Factors to be Measured of Environmental Noise and Its Subjectvie Responses Based on the Model of Auditory-Brain System

Yoichi Ando

Graduate School of Science and Technology, Kobe University, Rokkodai, Nada, Kobe 657-8501 Japan

Roberto Pompoli

Department of Engineering, University of Ferrara, Via Saragat, 1 - 44100 Ferrara, Italy

(Received 8 October 2001; accepted 17 January 2002)

An idea of modern system of measuring sound and noise for its identification and subjective evaluations is based on the model of auditory-brain system developed for concert hall acoustics [Concert Hall Acoustics, Springer-Verlag, Heidelberg, 1985; Architectural Acoustics, Blending Sound Sources, Sound Fields, and Listeners, AIP Press/Springer-Verlag, New York, 1998]. The model consists of the autocorrelation, interaural crosscorrelation mechanisms, and the specialization of human cerebral hemisphere. It is worth noticing that the power density spectrum is identical with the autocorrelation function of the signal. In order to describe primary sensations and any important subjective responses, three temporal factors extracted from the autocorrelation function and four temporal factors from the interaural crosscorrelation function are taken into consideration. A theory is reviewed here for identification and subjective evaluations, which would contribute to reduce the environmental noise properly.

Keywords: noise measurement method, factors, auditory-brain model, subjective effects

1. INTRODUCTION

Fundamental subjective attributes for sound fields are well described by a model of the auditory-brain system. It includes autocorrelation function (ACF) and interaural crosscorrelation function (IACF) mechanisms as shown in Fig. 1 [1, 2]. Important mechanisms in this model were discovered in relation to the auditory-brain activity [2]. It is discussed that primary sensations–loudness, pitch and timbre–, in addition duration sensation which is introduced here as a fourth, and spatial sensations are described by temporal factors extracted from the ACF. Also, spatial sensations such as localization, apparent source width (ASW), and subjective diffuseness are described by spatial factors extracted from the IACF. Based on an auditory-brain system with two cerebral hemispheres, a theory for identification of noise and any subjective evaluations. As typical examples, this paper demonstrates interference effects of noise and music during tasks with children from quiet living area and noisy living area.

2. MODEL OF AUDITORY-BRAIN SYSTEM

Specific characteristics of the electrophysiological responses of both left and right human cerebral hemispheres are taken into account for the model shown in Fig. 1 [2]. The sound source p(t) in this figure is located at a point r_0 in a three-dimensional space, and the listener sitting at r is defined by the location of the center of the head, $h_{l,r}$ $(r|r_0,t)$ being the impulse responses between r_0 and the left and right ear-canal entrances. The impulse responses of the external ear canal and the bone chain are respectively $e_{l,r}(t)$ and $c_{l,r}(t)$. The sensitivity of a human ear to a sound source in front of the listener is essentially determined by the physical system between the source and the oval window of the cochlea such that [1, 2],

$$S(t) = h(t) * e(t) * c(t) \tag{1}$$

where asterisks signify convolution.

The velocities of the basilar membrane are expressed by $v_{l,r}(x,t)$, x being the position along the membrane. The action potentials from the hair cells are conducted and transmitted to the cochlear nuclei, the superior olivary complex including the medial superior olive, the lateral superior olive, and the trapezoid body in the auditory pathway.

The input power density spectrum of the cochlea I(x', ω) to these nuclei can be mapped at a certain nerve position x', I(ω) [3, 4], and further as a temporal activity. Remarkably,

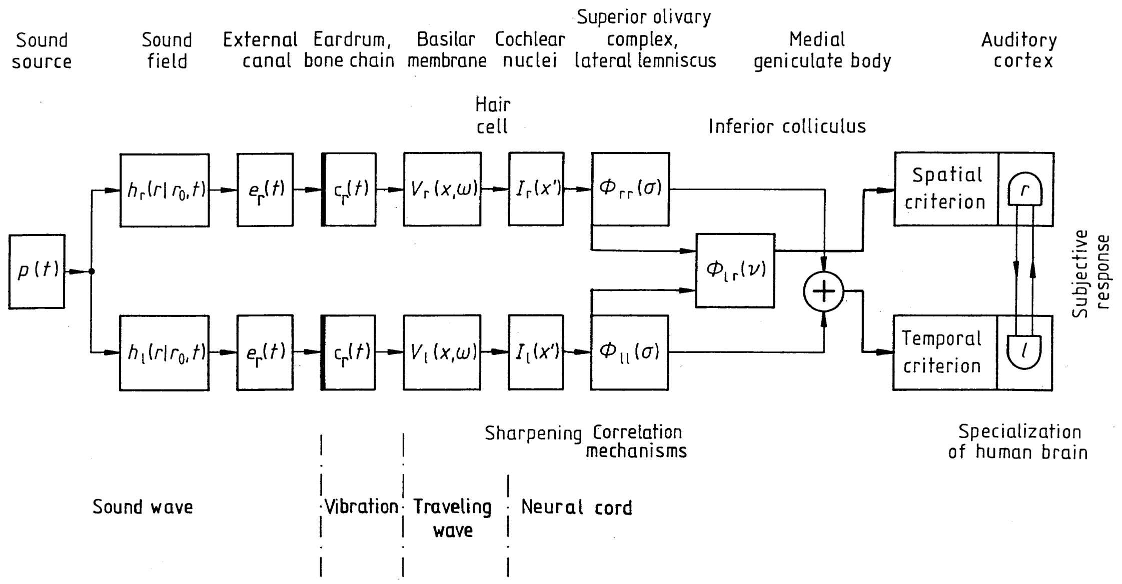

Fig. 1. Model of the auditory-brain system with autocorrelation and interaural crosscorrelation mechanisms and specialization of human cerebral hemispheres [2].

the time domain analysis of firing rate from auditory nerve of cat reveals a pattern of ACF rather than the frequency domain analysis [5]. It has been discovered that pooled interspike interval distributions resembles the short-time ACF for low-frequency component. Pooled interval distributions for sound stimuli consisting of high-frequency component resemble running ACF of the waveform envelope [6]. From a viewpoint of the human perception of missing fundamental or pitch of complex tones, The running ACF may be processed in the frequency range less than about 5 kHz [7]. and the fundamental frequency must be less than about 1.2 kHz [8]. Such neural activities, in turn, include information to produce the running ACF $\Phi_p(\tau,t)$ as shown in Fig. 2. In this figure, the running ACF of each frequency band, $\Phi_n(\tau)$, n = 1, 2, ... , N, is mapped to the spatially distributed neural activities.

As discovered by Ando et al., neural activities of wave IV_{left} and IV_{right} are reflected by the energies of sound arriving at two-ear entrances $\Phi_{rr}(0)$ and $\Phi_{ll}(0)$, respectively, and the neural activity (waves IV_{left}, IV_{right}, and V) correspond well to the IACC [9]. The interaural crosscorrelation function (IACF) mechanism is considered to exist at the inferior colliculus.

As indicated in Table 1 that the output signal of the interaural crosscorrelation mechanism including the IACC is dominantly connected to the right hemisphere [10-17]. Also the sound pressure level may be expressed by a geometrical average of $\Phi_{rr}(0)$ and $\Phi_{ll}(0)$ may be processed in the right hemisphere. On the other hand, temporal factors extracted from autocorrelation function may activate the left hemisphere. Such specialization of the human cerebral

Table 1. Hemispheric specialization obtained by analyses of AEP (SVR), EEG and MEG [10-17].

Factors changed	AEP(SVR) $A(P_1\text{-}N_1)$	EEG, ratio of ACF τ_e values of α-wave	MEG, ACF τ_e value of α-wave
Temporal			
Δt_1	L > R (speech)	L > R (music)	L > R (music)
T_{sub}	---	L > R (music)	---
Spatial			
LL	R > L (speech)	---	---
IACC	R > L (vowel /***a***/) R > L (band noise)	R > L (speech)	---

Sound sources used in experiments are indicated in the bracket. LL is given by Eq. (13).

hemispheres may be related to the highly independent contributions of spatial and temporal criteria to subjective attributes.

It is remarkable that "cocktail party effects," for example, can be well explained by the specialization of the human brain. The target speech is processed in the left hemisphere, and spatial information for any sound sources is mainly processed in the right hemisphere. These processes may enhance the target signal and suppress unwanted sound signals. Thus, we can describe any subjective attribute of noise and noise fields in term of processes of the auditory pathways and the brain.

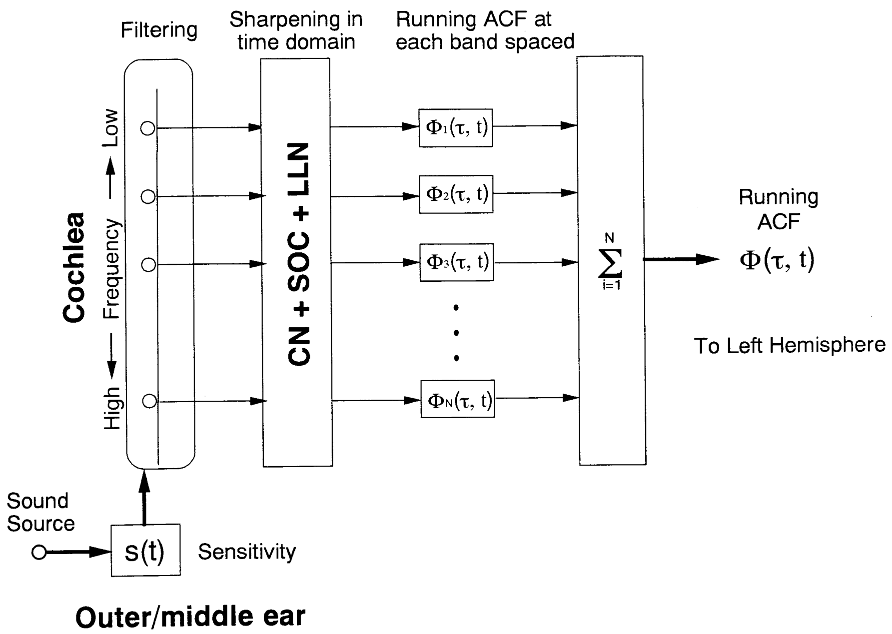

Fig. 2. Neural processing model of the running ACF for the low frequency range less than about 5 kHz (the fundamental frequency or pitch must be less than about 1.2 kHz).

3. TEMPORAL AND SPATIAL FACTORS OF NOISE ENVIROMNET

3.1 ACF and Factors

Applying the auditory-brain model (Fig. 1), first of all, we consider primary sensations of a given source signal p(t) located in front of a listener in a free field. The ACF is defined by

$$\Phi_p(t) = \frac{1}{2T}\int_{-T}^{+T} p'(t)p'(t+\tau)dt \qquad (2)$$

where p'(t) = p(t)*s(t), s(t) is given by Eq. (1) corresponding to the ear sensitivity, which is essentially formed by the transfer function of physical system to oval of cochlea, as is given by Eq. (1). For practical convenience, s(t) may be chosen as the impulse response of an A-weighted network [1,2]. The ACF and the power density spectrum contain the same information.

There are four significant factors, which can be extracted from the ACF as mentioned below.

(1) Energy represented at the origin of the delay, $\Phi_p(0)$;

(2) Fine structure, including peaks and delays (Fig. 3(a)). For instance, τ_1 and ϕ_1 are the delay time and the amplitude of the first peak of ACF, τ_n and ϕ_n being the delay time and the amplitude of the n-th peak. Usually, there are certain correlation between τ_1 and τ_{1+1}, and between ϕ_1 and ϕ_{1+1};

(3) Effective duration of the envelope of the normalized ACF, τ_e, which is defined by the ten-percentile delay and which represents a repetitive feature or a kind of reverberation containing the sound source itself. The normalized ACF

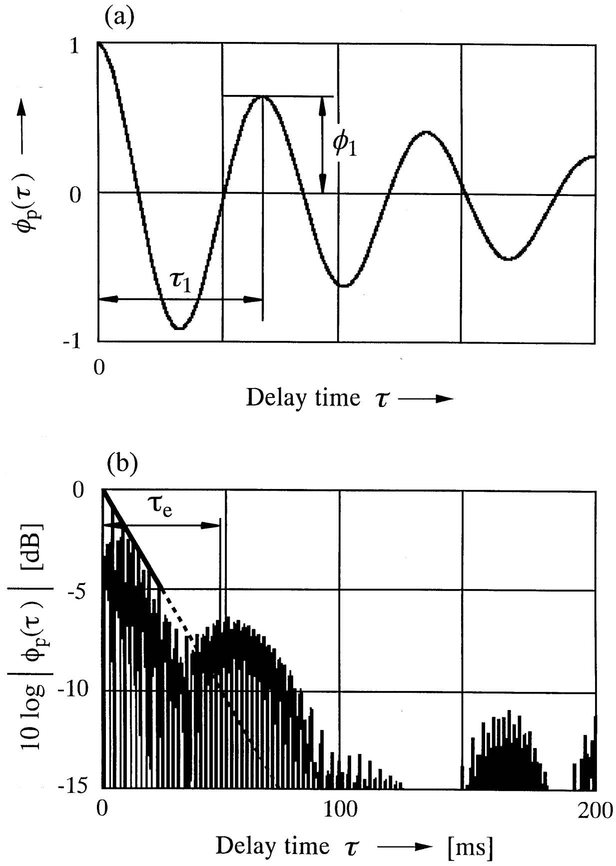

Fig. 3. Definition of independent factors other than $\Phi(0)$ extracted from the normalized ACF. (a) Values of τ_1 and ϕ_1 for the first peak; (b) The effective duration of the ACF τ_e, which is defined by the ten percentile delay (at −10 dB) and which is obtained practically by the extrapolation of the envelope of the normalized ACF during the decay, 5 dB initial.

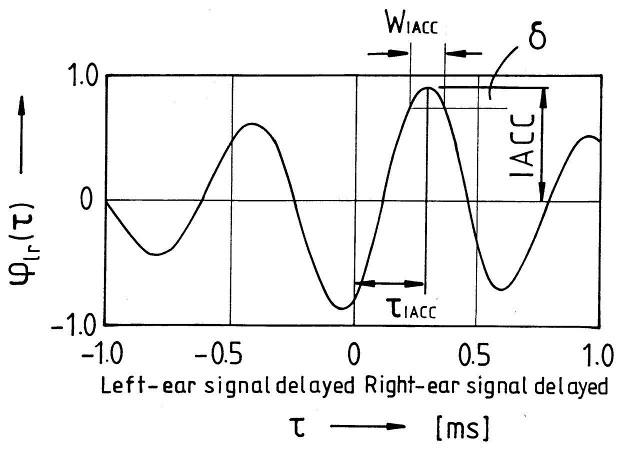

Fig. 4. Definition of independent factors IACC, τ_{IACC} and W_{IACC} extracted from the normalized IACF.

is defined by

$$\phi_p(0) = \Phi_p(\tau)/\Phi_p(0) \tag{3}$$

As a manner shown in Fig. 3(b), this value is obtained by fitting a straight line for extrapolation of delay time at −10 dB, if the initial envelope of ACF decays exponentially. Therefore, four orthogonal and temporal factors that can be extracted from the ACF are $\Phi_p(0)$, τ_1, ϕ_1, and the effective duration, τ_e.

3.2 Temporal Window in Auditory System

In analysis of the running ACF, of particular interest is so called an "auditory-temporal window", i.e., 2T in Eq. (2), that may be clarified. Since the initial part of ACF within the effective duration τ_e of the ACF contains the most important information of the signal. Thus, the recommended signal duration $(2T)_r$ to be analyzed is given by

$$(2T)_r = K_1(\tau_e)_{min} \text{ [s]} \tag{4}$$

where $(\tau_e)_{min}$ is the minimum value of τ_e obtained by a set of the running ACF for signal under investigation. From loudness and pitch sensations, K_1 is obtained about 30 [18]. The running step (R_s) is selected as $K_2(2T)_r$, K_2 being, say, in the range of 1/4–1/2.

3.3 IACF and Factors

The IACF is given by

$$\Phi_{lr}(t) = \frac{1}{2T}\int_{-T}^{+T} p'_l(t)p'_r(t+\tau)dt \tag{5}$$

where $p'_{l,r}(t) = p(t)_{l,r} * s(t)$, $p(t)_{l,r}$ are the sound pressure at the left-and right-ear entrances. Spatial factors, IACC, τ_{IACC}, and W_{IACC} extracted from the IACF are defined in Fig. 4 [2]. Also, the listening level, LL, is given by Eq. (13).

4. PRIMARY SENSATIONS

4.1 Loudness

Let us now consider primary sensations. Loudness s_L is given by

$$s_L = f_L(\Phi_p(0), \tau_1, \phi_1, \tau_e, D) \tag{6}$$

where the value of τ_1 corresponds to pitch of the noise and/or the missing fundamental as discussed in the following section, and D is the physical signal duration.

When p'(t) is measured with reference to the pressure 20 μPa leading to the level L(t), the equivalent sound pressure level L_{eq}, defined by

$$L_{eq} = 10\log\frac{1}{T}\int_0^T 10^{L(t)/10}dt \tag{7}$$

corresponds to $10\log[\Phi_p(0)/\Phi_{ref}(0)]$, $\Phi_{ref}(0)$ being the reference energy. Since the sampling frequency of the sound wave is more than the twice of the maximum audio frequency, this value is much more accurate than the L_{eq} which is measured by the usual sound level meter.

Scale values of loudness of complex noises (the center frequencies: 2 kHz and 3 kHz) and bandpass noise (the center frequency: 1 kHz) as a function of the bandwidth obtained by the paired-comparison tests as shown in Figs. 5(a) and 5(b), respectively. Paired-comparison tests were conducted for bandpass noises filtered with the slope of 1080–2068 dB/octave) under the condition of a constant $\Phi_p(0)$. As shown in Fig. 5, when noise has the similar repetitive feature, τ_e becomes a great value as like a pure tone, then the greater loudness results. Thus, a plot of loudness versus bandwidth is not flat in the critical band. Remarkable finding as demonstrated Figs. 5(a) and 5(b) is that similar scale values are obtained for complex noises and bandpass noise, when the fundamental frequencies corresponding to pitch are the same. This contradicts previous results of the frequency range centered on 1 kHz [19].

4.2 Pitch

The second primary sensation applying the ACF is the pitch s_P or the missing fundamental of the noise. It is given by

$$s_P = f_P(\Phi_p(0), \tau_1, \phi_1, \tau_e, D) \tag{8}$$

When a sound signal contains only a number of harmonics without the fundamental frequency, we hear the fundamental as a pitch [7, 8, 20]. This phenomenon is well explained by the delay time of the first peak in the ACF fine structure, i.e., τ_1, but is not explained by the use of power spectrum. According to experimental results on the pitch perceived when listening to bandpass noises without any fundamental frequency, the pitch sensation s_P is mainly expressed by τ_1 in Eq. (8) as well. The strength of the pitch sensation is described by the magnitude of the first peak of the ACF, ϕ_1 [21].

4.3 Timbre

The third primary sensation, timbre s_T is the most complicated one, because it includes pitch and loudness,

$$s_T = f_T(\Phi_p(0), \tau_1, \phi_1, \tau_e, D) \tag{9}$$

It is worth noticing that the speech intelligibility (single syllables) as a function of the delay time of single reflection is well be calculated by the four orthogonal factors extracted from the running ACF analyzed for the piece between consonant and vowel sounds [21]. A recent investigation, clearly show that timbre or dissimilarity judgment is an overall subjective response similar for the subjective preference of sound fields in concert hall [22].

4.4 Duration Sensation

The forth-primitive sensation, which is introduced here, is duration sensation s_D as a perception of signal duration. As is well known, musical notes include information of loudness, pitch and duration. Duration sensation may be given by

$$s_D = f_D(\Phi_p(0), \tau_1, \phi_1, \tau_e, D) \tag{10}$$

Some experiments have been performed, and results indicate that s_D depends on , τ_1, ϕ_1, and D [23]. In Table 2, these primary sensations are summarized.

5. SPATIAL SENSATIONS

5.1 Localization

The localization of a noise source in the horizontal plane may be described as

$$s = f(\mathrm{LL}, \mathrm{IACC}, \tau_{IACC}, W_{IACC}) \tag{11}$$

where

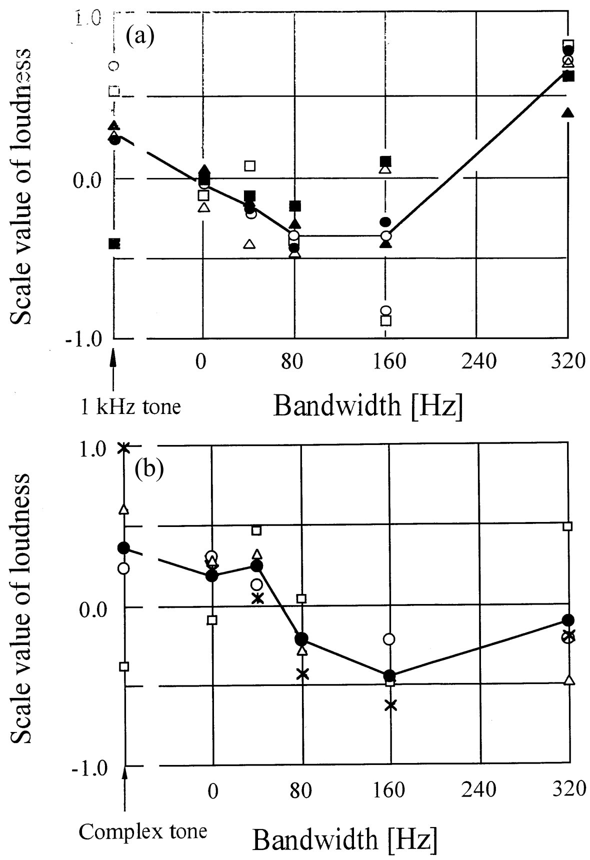

Fig. 5. Scale value of loudness as a function of the bandwidth. Different symbols indicate the scale values obtained with different subjects. (a) bandpass noises of 1 kHz center frequency. (b) Complex noises whose fundamental frequencies of 1 kHz.

$$\mathrm{LL} = 10\log_{10}\{\Phi_{ll}(0),\ \Phi_{rr}(0)\} \tag{12}$$

The symbol {} signifies a set, $\Phi_{ll}(0)$ and $\Phi_{rr}(0)$ being ACFs at $\tau = 0$ (sound energies), of the signals arriving at the left and right ear-entrances. Mathematically, LL is expressed by the geometrical mean of the energies of sound signals arriving at the both ear entrances. The listening level is given by

$$\mathrm{LL} = 10\log_{10}\left[\Phi_{ll}(0)\Phi_{rr}(0)\right]^{1/2} / \Phi_{ref}(0) \tag{13}$$

In these four orthogonal factors in Eq. (11), the value of τ_{IACC} defined within the possible interaural time delay is a significant factor in determining the perceived horizontal direction of the source. A well-defined direction is perceived when the normalized interaural crosscorrelation function has one sharp maximum, a high value of the IACC and a narrow value of the W_{IACC}, due to high frequency components. On the other hand, subjective diffuseness or no spatial directional impression corresponds to a low value of IACC (< 0.15) [24].

Table 2. Primary sensations in relation to factors extracted from the autocorrelation function and the interaural crosscorrelation function.

Factors		**Primitive sensations**			
		Loudness	Pitch	Timbre[a)]	**Duration**
ACF	LL	**X**	x	**X**	**X**
	τ_1	**X**	**X**	**X**	**X**
	ϕ_1	x	**X**	**X**	**X**
	τ_e	**X**	x	**X**	x
	D	x[b)]	x[b)]	**X**[b)]	**X**

X and x: Major and minor factors influencing the corresponding response.

D: Physical duration of sound signal.

$LL = 10 \log[\Phi(0)/\Phi_{ref}(0)]$, where $\Phi(0) = [\Phi_{ll}(0)\Phi_{rr}(0)]^{1/2}$.

It is suggested that loudness, pitch and timbre should be examined in relation to the signal duration.

a) In order to describe timbre, additional factors τ_1 and ϕ_1 (i = 2, 3, ... , N) must be taken into account on occasional cases.

b) It is recommended that loudness, pitch and timbre should be examined in relation to the signal duration D as well.

For localization of the white-noise source in the median plane, the four temporal factors extracted from the ACF of sound signal arriving at the ear-entrances may be taken into account [25]. But, this is hard to be explained by any of spectrum cues.

5.2 Apparent Source Width (ASW)

It is considered that the scale value of ASW is described mainly in terms of LL, IACC and W_{IACC}. A wider ASW may be perceived with a greater value of W_{IACC} (low frequency components) and by decreasing the IACC. The scale values of ASW were obtained by paired-comparison tests with ten subjects. In order to control the values of W_{IACC}, the center frequencies of 1/3 octave bandpass noises were changed [21]. Its center frequencies were 250 Hz, 500 Hz, 1 kHz, and 2 kHz. The values of IACC were adjusted by controlling the sound pressure ratio of the reflections with certain horizontal direction to the amplitude of the direct sound. Since the listening level affects ASW [26], the total sound pressure levels at the ear canal entrances of all noise fields were kept constant at a peak of 75 dBA. Listeners judged which of two noise sources they perceived to be wider. Results of the analysis of variance for the scale values s_{ASW} indicates that both of factors IACC and W_{IACC} are significant ($p < 0.01$), and contribute to s_{ASW} independently, thus

$$S_{ASW} \approx a_a (IACC)^{\alpha} + b_a (W_{IACC})^{\beta} \quad (14)$$

where coefficients $a_a \approx -1.64$, $b_a \approx 2.44$, $\alpha \approx 3/2$ and $\beta \approx 1/2$ are obtained by regressions of the scale values.

5.3 Subjective Diffuseness

The scale value of subjective diffuseness is assumed to be expressed in terms of LL, IACC and W_{IACC}. In order to obtain the scale value of subjective diffuseness, paired-comparison tests with bandpass Gaussian noise, varying the horizontal angle of two symmetric reflections have been conducted. Listeners judged which of two sound fields were perceived as more diffuse, under the constant conditions of LL, τ_{IACC}, and W_{IACC} [27]. The strong negative correlation between the scale value and the IACC can be found in the results with frequency bands between 250 Hz–4 kHz. Under the conditions of constant LL and W_{IACC}, the scale value of subjective diffuseness is inversely related to the IACC. The scale value of subjective diffuseness may be well formulated in terms of the 3/2 power of the IACC in a manner similar to the subjective preference for the sound field, i.e.,

$$S_{diffuseness} \approx a_d (IACC)^{\alpha} \quad (15)$$

where coefficient $a_d \approx -2.9$, and $\beta \approx 3/2$.

Table 3 indicates major and minor factors influencing each spatial sensation of the stationary noise field.

6. EFFECTS OF ENVIRONMENTAL NOISE AND MUSIC STIMULI ON THE PERFORMANCE OF TWO MENTAL TASKS

6.1 Procedure and Results

In this section, differential effects of reproduced noise and music on two kinds of mental tasks are demonstrated. We investigated left and right hemispheric tasks as indicated in upper parts of Figs. 6 and 7 [28-30], with children from noisy and quiet living areas (Table 4). Children under conditions of no stimulus, noise stimulus, and music stimulus carried out the tasks.

Tests were carried out in the classrooms (the reverberation

Table 3. Spatial sensations in relation to factors extracted from the autocorrelation function (ACF) and the interaural crosscorrelation function (IACF).

Factors		Spatial sensations			
		ASW	Subjective diffuseness	Horizontal direction	Vertical direction
ACF	τ_1				
	ϕ_1				X
	τ_e				X
IACF	$\Phi_{ll}(0)$	-	-	X	x
	$\Phi_{rr}(0)$	-	-	X	x
	LL	X	X	-	-
	τ_{IACC}	x	x	X	x
	W_{IACC}	X	X	X	x
	IACC	X	X	X	x

X and x: Major and minor factors influencing the corresponding response.
LL = 10 log[$\Phi(0)/\Phi_{ref}(0)$], where $\Phi(0) = [\Phi_{ll}(0)\Phi_{rr}(0)]^{1/2}$.
ASW: Apparent source width.

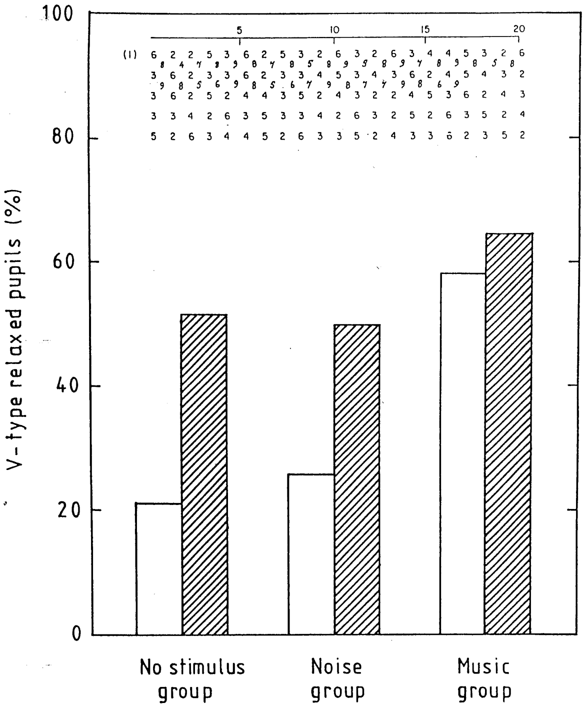

Fig. 6. Proportion of V-type relaxed children during the adding task . Upper part indicates the task of one period in N (= 15). Unshaded bars show results for children from quite living areas; shaded bars show results for children from noisy living areas.

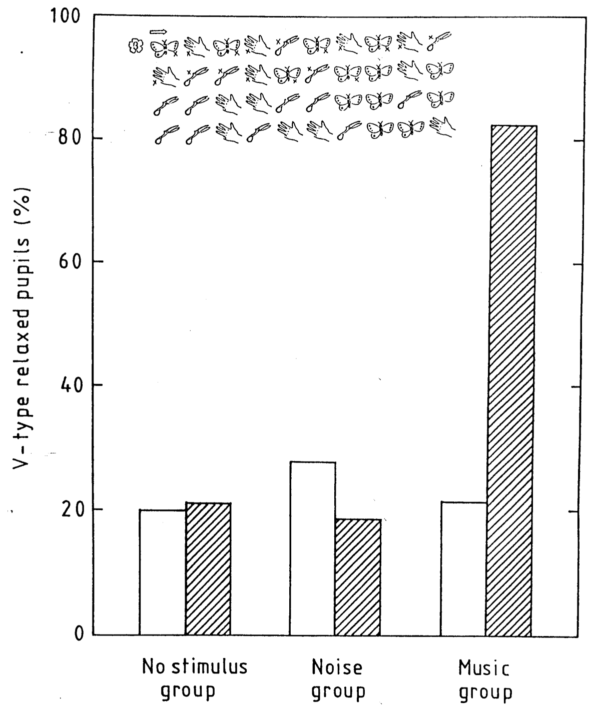

Fig. 7. Proportion of V-type relaxed children during the search task . Upper part indicates the task of one period in N (= 10). Unshaded bars show results for children from quite living areas; shaded bars show results for children from noisy living areas.

time: 0.5–0.9 s in the 500 Hz octave band) of two schools in each living area. The no-stimulus was tested in a normal classroom without reproduced any sound. The noise group was tested while being exposed to a jet plane noise of 95±5 dBA, peak. The music group was tested while listening to an excerpt of music from the fourth movement of Beethoven's Ninth Symphony (85±5 dBA, peak). As shown in Fig. 8, the time pattern and spectrum of the music were similar to those of jet noise which were measured by the traditional technique. The sound stimulus was reproduced from two loudspeakers set at the front of the classroom, during every alternative period during the tasks given by

$$i = 2n, \qquad (16)$$

Table 4. Number of subjects from both quiet and noisy living area monitored while performing metal tasks

Task	Age (years)	Living area	No-stimulus group	Noise group	Music group	Total
Addition (left-hemisphere)	9-10	noisy	146	151	34	331
		quiet	120	123	36	279
Pattern search (right-hemisphere)	7-8	noisy	183	183	34	396
		quiet	123	123	38	280

The total number of subjects was 1286 (varied data) [28].

where n = 1, 2, ... , 7 for the adding task, and n = 1, 2, ... , 5 for the search task. Examples of one period are shown in upper part of Fig. 6 (60 s/period) and Fig. 7 (30 s/period).

The individual work produced in each period, called the "working curve," was drawn for all test results. The mean work performance is not discussed here because there were no significant differences between the different conditions. Of particular importance in evaluating the tests results is the "V-type relaxation." This score is classified into two categories, according to the occurrence of a sudden large fall in the working curve during each task. This assessed by $M_i < M-(3/2)W$, $i = 1, 2, ..., N$, where M is the mean work performance and W is the average variation of the curve excluding an initial effect at the first period, $i = 1$. Such relaxation is thought to be caused by an abandonment of effort when mental functions are disturbed.

As shown in Fig. 6, in a quiet areas the percentage of relaxed children given the additional task (N = 15) was much greater in the music group than in either the no-stimulus group and the noise group ($p < 0.01$). In a noisy area, however, the percentage of relaxed children was always greater than that in the quiet area, particularly in the no-stimulus group ($p < 0.001$).

As shown in Fig. 7 for pattern-search task (N = 10), the percentage of relaxed children in a quiet area was similar under all test conditions, except for a slight increase in the noise group. The only significant change between the subjects from different living areas was found in the music group ($p < 0.001$).

The results of the mental tasks were not dependent on the sex, birth order, or birth weight of child, on whether or not the mother was working mother, during or suffered from toxicosis during her pregnancy, on the child's gestational age when the mother moved into the noisy area, or on child's feelings about aircraft noise [28].

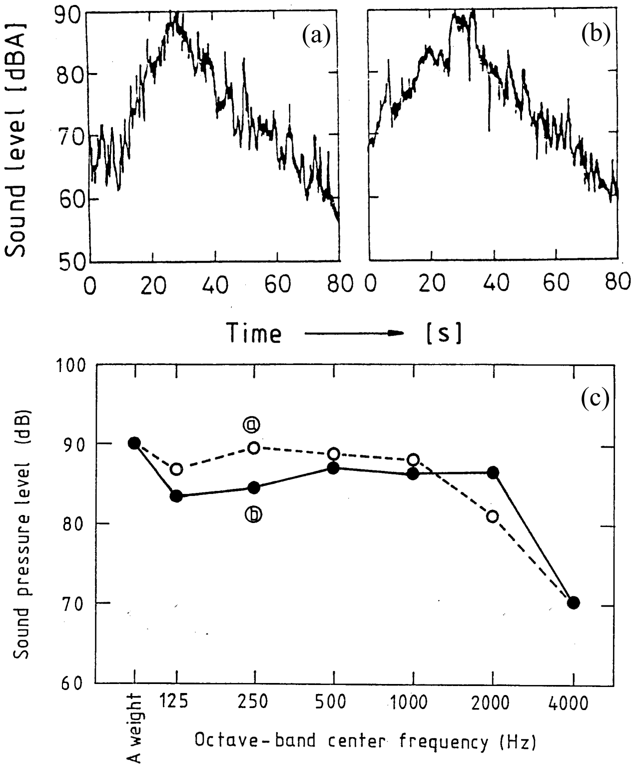

Fig. 8. Sound pressure levels (SPL) of stimuli and spectra measured by the traditional technique. (a) SPL of aircraft noise as a function of time. (b) SPL of music piece. (c) Spectra, a: aircraft noise; b: music.

6.2 Discussion

According to the method of measuring noise described in this paper, significant differences in the factors τ_1 and τ_e extracted from the running ACF as a function of time may be found as shown in Fig. 9. Due to the model shown in Fig. 1, these factors may stimulate the left hemisphere activated by the fluctuations of these factors. In the quiet living area [28], the effects of temporary music and noise stimuli on mental tasks are closely related to the content of the task being performed or to specialization of cerebral hemispheres. In the case of

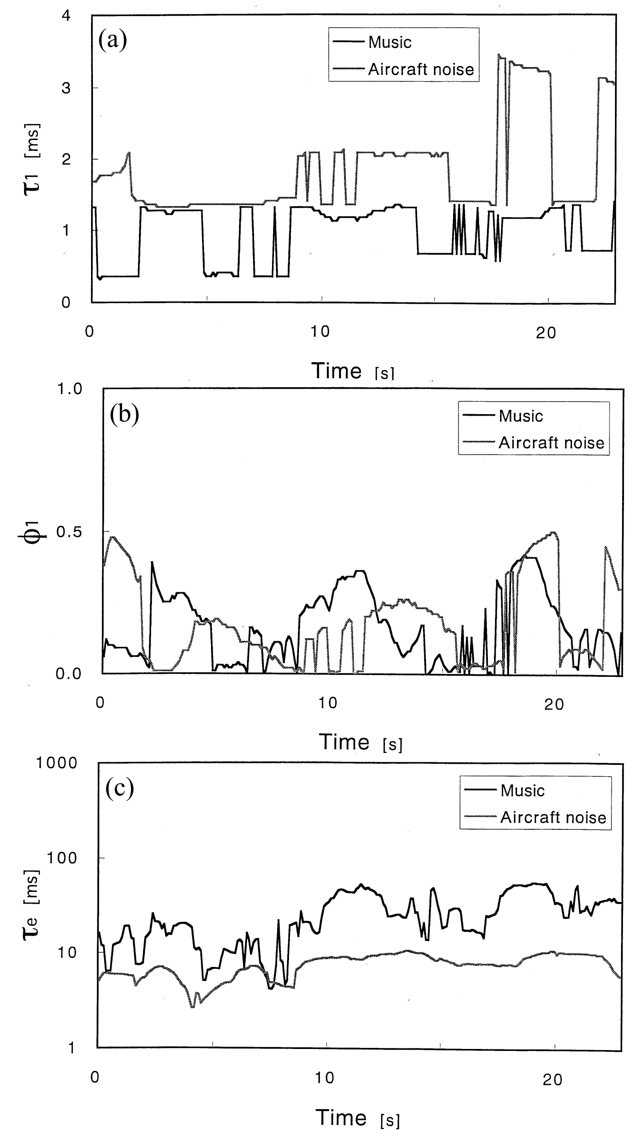

Fig. 9. Three orthogonal factors extracted from the ACF for the first 25 s of noise (-----) and music (.......), analyzed by 2T = 2 s and running interval of 100 ms. (a) Values of τ_1 corresponding to the pitch of the aircraft noise and the music. (b) Values of ϕ_1 corresponding to the strength of pitch of the aircraft noise and the music. (c) Values of τ_e corresponding to the similar repetitive feature signals of the aircraft noise and the music.

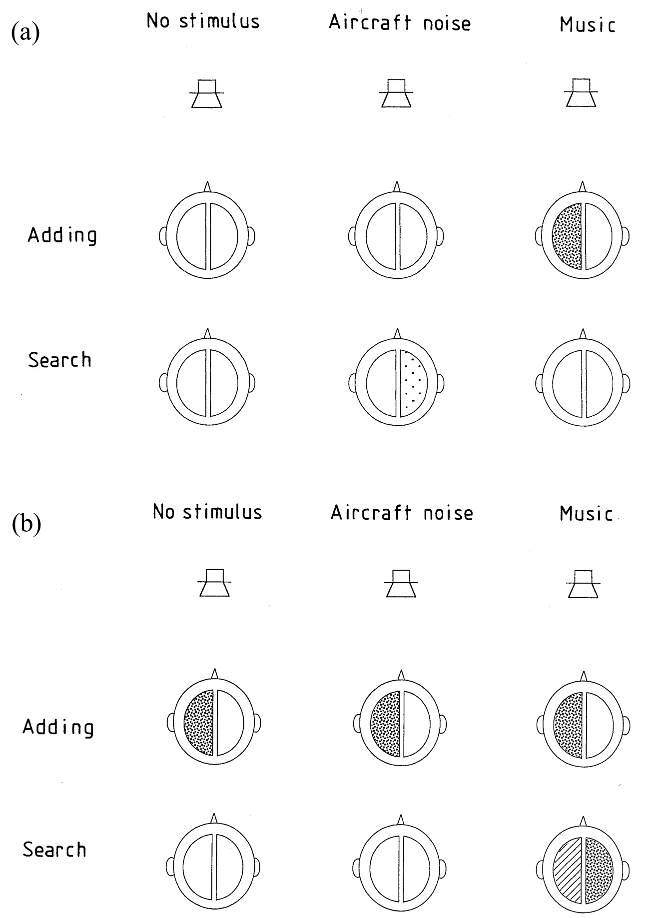

Fig. 10. Explanations of interference between mental tasks and sound stimuli. According to the auditory-brain system model used in the present work, noise and music are respectively associated mainly with the right hemisphere and the left hemisphere. And the adding task and search task respectively may be associated mainly with the left hemisphere and the right hemisphere. (a) For children from a quiet living area. (b) For children from a noisy living area. Interference effects shown by shaded areas differ remarkably from between children from noisy and quiet living areas.

the addition task, there were no significant differences between the noise group and the no-stimulus group in the percentage of V-type relaxed children. This may support the theory that noise and calculation tasks are separately processed in the right and left hemispheres, respectively [29]. Thus as illustrated in Fig. 10(a), no interference effects are evident. However, the percentage of relaxed children in the music stimulus group differs significantly from that in the noise group and the no-stimulus group. This may be explained by music perception and calculation being processed one after the other in the left hemisphere. On the other hand, music perception and search task may be independently processed in the left and right hemispheres. In the search task, although no significant differences in the number of V-type relaxed children could be observed under no-stimulus and music conditions. But, a difference was observed ($p < 0.1$), so that an interference in the right hemisphere seems to be discernible [30]. The rather dispersive results of several other investigations of mental tasks could be well described by this explanation.

As shown in Fig. 10(b), however, the effects of temporary sounds on mental tasks are quite different in the noisy area.

Table 5. Effects of noise on tasks and annoyance, in relation to factors extracted from the autocorrelation function (ACF) and the interaural crosscorrelation function (IACF), and orthogonal factors of the sound field.

	Factors	**Effects of noise on tasks**		**Annoyance**
		Left hemispheric task	**Right hemispheric task**	
ACF	τ_1	**X**		**X**
	ϕ_1	**X**		**X**
	τ_e	**X**		**X**
IACF	LL	**X**	**X**	**X**
	τ_{IACC}		**X**	**X**
	W_{IACC}		**X**	**X**
	IACC		**X**	**X**

X and x: Major and minor factors influencing the corresponding response.
LL = 10 log[$\Phi(0)/\Phi_{ref}(0)$], where ${}_r(0) = [\Phi_{ll}(0)\Phi_{rr}(0)]^{1/2}$.

In the case of the addition task, the proportion of V-type relaxed children was always increased in the noisy area, even under no-stimulus conditions (Fig. 6); this may thus be considered a chronic effect of daily on metal performance. In the search task, the percentage of relaxed children increased greatly in the music group, but not in the noise group.

It is worth noticing that comparing the interference between the subjects whose responses are shown in Figs. 9(a) and 9(b), that daily noise affects the development of hemisphere specialization in children.

7. REMARKS

For the subjects living in a quiet living area, Table 5 indicates summarization of effects of noise on tasks and annoyance. Annoyance as an overall response to temporary noise is considered to be described by all of factors extracted from the ACF and IACF [31].

For any sensation of a noise in a room, the temporal factors of the sound field must be taken into consideration, such as the initial-time delay gap between the direct sound and the first reflection (Δt_1) and the subsequent reverberation time (T_{sub}) in addition. As a typical example, Timbre might be expressed by

$$s_T = f_T(\tau_e,\ \tau_1,\ \phi_1,\ \Delta t_1, T_{sub})_{left} + f_T(LL,\ IACC,\ \tau_{IACC},\ W_{IACC})_{right} \qquad (17)$$

Further works are recommended to be conducted according to a suitable line suggested here.

REFERENCES

[1] Ando, Y. (1985). Concert hall acoustics, Springer-Verlag, Heidelberg.

[2] Ando, Y. (1998). Architectural acoustics, blending sound sources, sound fields, and listeners. AIP Press/Springer-Verlag, New York.

[3] Katsuki, Y., Sumi, T., Uchiyama, H. and Watanabe, T. (1958). Electric responses of auditory neurons in cat to sound stimulation. J. Neurophysiol. 21, 569-588.

[4] Kiang, N.Y.-S. (1965). Discharge pattern of single fibers in the cat’s auditory nerve. MIT Press, Cambridge, MA.

[5] Secker-Walker, H.E. and Searle, C.L. (1990). Time domain analysis of auditory-nerve-fiber firing rates. J. Acoust. Soc. Am., 88, 1427-1436.

[6] Cariani, P.A., and Delgutte, B. (1996). Neural correlates of the pitch of complextones. I. Pitch and pitch salience. J. Neurophysiology, 76, 1698-1716.

[7] Inoue, M., Taguti, T., and Ando, Y. (2001). On the pitch identification based uponthe autocorrelation function model. Proc. 17 Intern. Congr. Acoust. Vol. IV, Rome.

[8] Inoue, M., Ando, Y., and Taguti, T. (2001). The frequency range applicable to pitch identification based upon the auto-correlation function model. J. Sound Vib. 241, 105-116.

[9] Ando, Y., Yamamoto, K., Nagamastu, H., and Kang, S.H. (1991). Auditory brainstem response (ABR) in relation to the horizontal angle of sound incidence. Acoustic Letters, 15, 57-64.

[10] Ando, Y., Kang, S.H., and Nagamatsu, H. (1987). On the auditory-evokedpotential in relation to the IACC of sound field, J. Acoust . Soc. Jpn. (E) 8, 183-190.

[11] Ando, Y., Kang, S.H. and Morita, K. (1987). On the relationship between auditory-evoked potential and subjective preference for sound field, J. Acoust. Soc. Jpn. (E) 8, 197-206.

[12] Nagamatsu, H., Kasai, H. and Ando, Y. (1989). Relation between auditory evoked potential and subjective estimation - effect of sensation level. Report of Meeting of Acoust. Soc. Jpn., pp. 391-392. (in Japanese).

[13] Ando, Y. (1992). Evoked potentials relating to the subjective preference of soundfields, Acustica, 76, 292-296.

[14] Ando, Y., and Chen, C. (1996). On the analysis of autocorrelation function of α-waves on the left and right cerebral hemispheres in relation to the delay time of single sound reflection. J. Archit. Plann. Environ. Eng., Architectural Institute of Japan (AIJ), 488, 67-73.

[15] Chen, C., and Ando, Y. (1996). On the relationship between the autocorrelation function of the α-waves on the left and right cerebral hemispheres and subjective preference for the reverberation time of music sound field. J. Archit. Plann. Environ. Eng., Architectural Institute of Japan (AIJ), 489, 73-80.

[16] Sato, S., Nishio, K., and Ando, Y. (1996). On the relationship between

the autocorrelation function of the continuous brain waves and the subjective preference of sound field in change of the IACC. J. Acoust. Soc. Am., 100(A), 2787.

[17] Soeta, Y., Nakagawa, S., Tonoike, M., and Ando Y. (2001). Auditory evoked magnetic fields corresponding to the subjective preference of sound fields. Proceedings of 17th Intern. Congr. Acoust., Vol. III, Rome.

[18] Mouri, K., Akiyama, K., and Ando, Y. (2001). Preliminary study on recommended time duration of source signals to be analyzed, in relation to its effective duration of autocorrelation function. J. Sound Vib., 241, 87-95.

[19] Zwicker, E., Flottorp, G., and Stevens, S.S. (1957). Critical band width in loudness summation. J. Acoust. Soc. Am., 29, 548-557.

[20] Wightman, F.L., (1973). Pitch and stimulus fine structure. J. Acoust. Soc. Am. 54, 397-406.

[21] Ando, Y., Sakai, H., and Sato, S. Formulae describing subjective attributes for sound fields based on a model of the auditory-brain system. J. Sound Vib., 232, 101-127, 2000.

[22] Hotehama, T., Sato, S., Ando, Y. (2001). Dissimilarity Judgments in Relation to Temporal and Spatial Factors for the Sound Field in an Existing Hall. Proceedings of 17th Intern. Congr. Acoust., Vol. III, Rome.

[23] Saifuddin, K., Sakai, H., and Ando, Y. (2001). Duration sensation of the simulated environmental noise in relation to its autocorrelation function. J. Sound Vib., 241, 117-127, 2001.

[24] Damaske, P., and Ando, Y. (1972). Interaural crosscorrelation for multichannel loudspeaker reproduction. Acustica, 27, 232-238.

[25] Sato, S., Mellert, V., and Ando, Y. (2001). Cues for localization in the median plane extracted from the autocorrelation function. J. Sound Vib., 241, 53-56.

[26] Keet, M. V. (1968). The influence of early lateral reflections on the spatial impression. Proc. 6th Intern. Congr. Acoust., Tokyo, Paper E-2-4.

[27] Ando, Y. and Kurihara, Y. (1986). Nonlinear response in evaluating the subjective diffuseness of sound field. J. Acoust, Soc. Am., 80, 833-836.

[28] Ando, Y., Nakane, Y., and Egawa, J. (1975). Effects of aircraft noise on the mental work of pupils. J. Sound and Vib., 43, 683-691.

[29] Ando, Y. (1988). Effects of daily noise on fetuses and cerebral hemisphere specialization in children. J. Sound and Vib., 127, 411-417.

[30] Ando, Y. (2001). Differential effects of noise and music signals on the behavior of children. J. Sound Vib., 241, 129-140.

[31] Atagi, J., Fujii, K., and Ando, Y. (2001). Proceedings of 17th Intern. Congr. Acoust., Vol. III, Rome.