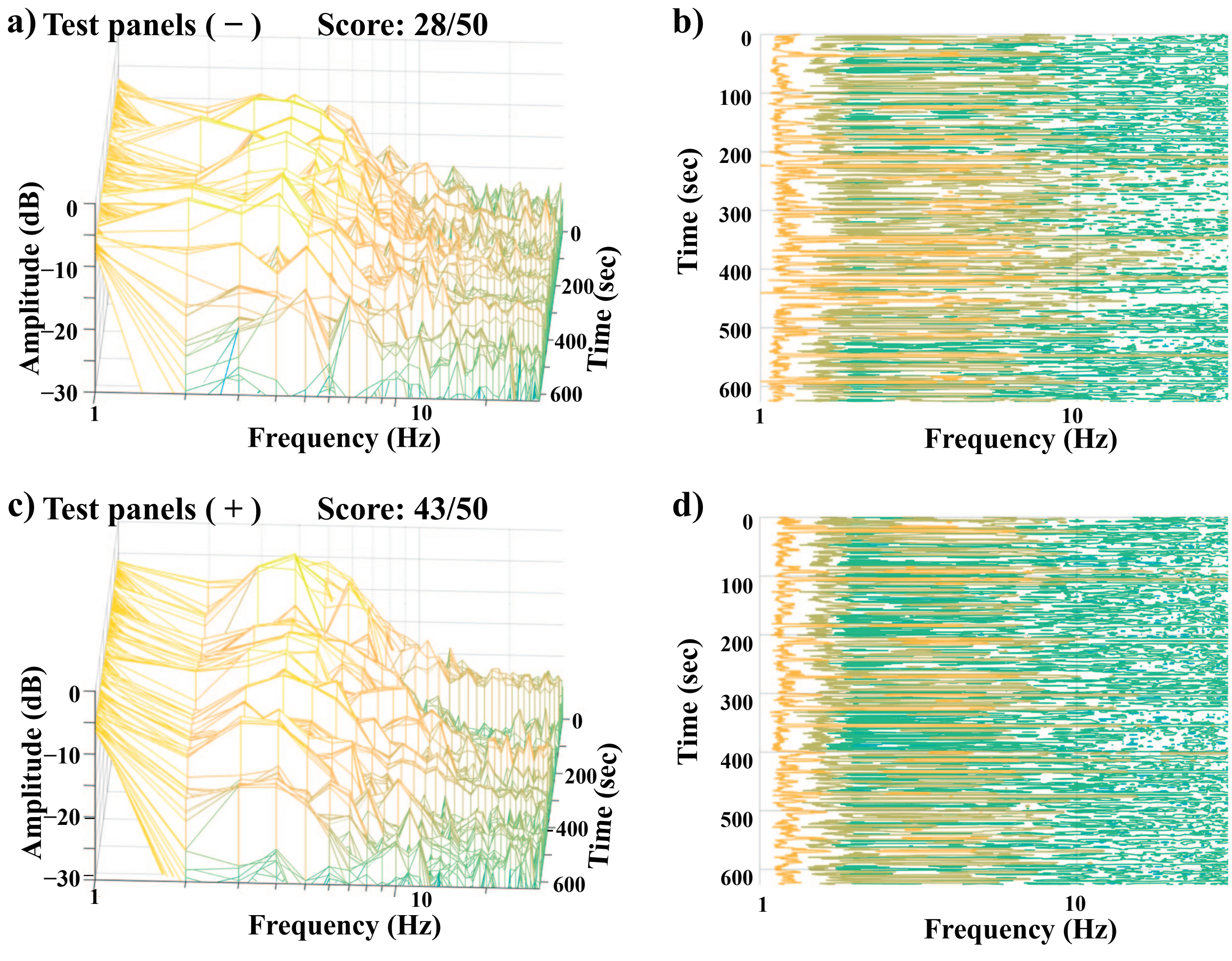

Fig. 7. **Time course of brain wave during the tri-syllable articulation test: Case1.**

A case of 22-year male. **a, c)** Time course of brain wave power spectrum after the sound stimulation for 625 seconds; frequency resolution 1 Hz; time resolution 0.5 second; X axis, frequency; Y axis, amplitude; Z axis, time. **b, d)** Contour map presentation of the time course of the frequent and power spectrum of brain waves especially in the α wave band; X axis, frequency; Y axis, time; Yellow, high level; Green, low level.

were used, and the score was high at (46/50) (*Fig. 8-a, b*). Even in the condition without the articulatory panels, there was a switch between rest and activity (excitement) of the brain, indicating a high concentration. When the articulatory panels are used, the green area increases, indicating that the brain is more relaxed (*Fig. 8-c, d*). The yellow areas are also observed regularly, and switching of the brain between rest and activity is also good.

In the β wave band (12 to 30 Hz) for both **Case 1** and **Case 2**, the green region indicating low levels is dominant when using the articulatory panels (*Fig. 7, 8-c, d*) as compared to the condition without the panels (*Fig. 7, 8-a, b*). This indicates that the use of the panels reduces β waves and relieves mental strain.

Next, the level of relaxation was analyzed from the ratio of the spectral intensity of the α and β waves. The state of relaxation becomes higher if the β waves which indicate a state of excitement are weak and the α waves are strong. *Fig. 9* shows the α wave / β wave ratio of the brain waves test conducted on the same experimental collaborators under three conditions (1) Without using articulatory panels (2) With articulatory panels installed behind the head, and (3) With articulatory panels installed for the entire room. With the increase in the area over which the articulatory panels are used, the α wave / β wave ratio shifts to the right, indicating that the β waves decrease while the α waves increase. This indicates that the subject is in a relaxed state while undergoing the test when using the articulatory panels.

Thinking requires neuronal activation and neurotransmitters. For this reason, the depletion or deterioration of neurotransmitters is a primary factor for the decline in thinking ability. For sustaining a high thinking ability, it is essential to prevent a deficiency of neurotransmitters by consuming sufficient neurotransmitters for stimulus but without unnecessary consumption. When using the articulatory panels, the period during which the brain is in standby and rest increases and from the α wave / β wave ratio, it is understood that the brain is in a relaxed state and carries out proper activities when needed. As a result, it is inferred that a high thinking ability can be sustained.

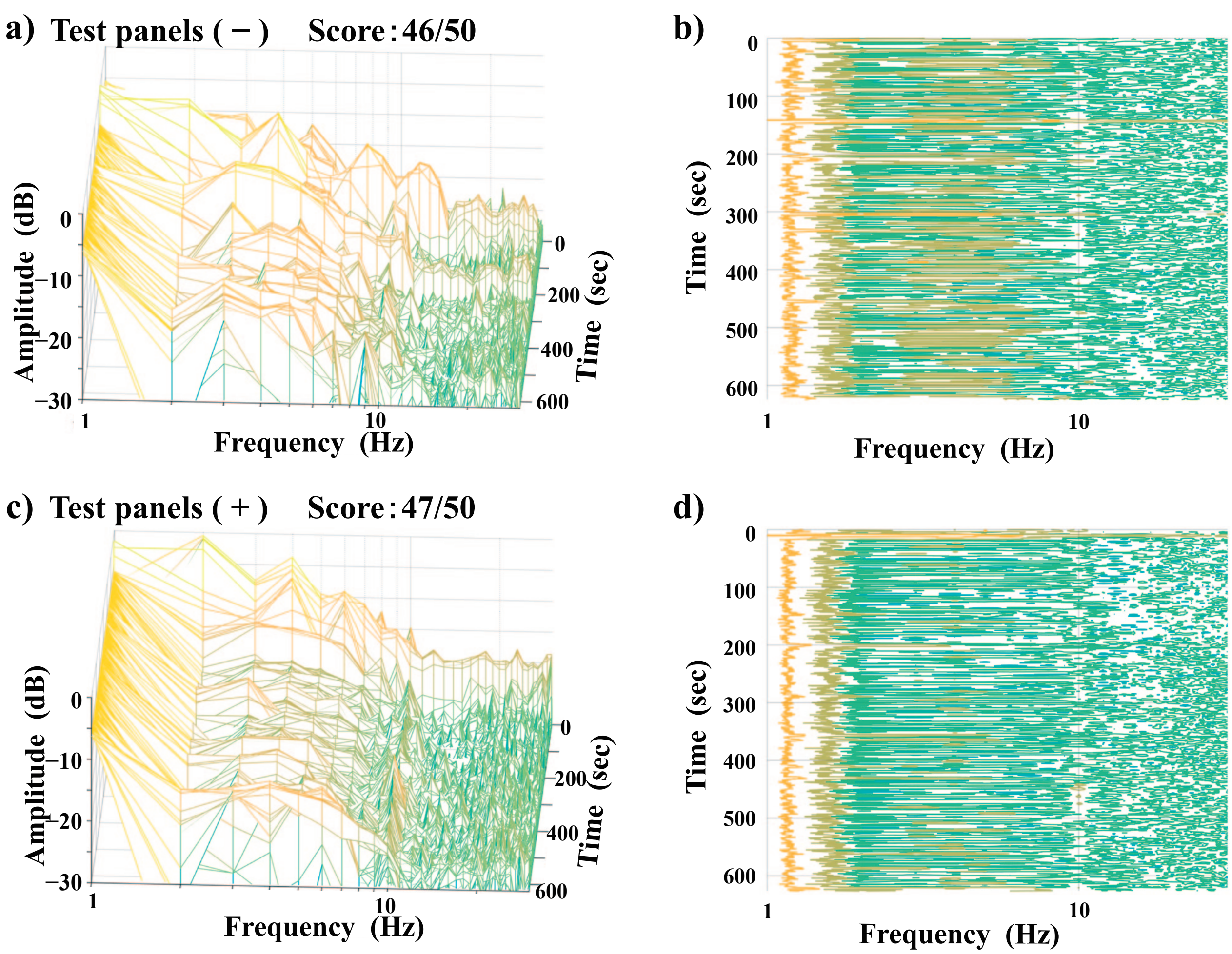

Fig. 8. **Time course of brain wave during the tri-syllable articulation test: Case 2.**

A case of 48-year male. **a, c)** Time course of brain wave power spectrum after the sound stimulation for 625 seconds; frequency resolution 1 Hz; time resolution 0.5 second; X axis, frequency; Y axis, amplitude; Z axis, time. **b, d)** Contour map presentation of the time course of the frequent and power spectrum of brain waves especially in the α wave band; X axis, frequency; Y axis, time; Yellow, high level; Green, low level.

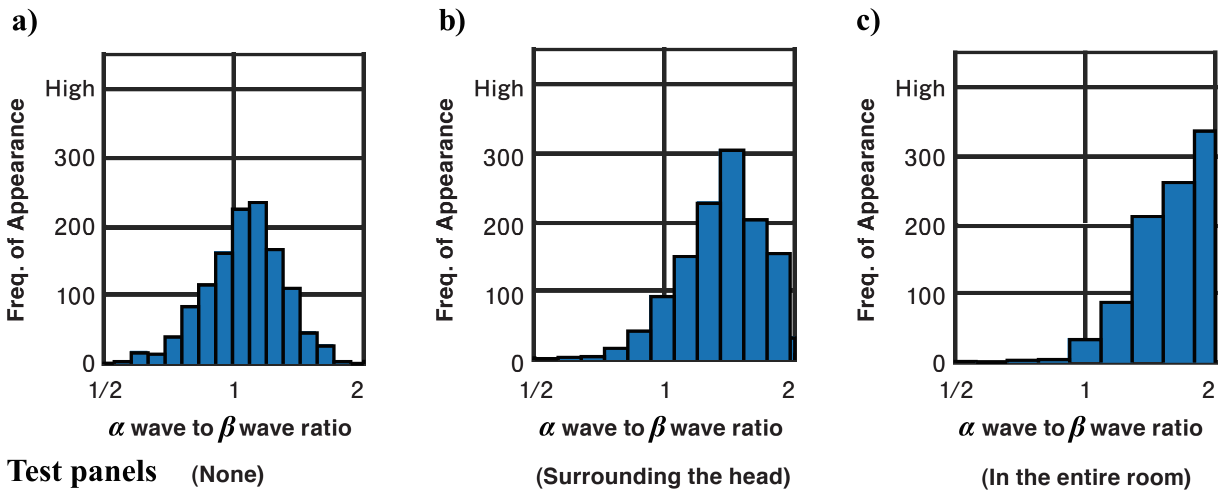

Fig. 9. **Comparison of α / β wave ratio between conditions with or without articulatory panels: Case 1.**

A case of 22-year male. Relation between the α / β wave ratio and frequency is presented when the area of articulatory panels surrounding the examinee is changed from the condition without panels **(a)** to the condition with panels surrounding his head **(b)** and to the condition with panels in the entire room wall **(c)**. X-axis: Ratio of α / β wave intensity (The intensity means the energy sum of power spectrum in each wave band); Y-axis: Frequency of appearance.

Conclusions

In this paper, damping and mitigation effect of the generated sound (800 Hz), noise reduction effect in the range other than the frequency of the generated sound (500 to 800 Hz, 2 to 20 kHz), and shortening effect of the reverberation time were observed as the fundamental characteristics of the new articulatory panels. The measurement of the reflective properties for sounds of various frequencies indicates that sounds around 500 Hz, 1.2 kHz and 2.9 kHz are reflected well, indicating the possibility that it may be easier to listen and comprehend Japanese vowels. As a result of analyzing the brain waves effect when conducting the three-syllable articulation test on experimental collaborators, it was confirmed that the ratio of low-level α waves increases and the ratio of β waves decreases when the new articulatory panels are used, suggesting that the subject may be relaxed and concentration is maintained. We plan to continue the research on these articulatory panels that are likely to contribute towards the improvement of study rooms for maintaining concentration, assistance in the auditory cognitive function of the elderly with hearing loss and also sleep quality, and future research results are expected.

Conflict of Interest Statement

The present study was partly supported by Tokyo Steel Industrial Co.,Ltd.

Acknowledgements

A part of this study was presented at the 2015 Autumn meeting of The Acoustical Society of Japan on September 16, 2015, Aizu-Wakamatsu, Fukushima, Japan

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