

Auditory Display for Deep Brain Activation: Hypersonic Effect

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ABSTRACT

We have found that sounds containing high-frequency components above the human audible range (20kHz) significantly increase the regional blood flow in the deep-lying brain structure and the power of the alpha frequency range of the spontaneous electroencephalogram (EEG), and positively affect sound perception. We have termed this phenomenon the "hypersonic effect" [1]. To carry out further experiments on this effect, we developed "Authentic Signal Disc" that is super audio CD (SACD) software containing the authentic signals for the hypersonic effect and "Authentic Hypersonic Audio System" that could reproduce the hypersonic effect. "Authentic Hypersonic Audio System" consists of a custom-made SACD player, a de-emphasis controller, filters, two stereo power amplifiers, an output meter unit, and two-way stereo speakers and tweeters. Using these system and disc, we examined recorded EEGs, psychological evaluations based on Scheffe's method, and behavioral evaluations on the optimum listening level, and confirmed the introduction of the hypersonic effect. This system enables us to create some new applications of auditory display.

1. INTRODUCTION

It is generally accepted that audio frequencies above 20 kHz do not affect human sensory perception since they are beyond the audible range. Thus, for example, most of the conventional commercial digital audio formats have been standardized to a frequency range that does not allow such high-frequency components (HFCs) of sounds to be included. Interestingly, artists and engineers working to produce acoustically perfect

music for commercial purposes are convinced that the intentional manipulation of HFC above the audible range can positively affect the perception of sound quality [2]. Indeed, the natural environment, such as tropical rain forests, usually contains sounds that are extremely rich in HFCs over 100 kHz [3]. From an anthropogenetic point of view, the sensory system of human beings exposed to a natural environment would stand a good chance of developing some physiological sensitivity to HFCs. We also found that some musical instruments, such as a gamelan of Bali, Indonesia, produce a significant number of HFCs over 100 kHz [3]. It is premature to conclude that consciously inaudible high-frequency sounds have no effect on the physiological state of listeners.

Noninvasive physiological measurements of brain responses provide evidence that sounds containing HFCs above the audible range significantly affect the brain activity of listeners. We used the gamelan music of Bali, which is extremely rich in HFCs with a non-stationary structure, as a natural sound source, dividing it into two components: an audible low-frequency component (LFC) below 22 kHz and an HFC above 22 kHz. Brain electrical activity and regional cerebral blood flow (rCBF) were measured as markers of neuronal activity while subjects were exposed to sounds with various combinations of LFCs and HFCs. None of the subjects recognized an HFC as sound when it was presented alone. Nevertheless, the power spectra of the alpha frequency range of the spontaneous electroencephalogram (alpha-EEG) recorded from the occipital region increased with statistical significance when the subjects were exposed to sound containing both an HFC and an LFC, compared with an otherwise identical sound from which the HFC was removed (i.e., LFC alone). In contrast, compared with the baseline, no enhancement of alpha-EEG was

evident when either an HFC or an LFC was presented separately [1, 3]. Positron emission tomography (PET) measurements revealed that, when an HFC and an LFC were presented together, the rCBF in the brain stem and the left thalamus increased significantly compared with a sound lacking the HFC above 22 kHz but that was otherwise identical [1, 3]. Simultaneous EEG measurements showed that the power of occipital alpha-EEGs correlated significantly with the rCBF in the left thalamus [1, 3]. Psychological evaluation indicated that the subjects felt the sound containing an HFC to be more pleasant than the same sound lacking an HFC [1, 3, 4]. Behavioral assessments focusing on the optimum sound level showed that the subjects were introduced to louder listening conditions when they listened to the sound containing an HFC than the same sound lacking an HFC [3]. These results suggest the existence of a previously unrecognized response to complex sound containing particular types of high frequencies above the audible range. We term this phenomenon the "hypersonic effect" (HSE) and the sounds introducing this effect the "hypersonic sound."

In addition, the sounds from which HFCs over 22 kHz were removed decreased the rCBF in the brain stem and the thalamus and decreased the alpha-EEG with statistical significance even when compared with background noise [1, 3]. Since the activities of the brain stem and the thalamus have a close relationship to many contemporary diseases, such as lifestyle-induced diseases, psychosomatic diseases and some kinds of psychiatric disorders, the discovery of this phenomenon is highly significant from the viewpoint of the possible contribution of audio engineering technology to health and welfare. An auditory display system that activates functions of the deep brain by HSE may have a positive effect on human health.

Since we reported on HSE in the Journal of Neurophysiology [1], many people in various fields, including medicine, physiology, acoustics, information and communication science, psychology, urban engineering, have shown interest in this phenomenon. Thus, the application and further examination of this phenomenon have been urged. However, the reproduction of HSE cannot be sufficiently achieved in the present situation. One of the main reasons is that most of the currently available systems related to sound source, representation, measurement and evaluation of human reactions do not conform to what research on HSE requires. Without restructuring these systems, it is difficult to produce and detect HSE. In fact, it has taken us more than fifteen years to succeed in our experiments.

As part of our responsibility as the discoverer of HSE, we are working on the development of a system to stably reproduce HSE. So far, we have developed a sound source and a reproduction system, which is available for anybody who intends to study and utilize HSE. This system will be also useful for practical applications of HSE, for example, amenity design of a sound environment by activating the deep brain.

2. REQUIRED FEATURES OF THE SYSTEM FOR HSE

The most notable structural feature of sounds introducing HSE is that they are rich in HFCs over 20 kHz. The highest frequency of the sound sources in our experiments exceeded 100 kHz. Such HFCs are also accompanied by a non-stationary fluctuation in a micro temporal domain of a few milliseconds or

less. When these non-stationary structures were replaced by stationary random noise, HSE was not introduced [5].

Consequently, one of the most significant problems is creating the software for the experiments; finding sound sources having a non-stationary fluctuating structure, recording and editing them as precisely as possible, and storing them on a stable medium after making a master. Another problem is how to transduce the sound signal stored on a recording medium to an aerial elastic wave as faithfully as possible, and to present it to subjects during physiological, psychological or behavioral experiments.

To satisfy the required features, we originally developed a system for sound recording, editing, mastering, reproduction, and presentation as shown in Figure 1 and 2.

3. DEVELOPMENT OF SOUND SOURCE SOFTWARE "AUTHENTIC SIGNAL DISC"

3.1. Sound Source

We collected and recorded, from all over the world, sounds from musical instruments and from the natural environment that were rich in HFCs accompanied by non-stationary fluctuating structures.

3.2. Recording Methods

The sound sources were recorded mainly by a B&K4135 1/4 inch condenser microphone, which has a flat free field frequency response of up to 100 kHz. The signals were digitally coded with Dr. Yoshio Yamasaki's high-speed one-bit coding signal processor with an A/D sampling frequency of 3.072 MHz, which decreased the noise floor in the high-frequency range. We stored the sounds in a digital recorder also designed and constructed by Dr. Yamasaki [6].

3.3. Requirements for the Recording Medium

Uniformity and assurance of reproduction must be considered in the selection of a recording medium for an authentic sound sample. Consequently, a non-rewritable optical disc recording system was more suitable for our purpose than a fictile magnetic recording system. The system also had to have an upper limit for the recordable frequency of more than 100 kHz, since the frequency range of the sound source went over 100 kHz. Moreover, we had to confirm that the package software and the equipment to play it on were both of the highest quality. We felt that a super audio CD (SACD) based on DVD technology would best meet our conditions for reconstruction and arrangement, and thus, we adopted the SACD, with considerable modification of the player, for our recording medium.

3.4. Signal Processing

We adopted Dr. Yamasaki's high-speed one-bit coding signal processing, which had made a significant contribution to our study on HSE, as the signal processing method for this system. The source sounds, described in section 3.2, were re-converted into an analogue signal, edited, and then converted into a DSD format with Dr. Yamasaki's 1-bit A/D converter, which supports the DSD format with an A/D sampling frequency of 2.8224 MHz. An emphasis process was introduced in order to

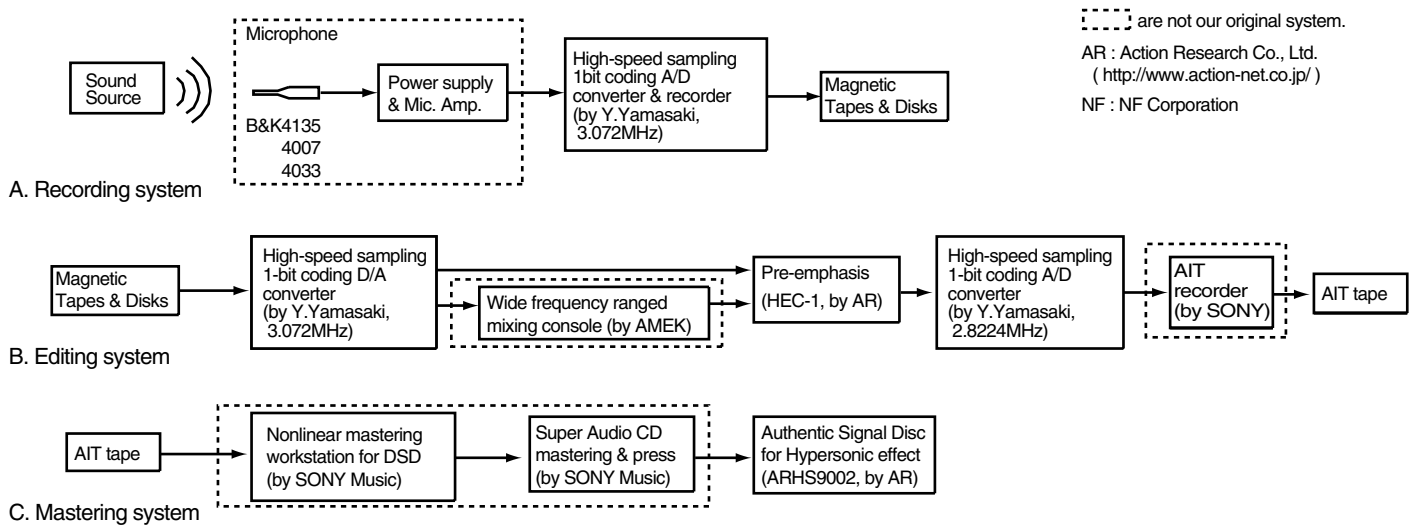


Figure 1 Recording, editing, and mastering system for "Authentic Signal Disc"

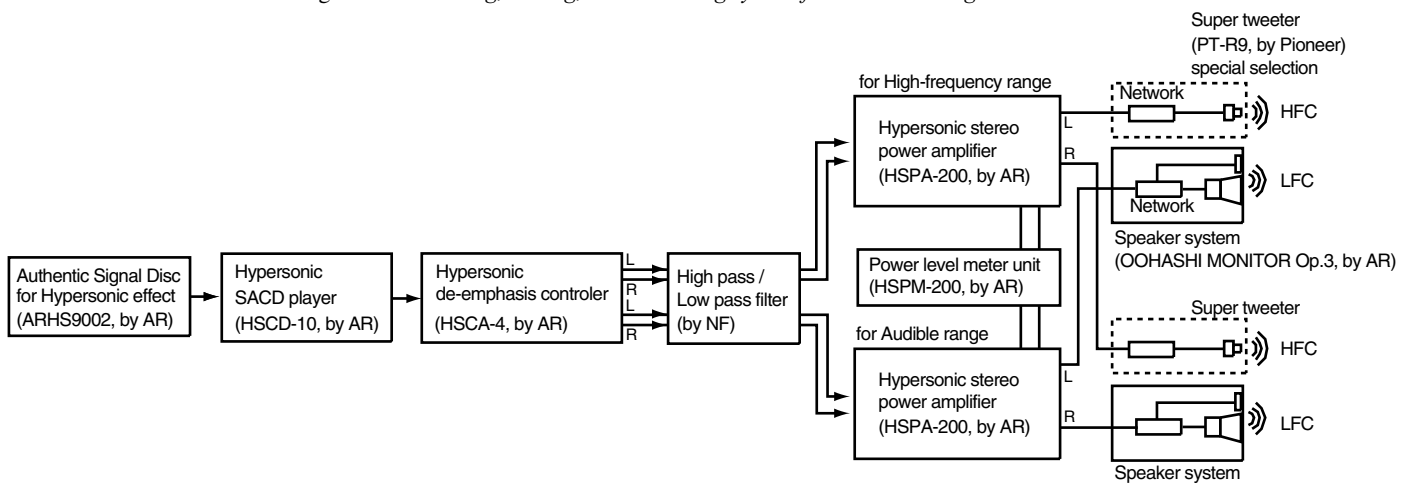


Figure 2 "Authentic Hypersonic Audio System"

Table 1 Contents of "Authentic Signal Disc" ARHS9002

< I. Test signals >

Track No.	Signal form	Parameters
1	sinewave	L / R 1kHz
2	sinewave	L / R 10 kHz
3	sinewave	L / R 100 Hz
4	white noise	L-ch only
5	white noise	R-ch only
6	white noise	L / R in phase
7	white noise	L / R opp.phase
8	sinewave	L / R 2 Hz
...		
40	sinewave	L / R 150 kHz
41	baseline	Analog signal mute
42	blank	Digital signal mute

< II. Sound sources for experiments on hypersonic effect >

Track No.	Contents	Construction
43	"Gambang Kuta" (Balinese gamelan music)	L/R (2 ch stereo)
44	"Gambang Kuta" components (Balinese gamelan music)	L= High-frequency component above 22kHz, attenuation slope 80dB/oct. R= Low-frequency component below 22kHz, attenuation slope 80dB/oct.
45	"I Got Rhythm" by George GERSHWIN (Music box sounds)	L/R (2 ch stereo)
46	"I Got Rhythm" by George GERSHWIN components (Music box sounds)	L= High-frequency component above 22kHz, attenuation slope 80dB/oct. R= Low-frequency component below 22kHz, attenuation slope 80dB/oct.

< III. From "Hypersonic sound series" >

Track No.	Title	Credits
47	"Ranka" from ASIAN ECHOSCAPE	Composed by YAMASHIRO Shoji Keyboard played by SHIKANO Akira (Ecophonic sound)
48	"Ikaruga" from ASIAN ECHOSCAPE	Composed by YAMASHIRO Shoji Keyboard played by SHIKANO Akira (Ecophonic sound)
49	"Ektenia"	Traditional chants of Bulgaria Arranged by Dobri HRISTOV Played by "QUARTET SLAVE!"
50	"Ujan mas"	Composed by Cok. Alit HENDRAWAN Played by "YAMASARI" (Contemporary Balinese gamelan music)
51	"Je te veux"	Composed by Erik SATIE Arranged by SAITOH Misao (Music box sound)
52	"La Primavera"	Composed by Antonio VIVALDI Arranged by SAITOH Misao (Music box sound)

prevent the reproduced signal from being contaminated by 1-bit noise.

3.5. Authentic Signal Disc

The SACD named "Authentic Signal Disc" (ARHS9002 by Action Research Co. Ltd. [AR], Tokyo, Japan) (see Table 1) was produced from a master of the data constructed in section 3.4.

4. DEVELOPMENT AND COMPOSITION OF REPRODUCTION SYSTEM "AUTHENTIC HYPERSONIC AUDIO SYSTEM"

4.1. Hypersonic SACD Player

We have raised the response to the super high-frequency range of the current SACD player, which was attenuated at the range over 50 kHz. A response of -6 dB at 100 kHz was achieved on an AR hypersonic SACD player HSCD-10. "Authentic Signal Disc" should be played on this player.

4.2. Amplifiers

4.2.1. Frequency Response

The amplifiers should have a good response to a frequency range of up to at least 100 kHz.

4.2.2. De-emphasis Controller / Pre-amplifier

We developed a de-emphasis controller with a pre-amplifier function. This system effectively eliminates 1-bit noises from high frequency components, de-emphasizing the reproductive output from "Authentic Signal Disc" on which the emphasized signals were recorded.

We also proposed a bi-channel sound presentation system [4]. In this system, the input signals are first divided into a high-band signal and a low-band signal. Then each signal is amplified and reproduced separately. With this equipment, it is possible to reproduce and present LFC and HFC separately or simultaneously. To construct the bi-channel sound presentation system, we designed a pre-amplifier with an L/R x 1 channel of input divided into an L/R x 2 channels of output (HSCA-4, by AR).

4.2.3. Power Amplifiers

We prepared two stereo power amplifiers, one for the audible range and the other for the inaudible range. To get an accurate transient response, the power amplifiers were designed to have bridged operation amplifier units consisting of discrete differential amplifier circuits. Each channel of the amplifiers was designed with a mono block construction, including a power supply unit with a massive toroidal transformer, in order to response to an instantaneously changeable load up to an inaudible high frequency. The power of the output is 100 W per channel (HSPA-200, by AR).

4.2.4. Power Level Meter Unit

A power level meter installed in a power amplifier may cause unexpected damage to response and sound quality in the final

stage of audio signal processing, because both the speakers and the meter are driven in parallel. To overcome this problem, we developed a power level meter unit independent of the power amplifier.

4.3. Method for Band Division

When an HSE experiment is conducted, it is necessary to divide the source signal into audible and inaudible high-frequency components in the bi-channel sound presentation system. For this purpose, the high-pass filter (CF-6FH series by NF Electronic Instruments) and low-pass filter (CF-6FL series) certified by previous experiments on HSE are recommended.

4.4. Speaker System

4.4.1. Configuration of the Speaker System

The speaker system was designed with a 2-way system for the audible range and a super tweeter for the inaudible high-frequency range.

4.4.2. System for the Audible Range

To flexibly arrange the crossover frequency of the bi-channel sound presentation system, the speaker system for the audible range should have a good response up to around 40 kHz. Our system was designed with a cone-type woofer and a bending-wave, semi-full-range tweeter (OOHASHI MONITOR Op. 3 by AR).

4.4.3. Super Tweeter

Selection of super tweeters for the experimental system is flexible according to a user's objective or the reproduction environment. Ribbon type super tweeters are provided as the standard set of super tweeters. We specially selected units with superior characteristics for high frequencies over 100 kHz from among the Pioneer beryllium-ribbon type super tweeter (PT-R9, by pioneer) which have the best response to high frequency ranges of all current products.

The system described in this paper has not only almost flat frequency response between 30 Hz and over 100 kHz but also superior impulse responses.

5. EXPERIMENT EVALUATION

We conducted experiments to confirm that the sound that was presented by our system induced HSE. We examined recorded EEGs, psychological evaluations based on Scheffe's method, and behavioral evaluations on the optimum listening level based on the previous findings [7, 8].

Our results showed that the power spectra of the occipital alpha-EEG increased with statistical significance ($p < 0.05$) when the subjects were exposed to sounds containing both an HFC and an LFC (i.e., Full Range Sound: FRS), compared with exposure to an otherwise identical sound from which the HFC was removed (i.e., High Cut Sound: HCS) (Figure 3). Psychological evaluation indicated that the subjects felt the sound containing an HFC to be more pleasant than the same sound lacking an HFC with statistical significance ($p < 0.01$ or 0.05). A tendency was also observed with statistical significance ($p < 0.05$) for the subjects to adjust to the optimum

listening level at a higher magnitude for FRS than HCS (Figure 4). These results conform well to our former findings. Thus, we can confirm the emergence of HSE using our “Authentic Hypersonic Audio System” and “Authentic Signal Disc” reported in this paper.

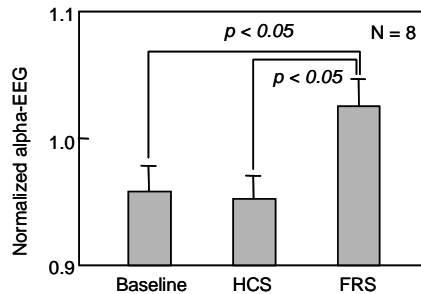


Figure 3. Power of occipital alpha-EEG during each sound condition.

Baseline: No sound presentation
 HCS: High Cut Sound (LFC only)
 FRS: Full Range Sound (HFC + LFC)

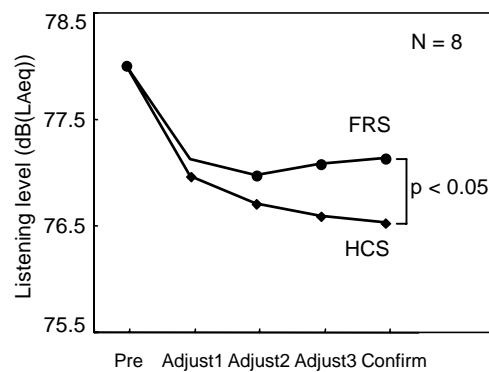


Figure 4. Change of adjusted sound listening level for each sound condition.

6. CONCLUSION

To establish a system that can reproduce a hypersonic effect (sounds containing high-frequency components above the audible range positively affect human physiological and psychological states and behavior, activating the deep brain.), we developed a sound source “Authentic Signal Disc” and a reproduction system “Authentic Hypersonic Audio System.” In our experiments using these system and disc for EEG recordings, psychological evaluations, and behavioral evaluations, we observed statistically significant tendencies that conform well to our previous findings. The results suggest the effectiveness of our system. The system and the disc are provided by Action Research Co. Ltd (<http://www.action-net.co.jp/>), and will be used in further experiments on HSE and in applications of HSE, such as amenity design of a sound environment.

7. ACKNOWLEDGMENT

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APPENDIX: Specifications of the sound reproduction equipment (Authentic Hypersonic Audio System)

Hypersonic SACD player: HSCD-10	
Frequency response	10 – 100,000 Hz (+0dB, -6dB)
Dynamic range	above 105 dB
Output level	BALANCED: 4 Vrms UNBALANCED: 2 Vrms
Dimensions	Width 430 mm x Height 149 mm x Depth 420 mm

Power level meter unit for HSPA-200: HSPM-200	
Input impedance	Above 100 k Ω
Input	2sets of stereo speaker terminals (selectable for A or B channel)
Power level meters	VU meters with illumination
Dimensions	Width 482.6 mm x Height 100 mm x Depth 330 mm

Hypersonic de-emphasis controller: HSCA-4	
Frequency response (1W) (De-emphasis ON)	2 – 100,000 Hz (+/-0.5dB)
Frequency response (1W) (De-emphasis OFF)	2 – 200,000 Hz (+0dB, -3dB)
Input sensitivity / Impedance (1 kHz)	BALANCED: 450 mV/20 k Ω UNBALANCED: 450 mV/20 k Ω
Output voltage / Impedance (1 kHz)	BALANCED: 1000 mV/600 k Ω UNBALANCED: 1000 mV/600 k Ω
Distortion factor (1 kHz)	0.02 %
Attenuation characteristics	Master: - ∞ – 0 dB (20steps) LOW: - ∞ – 0 dB (20steps) HIGH: - ∞ – 0 dB (20steps)
Dimensions	Width 482.6 mm x Height 100 mm x Depth 330 mm

Hypersonic monitor speaker	
Two-way system for audible range: OOHASHI MONITOR Op.3	
Power rating	80 W (RMS) 320 W (Peak)
Sensitivity	91 dB (1W/m)
Frequency response	29 – 35,000 Hz
Impedance	4 Ω
Crossover frequency	180 Hz
Dimensions	Width 273 mm x Height 620 mm x Depth 411 mm

Hypersonic stereo power amplifier: HSPA-200	
Output power (8 Ω)	100W + 100 W
Frequency response (1W)	5 – 200,000 Hz (+0dB, -3dB)
Input sensitivity / Impedance (1 kHz)	BALANCED: 1.4 V/20 k Ω UNBALANCED: 1.4 V/20 k Ω
Distortion factor (1 kHz)	0.01 %
Load impedance	4 – 8 Ω
Dimensions	Width 482.6 mm x Height 146 mm x Depth 410 mm

Super tweeter for high-frequency range: PT-R9 special selection	
Power rating	100W (Peak)
Sensitivity	97.5 dB (1W/m)
Frequency response	5,000 – 120,000 Hz
Impedance	8 Ω
Dimensions	Width 134 mm x Height 89 mm x Depth 179 mm