

## Chapter 2

# Model of Auditory Brain System

### 2.1 Slow-Vertex Responses (SVR) Corresponding to Subjective Preference of the Sound Field

Neural response correlates of subjective preference were found in the latency of SVR peaks. Figure 2.1 summarizes the relationship between subjective preference scale values and three acoustic parameters (SL,  $\Delta t_1$ , and IACC). Applying the paired method of stimuli, both the SVRs and the subjective preferences for sound fields were investigated as functions of these parameters (Ando 1998). The source signal was 0.4–0.9 s of segment. The lower part of the figure indicates the appearance of latency components.

1. As shown in the left and center columns in the figure, the neural information related to subjective preference appeared typically in an  $N_2$ -latency of 250–300 ms, when SL and  $\Delta t_1$  were changed. In general, subjective preference may be regarded as a predisposition towards maintaining life, making the appearance of such primitive survival-oriented responses in neuronal observables all the more expected.
2. Further details of the latencies for both the test sound field and the reference sound field, when  $\Delta t_1$  was changed, are shown in Fig. 2.2. The parallel latencies at  $P_2$ ,  $N_2$  and  $P_3$ , were clearly observed as functions of the delay time  $\Delta t_1$ . However, latencies for the reference sound field ( $\Delta t_1 = 0$ ) in the paired stimuli were found to be relatively shorter, while the latencies for the test sound field with  $\Delta t_1 = 25$  ms, the most preferred delay, became longest. This pattern may indicate a kind of *relative* behavior of the brain, which leads to underestimating the reference sound field when the test sound field in the pair is the most preferred condition.
3. Relatively long-latency responses are always observed in the subjectively preferred range of each factor.

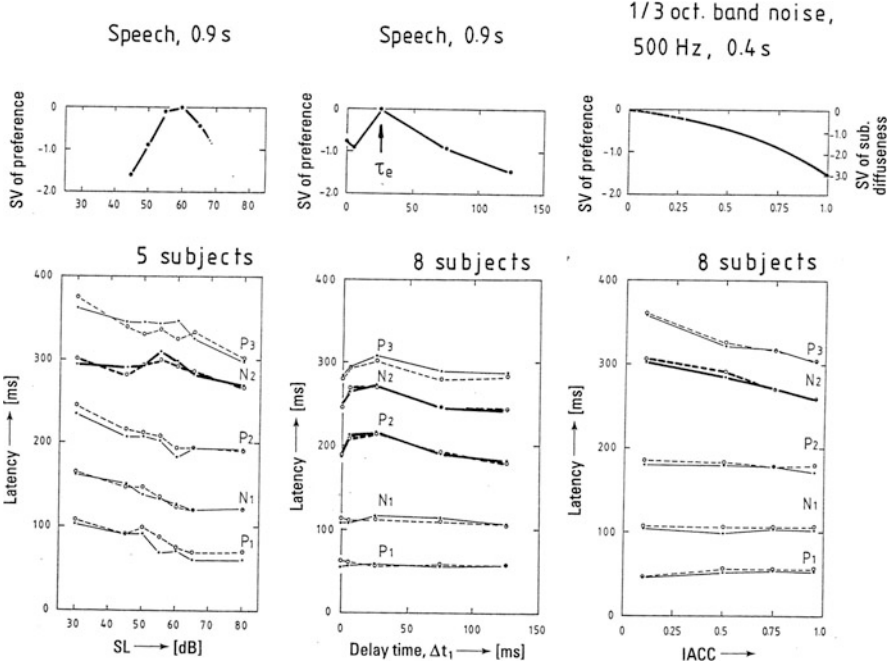


**Fig. 2.1** Relationships between averaged latencies of the SVR and scale values of subjective preference for three factors of the sound field (—): left hemisphere; (----): right hemisphere

- (a) As a function of the sensation level (SL)  
 (b) As a function of the delay time of reflection,  $\Delta t_1$   
 (c) As a function of the IACC

4. Thus, the difference of  $N_2$ -latencies over both hemispheres in response to a pair of sound fields contains almost the same information as that obtained from PCTs for subjective preference.

The right column of Fig. 2.1 shows the effects of varying the IACC using the 1/3-octave-band noise (500 Hz) (Ando 1987b, 1992). At the upper part, the scale value of the subjective diffuseness is indicated as a function of the IACC. The scale value of subjective preference also has a similar behavior plotted against the IACC.

5. The information related to subjective diffuseness or subjective preference, therefore, appears in the  $N_2$ -latency, ranging between 260 and 310 ms, in which a tendency for an increasing latency while decreasing the IACC was observed for eight subjects (except for the left hemisphere of one subject). The relationship between the IACC and the  $N_2$ -latency was found to be linear, and the correlation coefficient between them was  $-0.99$  ( $p < 0.01$ ).
6. Furthermore, let us look at the behavior of early latencies at  $P_1$  and  $N_1$ , which remained almost constant when the delay time and the IACC were changed. However, the information related to the SL may be found typically at the  $N_1$ -latency. This tendency agrees well with the results of Botte et al. (1975).

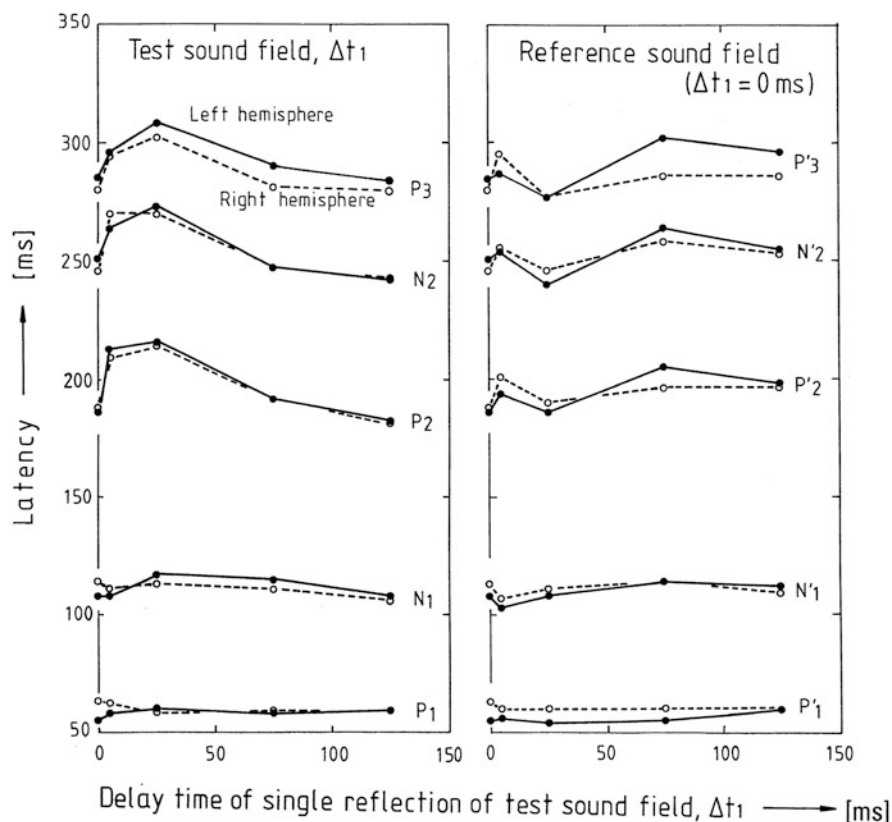


**Fig. 2.2** Averaged latencies for both the test sound field and the reference sound field for paired stimuli, as a function of the delay time of the reflection,  $\Delta t_1$ . (—): left hemisphere; (---): right hemisphere

Maximum latencies of  $P_2$ ,  $N_2$ , and  $P_3$  are found at  $\Delta t_1 = 25$  ms for the test sound field, whereas relatively short latencies of  $P'_2$ ,  $N'_2$ , and  $P'_3$  are observed for the reference sound field. This is typical brain activity showing "relativity"

7. Consequently from 40 to 170 ms of the SVR, the hemispheric dominance may be found for the amplitude component, which may be related to respective functional specializations of the hemispheres. Early latency differences corresponding to the SL may be found in the range between 120 and 170 ms.
8. Finally, we found that the  $N_2$ -latency components in the delay range between 200 ms and 310 ms may correspond well with subjective preference relative to the listening level, to the time delay of the reflection, and, indirectly, to the IACC.
9. Since the longest latency was always observed for the most preferred condition, one might speculate that the brain is most relaxed at the preferred condition and that this causes the observed latency behavior to occur. Therefore, a correlation

may exist between the duration of latency periods and the duration of alpha wave periods in electroencephalography (EEG) and magnetoencephalography (MEG) during the human waking stage as discussed in the following chapters.

## 2.2 Electroencephalographic (EEG) and Magnetoencephalographic (MEG) Correlates of Subjective Preference of the Sound Field

*In order to attain further knowledge of brain activities, we conducted a series of experiments to find EEG correlates of subjective preference. Since the effects of changes in reverberation time ( $T_{\text{sub}}$ ) could not be seen from auditory-evoked potentials by applying short signals less than 0.9 s in duration, we had to use longer time frames to enable continuous sounds to find some distinctive feature in EEG signals that would follow changes in the  $T_{\text{sub}}$ . First, we changed the delay time of the single reflection ( $\Delta t_1$ ), which reconfirmed the SVR results. Analysis of the data led us to discover an EEG correlate of subjective preference in the effective duration of the autocorrelation function of the alpha wave range (Ando 2009), i.e., in the duration that alpha rhythms persist in the brain (Fig. 2.3). To discriminate*

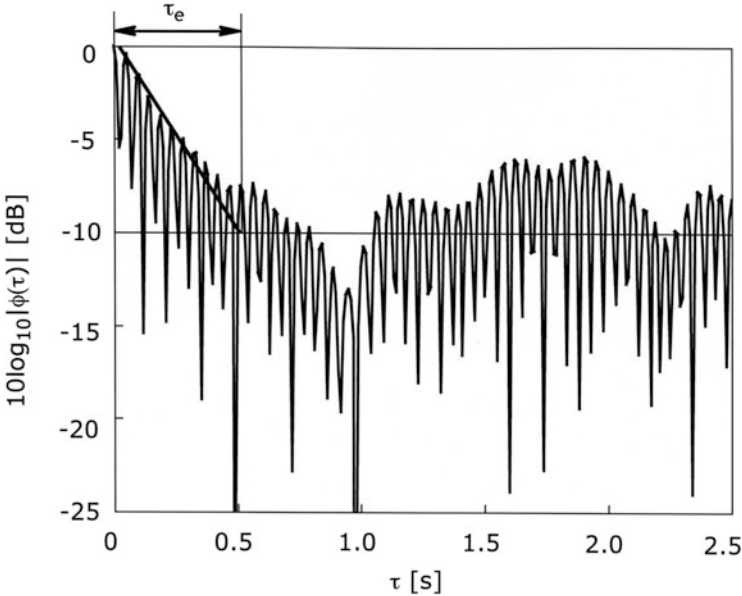


**Fig. 2.3** Determining the effective duration ( $\tau_e$ ) of the alpha rhythm by estimating the slope of the envelope of the autocorrelation function and determining the delay at which it reaches 10 % of its maximal at zero-lag value of 0 dB. Effective duration measures duration of temporal coherence, i.e., the duration over which a repetitive structure persists in a signal. Such activity in the alpha rhythm is an indication of subjective preference that may be measured even in newborn babies

*more clearly between individual perceptions, we investigated further by using MEG to chart individual responses following changes to  $\Delta t_1$ . Ultimately, effects of the typical temporal factor ( $T_{\text{sub}}$ ) and spatial factor (IACC) were searched in EEG recordings.*

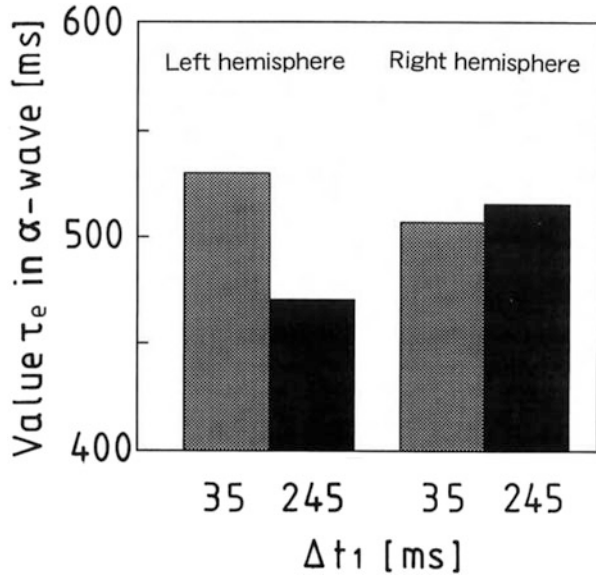
### 2.2.1 EEG in Response to Change of $\Delta t_1$

In this experiment, music motif B (Arnold's Sinfonietta, Opus 48, a 5-s segment of the 3rd movement) was selected as the sound source (Burd 1969; Ando 1985). The delay time of the first, single reflection  $\Delta t_1$  was alternatively adjusted to 35 ms (a preferred condition) and 245 ms (a condition of clear echo percept). The EEG of ten pairs from positions T3 and T4 was recorded for about 140 s in response to ten delay-change pairs, and experiments were repeated over a total of 3 days. Eleven 22–26-year-old subjects participated in the experiment. Each subject was asked to close their eyes while listening to the music during the recording of the EEG. Two loudspeakers were arranged in front of the subject. Thus, the IACC was kept at a constant value near unity. The sound-pressure level was fixed at a 70 dBA peak, in which the amplitude of the single reflection was the same as that of the direct sound,  $A_0 = A_1 = 1$ . The leading edge of each sound signal was recorded as a time stamp so that the recorded EEG responses could be precisely synchronized to and correlated with the presented sound. EEG signals amplified, passed through a filter with a 5–40 Hz bandwidth and a slope of 140 dB/octave, and were then digitally sampled at 100 Hz or more.

In order to find brain activity patterns corresponding to subjective preference, we analyzed the effective duration  $\tau_e$  of the ACFs in the  $\alpha$ -wave range (8–13 Hz) of the EEG. First, considering that the subjective preference judgment needs at least 2 s to develop a psychological present, the running integration interval (2T) was examined for periods between 1.0 s and 4.0 s. Remarkable findings are:

1. A satisfactory duration  $2T = 2\text{--}3$  s in the ACF analysis was found only from the left hemisphere (Ando and Chen 1996). Values of  $\tau_e$  at  $\Delta t_1 = 35$  ms are significantly longer than at  $\Delta t_1 = 245$  ms ( $p < 0.01$ ) only in the left hemisphere, but not in the right (Fig. 2.4).
2. Ratios of  $\tau_e$  values in the  $\alpha$ -wave range at  $\Delta t_1 = 35$  ms and 245 ms, for each subject, are shown in Fig. 2.5. Remarkably, all individual data indicate that the ratios in the left hemisphere at the preferred condition of 35 ms are much longer than in the right hemisphere.
3. The results reconfirm that when  $\Delta t_1$  is changed, the left hemisphere is highly activated, and the values of  $\tau_e$  of  $\alpha$ -rhythms in this hemisphere correlate well with subjective preference. The  $\alpha$ -rhythm has the longest period in the EEG in the waking state of the adult human and may indicate feelings of “pleasantness” and “comfort” – a preferred condition, which is widely accepted. A long

**Fig. 2.4** Averaged ACF  $\tau_e$  values of the EEG alpha wave upon change of  $\Delta t_1$  between 35 ms and 245 ms (11 Subjects). *Left:* left hemisphere. *Right:* right hemisphere. Significant difference in ACF  $\tau_e$  values may be found in the left hemisphere associated with the temporal factors, but not in the right hemisphere (associated with spatial factors)



effective duration  $\tau_e$  of  $\alpha$ -rhythms may relate to the long  $N_2$ -latency of the SVR in the preferred condition that was shown in Fig. 2.1.

### 2.2.2 MEG in Response to Change of $\Delta t_1$

*In MEG studies, the weak magnetic fields produced by electric currents flowing in neurons are measured with a multiple channel SQUID (superconducting quantum interference device for magnetism detection) gradiometers, which enables the study of many interesting properties of the working human brain. MEG accurately detects superficial tangential currents, whereas EEG is sensitive to both radial and tangential current sources and reflects activity in the deepest parts of the brain. Only currents that have a component tangential to the surface of a spherically symmetric conductor produce a sufficiently strong magnetic field outside of the brain; radial sources are thus externally silent. Therefore, MEG mainly measures neuronal activity from the fissures of the cortex, which often simplifies interpretation of the data. Fortunately, all the primary sensory areas of the brain – auditory, somato-sensory, and visual – are located within fissures. The advantages of MEG over EEG result mainly from the fact that the skull and other extracerebral tissues are practically transparent to magnetic fields but do substantially alter electrical*

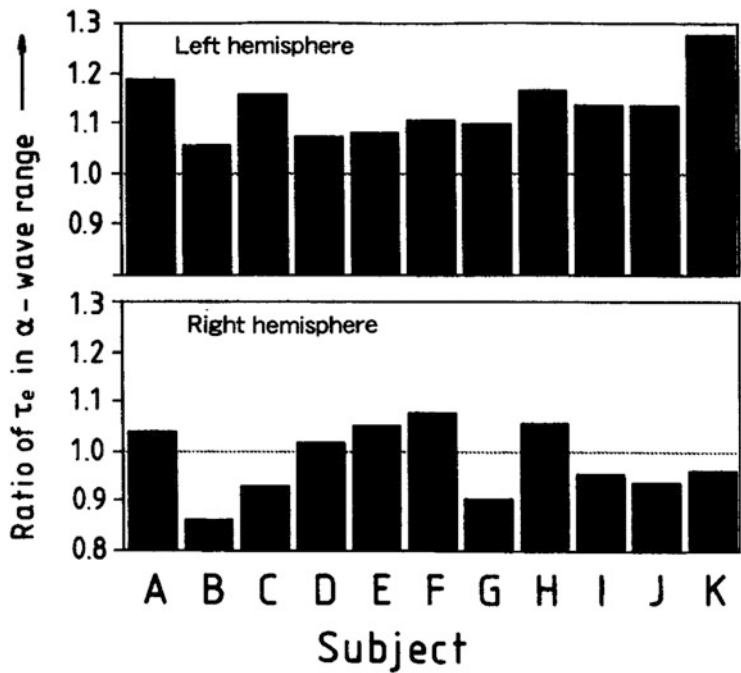


**Fig. 2.5** Ratios of ACF  $\tau_e$  values of the EEG alpha wave upon change of  $\Delta t_1$  between 35 ms and 245 ms for each individual subject, A–K: [ $\tau_e$  value at 35 ms]/[ $\tau_e$  value at 245 ms]  
*Above: left hemisphere. Below: right hemisphere*  
Ratios of ACF  $\tau_e$  values of the EEG alpha wave are always greater on the left hemisphere than on the right

current flows. Thus, magnetic patterns outside the head are less distorted than the electrical potentials on the scalp. Further, magnetic recording is reference-free, whereas electric brain maps depend on the location of the reference electrode.

Measurements of MEG responses were performed in a magnetically shielded room using a 122-channel whole-head neuromagnetometer as shown in Photo 2.1 (Neuromag-122<sup>TM</sup>, Neuromag Ltd., Finland) (Soeta et al. 2002

The source signal was the word “piano,” which had a 0.35-s duration. The minimum value of the moving effective duration  $\tau_e$ , i.e.,  $(\tau_e)_{\min}$ , was about 20 ms. It is worth noting that this value is close to the most preferred delay time of the first reflection of sound fields with continuous speech (Ando and Kageyama 1977). In the present experiment, the delay time of the single reflection ( $\Delta t_1$ ) was set at five levels (0, 5, 20, 60, and 100 ms). The direct sound and a single reflection were mixed, and the amplitude of the reflection was the same as that of the direct sound ( $A_0 = A_1 = 1$ ). The auditory stimuli were binaurally delivered through metal-free plastic tubes and earpieces into the ear canals. The sound-pressure level, which was measured at the end of the tubes, was fixed at 70 dBA.

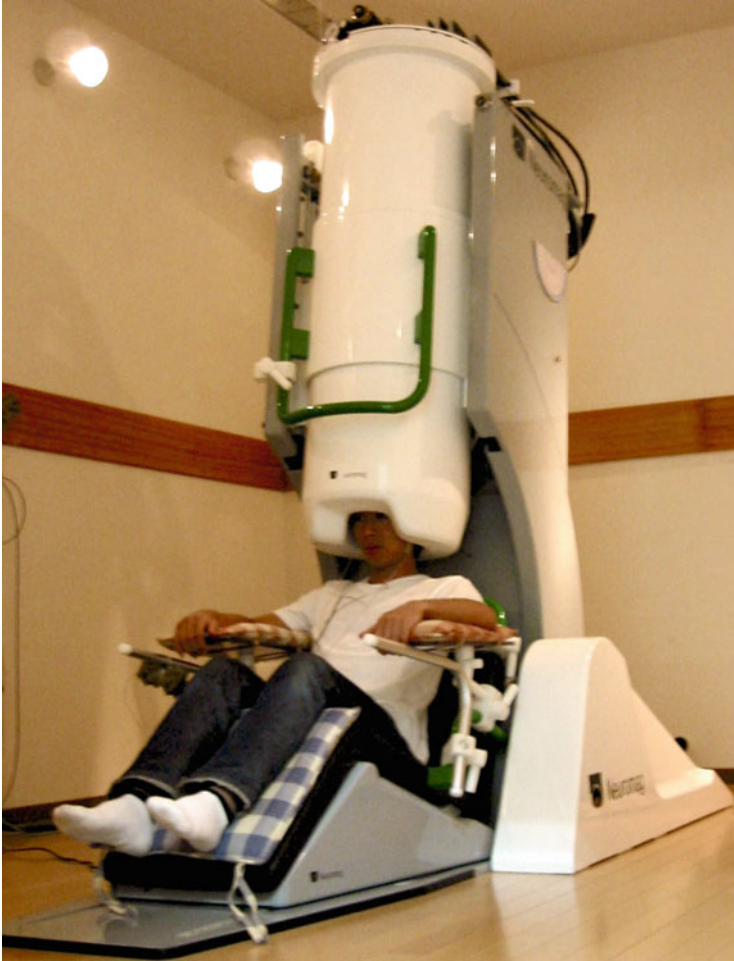


**Photo 2.1** Magnetometer used in recording the magnetoencephalogram (MEG)

Seven 23–25-year-old subjects with normal hearing participated in the experiment. In accordance with the PCT methodology, each subject compared ten possible stimulus pairs per session, and a total of ten sessions were conducted for each subject. Measurements of magnetic responses were performed in a magnetically shielded room. Similar to the EEG measurements described in the previous section, the paired-auditory stimuli were presented in the same way as in the subjective preference test. During measurements, the subjects sat in a chair with their eyes closed. To compare the results of the MEG measurements with the scale values of the subjective preference, combinations of a reference stimulus ( $\Delta t_1 = 0$  ms) and test stimuli ( $\Delta t_1 = 0, 5, 20, 60$ , and  $100$  ms) were presented alternately 50 times, and the MEG signals were analyzed. The magnetic data were recorded continuously

with a filter of 0.1–30.0 Hz and digitized with a sampling rate of 100 Hz. Eight channels that had larger amplitudes of N1m response in each hemisphere were selected for the ACF analysis. We analyzed the MEG alpha band signal for each of the paired stimuli for each subject, computed their normalized autocorrelation functions, and plotted them using logarithmic units of magnitude. The envelope of the ACF is fitted with a straight line and its intercepts with the –5 and –10 dB magnitude values are determined. The –10 dB (10 % of maximum value) intercept is defined as the effective duration (Fig. 4.27 in Ando 2009). Naturally, for the preferred condition at  $\Delta t_1 = 5$  ms where the first reflection time is short, the computed effective duration value of the MEG alpha band response is long ( $\tau_e \approx 0.5$  s), compared to the effective duration of  $\tau_e \approx 0.3$  s that is seen for the unfavorable condition of echo disturbance ( $\Delta t_1 = 100$  ms).

The results from the eight subjects confirmed a linear relationship between the averaged  $\tau_e$  values in the MEG alpha band and the averaged scale values of subjective preference. The left hemisphere dominates the temporal factor  $\Delta t_1$ , which reconfirms the aforementioned SVR and EEG studies. Therefore, we analyzed individual results from the left hemispheres of the subjects. We concluded that:

1. An almost direct relationship between individual scale values of subjective preference and the  $\tau_e$  values over the left hemisphere was found in each of the eight subjects. Results for each of the eight subjects are shown in Fig. 2.10.
2. Remarkably, the correlation coefficient,  $r$ , was above 0.94 for all subjects.
3. It is worth noting that there was only weak correlation between the scale values of subjective preference and the amplitude of the  $\alpha$ -wave,  $\Phi(0)$ , for either hemisphere ( $r < 0.37$ ).
4. The value of  $\tau_e$  in the alpha wave band is the persistence of alpha rhythms in time, so that under the preferred conditions, the brain repeats a similar rhythm of alpha activity for a longer period of time. This tendency for a longer effective duration  $\tau_e$  of the alpha rhythm under the preferred condition is much more significant than the aforementioned results that were obtained through similar analyses of EEG signals.

### 2.2.3 EEG in Response to Change of $T_{sub}$

Now, let us examine how effective durations  $\tau_e$  of  $\alpha$ -rhythms change in response to subsequent reverberation times ( $T_{sub}$ ) and their subjective preference values. Ten student subjects participated in the experiment (Chen and Ando 1996). The sound source used was music motif B, herein described as having a minimum effective duration of  $(\tau_e)_{min} \sim 40$  ms, so that the most preferred reverberation time can be calculated as  $(T_{sub})_p \sim 23 (\tau_e)_{min} = 0.92$  s (Eq. 6.5). Ten 25–33-year-old subjects participated in the experiment. EEG signals from the left and right hemispheres were recorded. Values of  $\tau_e$  in EEG signals in the  $\alpha$ -band were also analyzed for the duration of  $2T = 2.5$  s.

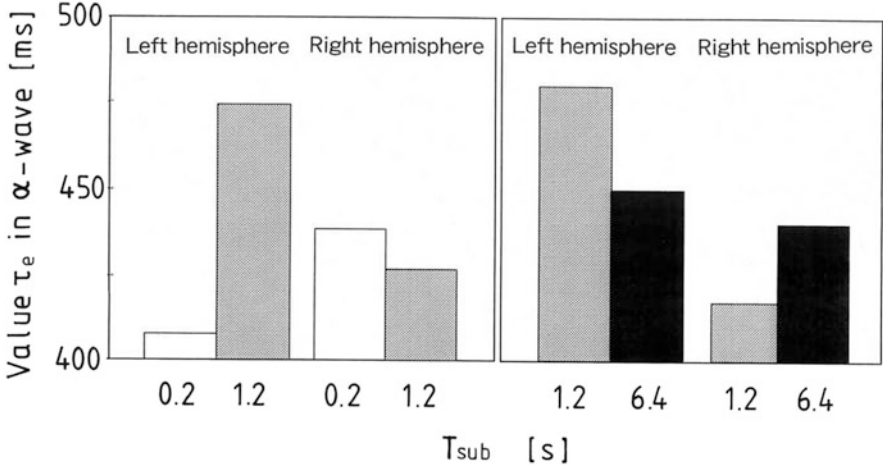


**Fig. 2.6** Averaged value of ACF  $\tau_e$  of the EEG alpha wave upon change of  $T_{sub}$ : 0.2 s and 1.2 s; 1.2 s and 6.4 s for 10 subjects. The *left column* in each figure depicts results from the left hemisphere, and the *right column* depicts results from the right hemisphere

First, let us consider the averaged values of the effective duration  $\tau_e$  of  $\alpha$ -activity, shown in Fig. 2.6.

1. Clearly, for the left hemisphere the values of  $\tau_e$  are much longer close to the preferred condition 0.92 s, i.e., at  $T_{sub} = 1.2$  s, than at either of the non-preferred conditions  $T_{sub} = 0.2$  s and 6.4 s.
2. Thus, alpha rhythms persist longer in the left hemisphere for preferred reverberation time values. However, the contrary is true for the right hemisphere, where the non-preferred reverberation times produced longer effective durations of alpha activity.

The results of the analysis of variance (ANOVA) reveal that although there are vast individual differences, a significant difference is achieved for  $T_{sub}$  in the pair of 0.2 s and 1.2 s ( $p < 0.05$ ), and interference effects are observed for factors Subject and LR ( $p < 0.01$ ), and LR and  $T_{sub}$  ( $p < 0.01$ ). No such significant differences are achieved for the pair at 1.2 s and 6.4 s, but there are interference effects between subject and LR, and subject and  $T_{sub}$ . Different individual scale values of preference, however, are well correlated to ratios of values of  $\tau_e$  for the  $\alpha$ -wave band in the left hemisphere (Chen and Ando 1996; Ando 1998, 2009).

### 2.2.4 EEG in Response to Change of the IACC

The EEG response to changes in the IACC was also investigated. Eight student subjects participated in the paired-comparison experiment (Sato et al. 2003). Music

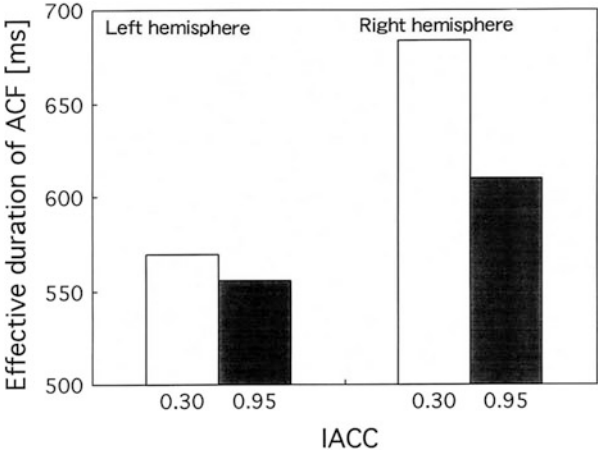


**Fig. 2.7** Averaged values of ACF  $\tau_e$  of the EEG alpha wave upon change of the IACC for the pair of IACC = 0.30 and 0.95. The *left column* in the figure is from the left hemisphere, and the *right column* is from the right hemisphere

motif B was again used as the stimulus. Changes in the IACC reflected clearly in right hemisphere dominance. The effective duration  $\tau_e$  of  $\alpha$ -band activity was found to be substantially longer in the preferred condition (IACC = 0.30). A significant difference was achieved in the right hemisphere for the pair of sound fields with IACC = 0.95 and 0.30 ( $p < 0.01$ ) as shown in Fig. 2.7.

1. In seven of eight subjects, the ratios of effective durations  $\tau_e$  for  $\alpha$ -band responses to IACC change,  $[\tau_e (\text{IACC} = 0.3)/\tau_e (\text{IACC} = 0.95)]$ , in the right hemisphere were greater than in the left hemisphere except for subject B (Fig. 2.8). Thus, as far as the IACC is concerned, the more preferred condition with a smaller IACC is related to longer  $\alpha$ -rhythm effective durations in the right hemisphere in most of subjects tested.
2. As shown the most clearly in Fig. 2.9, a wave of alpha rhythm activity in the right hemisphere (T4) at IACC = 0.3, later propagates toward the left hemisphere (T3).
3. Additionally, experiments using MEG measurements tested a speech signal that was altered by changes made to the IACC (0.27, 0.61 and 0.90). The results reconfirmed that effective duration  $\tau_e$  and the maximum amplitude of the CCF increased when the IACC decreased in the right hemisphere (Soeta et al. 2005).

Table 2.1 summarizes hemispheric dominance results obtained by analysis of the effective durations  $\tau_e$  of  $\alpha$ -rhythms, with respect to changes in listening level LL, first reflection time  $\Delta t_1$ , reverberation time  $T_{\text{sub}}$ , and the interaural crosscorrelation coefficient IACC. This finding suggests that the value of  $\tau_e$  in the  $\alpha$ -band is an objective index for designing excellent human acoustic environments.

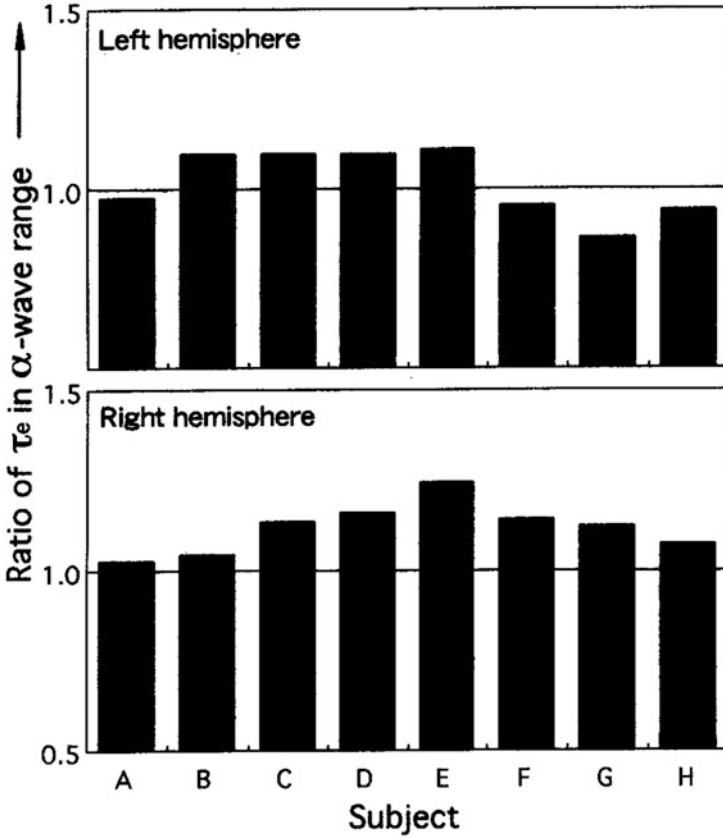


**Fig. 2.8** Ratio of ACF  $\tau_e$  values of the EEG alpha wave from the left hemisphere (T3) and the right hemisphere (T4) for each of 8 subjects, A–H:  $[\tau_e \text{ value at IACC} = 0.30]/[\tau_e \text{ value at IACC} = 0.95]$ . Ratio of ACF  $\tau_e$  values is greater on the right hemisphere than on the left except for subject B

### 2.3 Specialization of Cerebral Hemispheres for the Sound Field

Four significant, orthogonal physical factors for describing sound fields have been found. Two of them are temporal aspects, i.e., the initial time delay gap between the direct sound and the first reflection,  $\Delta t_1$ , and the subsequent reverberation time,  $T_{\text{sub}}$ , while the other two are spatial aspects, i.e., the magnitude of the interaural crosscorrelation function, the IACC, and the volume of the binaural listening level, LL. Specialization of the cerebral hemispheres according to the temporal and spatial factors when each of these four factors is changed during the experiments has been identified.

**Fig. 2.9** Propagation of the alpha wave flow from the right hemisphere to the left in response to a change of IACC. Real numbers reflect the median values of alpha rhythm correlation magnitudes (maximum absolute values) between alpha band EEG signals from electrode T4 and the indicated electrodes

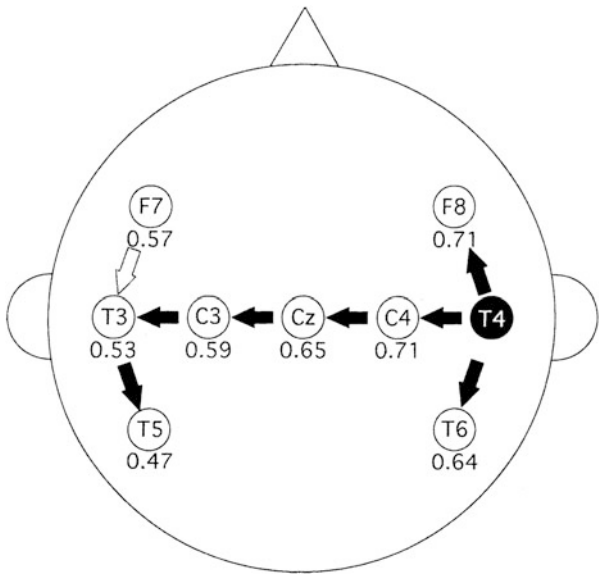


**Table 2.1** Hemispheric specializations determined by AEP, EEG, and MEG of the left and right hemispheres for temporal and spatial factors of the sound field, respectively

| Factors changed                    | AEP (SVR)<br>$A(P_1 - N_1)$      | EEG, ratio of ACF $\tau_c$<br>values of $\alpha$ -wave | AEP<br>(MEG)<br>$N1m$                   | MEG, ACF $\tau_c$<br>value of $\alpha$ -wave |
|------------------------------------|----------------------------------|--------------------------------------------------------|-----------------------------------------|----------------------------------------------|
| <i>Temporal</i>                    |                                  |                                                        |                                         |                                              |
| $\Delta t_1$                       | $L > R$<br>(speech) <sup>1</sup> | $L > R$ (music)                                        |                                         | $L > R$ (speech)                             |
| $T_{sub}$                          | –                                | $L > R$ (music)                                        | –                                       |                                              |
| <i>Spatial</i>                     |                                  |                                                        |                                         |                                              |
| LL                                 | $R > L$<br>(speech)              | –                                                      | –                                       |                                              |
| IACC                               | $R > L$ (vowel/<br>a/)           | $R > L$ (music) <sup>2</sup>                           | $R > L$<br>(band<br>noise) <sup>3</sup> |                                              |
|                                    | $R > L$ (band<br>noise)          |                                                        |                                         |                                              |
| $\tau_{IACC}$                      |                                  |                                                        | $R > L$<br>(band<br>noise) <sup>3</sup> |                                              |
| Head-related<br>transfer functions |                                  |                                                        | $R > L$<br>(vowels) <sup>4</sup>        |                                              |

<sup>1</sup>Sound source used in experiments is indicated in the bracket  
<sup>2</sup>The flow of EEG  $\alpha$ -wave from the right hemisphere to the left hemisphere in response to music stimulus in change of the IACC was determined by the CCF  $|\phi(\tau)|_{max}$  between  $\alpha$ -waves recorded at different electrodes  
<sup>3</sup>Soeta and Nakagawa (2006)  
<sup>4</sup>Palomaki et al. (2002)

Recordings of brain activity over the left and right hemispheres, including the slow-vertex response (SVR), electroencephalogram (EEG), and magnetoencephalogram (MEG), have revealed evidences as listed in Table 2.1. Formulation of such a neurally grounded strategy for acoustic design has been initiated through a study of auditory-evoked electrical potentials, i.e., the slow-vertex responses (SVR), which are generated by the left and right human cerebral hemispheres. The goal of these experiments was to identify potential neuronal response correlates of subjective preference for the orthogonal acoustic parameters related to sound fields. Using the paired-comparison method, it had been established that particular ranges of the four orthogonal factors were preferred by most listeners. These factors and auditory-evoked potentials (AEPs) are integrated by the triggering technique, so that reliable predictions of subjective preference could be made. Similarly, in the study the SVR for paired stimuli was integrated, and scale values of subjective preference based on the paired-comparison method were obtained. Typically, SVRs are the strongest when stimulus patterns change abruptly, i.e., there is a contrast between the paired stimuli in which spatial and/or temporal factors change. The method of paired stimuli is therefore the most effective procedure because of this relativity of the brain response.

Main results are as follows:

1. The left- and right-relative peak amplitudes of the first major SVR waves indicate lateralization of responses associated with the temporal factor ( $\Delta t_1$  in the left hemisphere) and spatial factors (LL and IACC in the right hemisphere) (Fig. 2.1; Ando et al. 1987a, b; Ando 2003). Correlates of loudness, the sensation level SL and the binaural listening level LL, were classified as temporal-monaural factors from a physical viewpoint. However, results of the SVR indicate that the neural correlates of these parameters were predominantly observed over the right hemisphere. Thus, SL and LL should be reclassified as spatial factors as far as specialization of the hemispheres is concerned. Classification of the LL as a spatial factor is natural because it is accurately measured by the geometric average of sound energies arriving at the two ears.
2. Results of EEG recordings that showed hemispheric lateralization of the temporal factors, i.e.,  $\Delta t_1$  and  $T_{\text{sub}}$  (reverberation time), reconfirmed left hemisphere dominance for these factors (Ando and Chen 1996; Chen and Ando 1996). Similarly, spatial factors associated with the interaural magnitude IACC showed right hemispheric dominance (Sato et al. 2003; Sato and Prodi 2009). It is worth noting that the scale value of subjective preference has a tendency to increase as IACC decreases. Thus, judging by the evidence provided by the measured subjective neural responses to varying temporal and spatial factors, there appears to be a high degree of independence between the left and right hemispheres.
3. Scale values of subjective preferences are well predicted from the values of the effective durations  $\tau_e$  (extracted from the ACF) of EEG alpha band activity (8–13 Hz) over the left and right hemispheres. Neural correlates of preferences related to changing temporal and spatial factors of the sound fields dominate in the left and right hemisphere EEG signals, respectively (Figs. 2.7 and 2.8).

4. Recorded MEG amplitudes reconfirmed the left hemisphere specialization for the first reflection time  $\Delta t_1$  (Soeta et al. 2002).
5. Scale values of individual subjective preferences relate directly to the value of effective duration  $\tau_e$  extracted from the ACF of the alpha band activity of the MEG (Fig. 2.10). Note that it is the effective durations of the alpha rhythms in EEG and MEG recordings, and not the absolute amplitudes of these waves, that correspond to scale values of subjective preferences.
6. In addition to the temporal response patterns described above, propagation of a wave of alpha rhythm activity in the right hemisphere from electrode T4 to the whole brain including the left hemisphere is demonstrated in Fig. 2.9. Here, spatial patterns of cortical neural response were analyzed by examining crosscorrelations between alpha band activity at different scalp locations in the two hemispheres using EEG and MEG recordings. The results indicate alpha rhythm activity over larger areas of the cerebral cortex in response to preferred sound fields (Soeta et al. 2003). These findings indicate that the brain repeats a similar temporal rhythm in the alpha frequency range over a wider area of the scalp when preferences are better satisfied. It is also noteworthy that the alpha rhythm has the longest period of brain waves in the waking state and is deeply related to relaxation and health. Previously, the left hemisphere has been mainly associated with identification of time sequences and functions, and the right hemisphere has been known to be fundamentally concerned with spatial identification.

Left hemispheric specialization for speech signals has been reported by a number of authors using EEG and MEG recordings. However, when the IACC was changed for speech and music signals, right hemispheric dominance was observed as indicated in Table 2.1. Therefore, rather than having an absolute response bias for particular kinds of signals, hemispheric response dominance is relative and depends on which factor is changed in the comparison pair.

These findings and the theory of subjective preference reconfirm the central auditory signal-processing model (Ando 1985) as shown in Fig. 2.11 (Ando 1998, 2007, 2009).

## 2.4 Model of Auditory Brain System

*Based on the above-mentioned physical system and physiological responses, a high-level signal-processing model of the central auditory system (Ando 1985) has been reconfirmed as shown in Fig. 2.11. Applying this model can yield a wide range of research works. For example, research has been initiated for enabling automatic speech recognition over the telephone and in rooms, which would allow identifying which one of the 7000 languages that are alive in the world today is being spoken (Ando 2015). If the neural ACF is extended in time to cover longer time delays than those present in neural responses, then a running neural ACF*

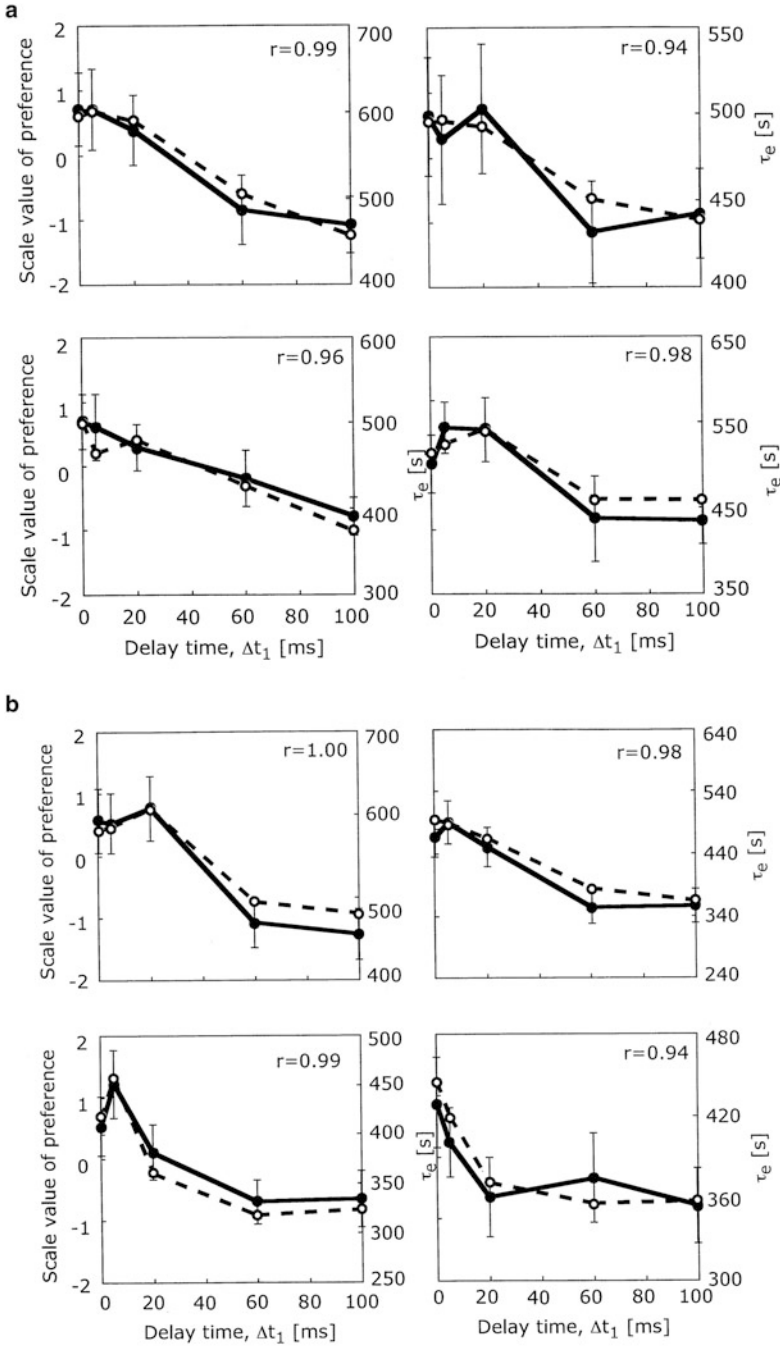


**Fig. 2.10** Good correspondence between the scale value of subjective preference and the averaged ACF  $\tau_e$  value of the MEG alpha wave over the left hemisphere (8 subjects). The averaged  $\tau_e$  value and the scale value are the highest correlation over the eight channels. ○: scale values of subjective preference. ●: averaged  $\tau_e$  values of MEG alpha wave, error bars being standard errors

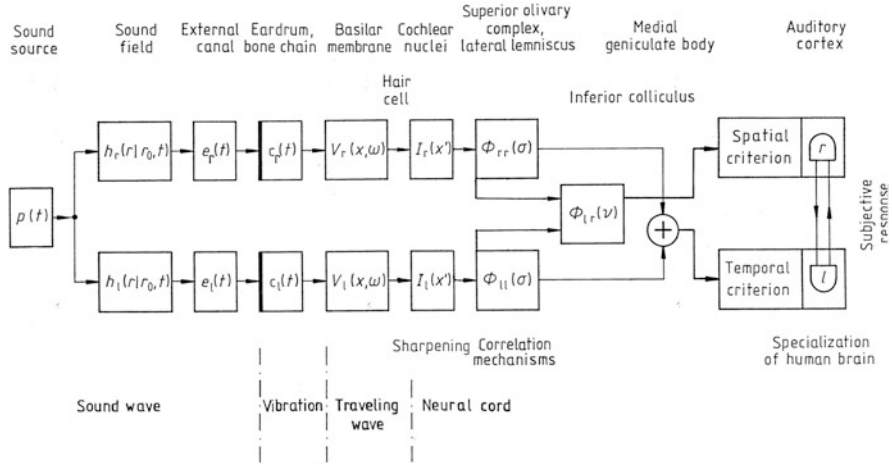


**Fig. 2.11** Central auditory signal-processing model for subjective responses (Ando 1985)

$p(t)$ : source sound signal in the time domain.  $h_{l,r}(r|r_0, t)$ : head-related impulse responses from a source position of  $r_0$  to the left and right ear entrances of a listener at  $r$ .  $e_{l,r}(t)$ : impulse responses of left and right external canals, from the left and right ear entrances to the left and right eardrums.  $c_{l,r}(t)$ : impulse responses for vibration of left and right bone chains, from the eardrums to oval windows, including transformation factors into vibration motion at the eardrums –  $V_{l,r}(x, \omega)$ : travelling wave forms on the basilar membranes, where  $x$  is the position along the left and right basilar membrane measured from the oval window.  $I_{l,r}(x')$ : sharpening in the cochlear nuclei corresponding to roughly the power spectra of input sound, i.e., responses of a single pure tone  $\omega$  tend to a limited region of nuclei. These neural activities may be enough to be converted into activities similar to the ACF.  $\Phi_{ll}(\sigma)$  and  $\Phi_{rr}(\sigma)$ : ACF mechanisms in the left and right auditory pathways, respectively. Symbol  $\oplus$  signifies that signals are combined.  $\Phi_{lr}(\nu)$ : IACF mechanism (Ando 1985).  $r$  and  $l$ : specialization for temporal and spatial factors of the left and right human cerebral hemispheres, respectively. Temporal and spatial percepts (Sect. 4.2) may be processed in the left and right hemisphere according to the temporal factors extracted from the ACF and the spatial factors extracted from the IACF, respectively. The overall subjective preference and annoyance may be processed in both hemispheres in relation to the temporal and spatial factors (Ando 2002, 2009)

*could potentially come to aid in a broader spectrum of societal activities. It would be possible to classify music based on the effective duration of the ACF  $(\tau_e)_{min}$  of musical notes in order to select concert programs that blend preferred temporal factors with ideal acoustic spaces (Ando 2009); use automatic identification of noise source by implementing ACF factors for the purposes of reducing aircraft or traffic noise (Soeta and Ando 2015); study the effects that environmental noise has on the developing brain and its specialization and the accumulated effects that noise has on the mind (Ando 2011).*

The model consists of monaural autocorrelation mechanisms, the interaural crosscorrelation mechanism between the two auditory pathways, and the specialization of the human cerebral hemispheres for temporal and spatial factors of the sound field. In addition, according to the relationship between temporal and spatial

percepts of sound as well as subjective preference of the sound field and changes in physiological phenomena in response to variations in the acoustic factors, a model is reconfirmed and formed as shown in Fig. 2.11 (Ando 1998, 2009). In this figure, a sound source  $p(t)$  is located at position  $r_0$  in a three-dimensional space, and a listener is sitting at position  $r$ , which is defined by the location of the center of the head.  $h_{l,r}(r|r_0, t)$  are the impulse responses of the two sound paths through the room between  $r_0$  and the left and right ear canal entrances. The impulse responses of the external ear canal and the bone chain are  $e_{l,r}(t)$  and  $c_{l,r}(t)$ , respectively. The velocity of the basilar membrane is expressed by  $V_{l,r}(x, \omega)$ ,  $x$  being the position along the membrane.

In fact, the time domain analysis, rather than the frequency domain analysis, of firing rates of cat auditory nerve fibers revealed a pattern of the ACF (Secker-Walker and Searle 1990).

In contrast with neural representations that are based on neural firing rates, which tend to change their form and degrade at higher sound levels, representations based on temporal spike information remain largely invariant in form over the whole dynamic range of hearing and thus mirror the behavior of auditory percepts. For stimuli consisting of low-frequency components that are resolved by cochlear filters, “pooled all-order interspike interval distributions” or simply “population-interval distributions” resemble the autocorrelation of the stimulus itself. For sound stimuli consisting of higher-frequency components that are not resolved by cochlear filters, population-interval distributions resemble the autocorrelation of their waveform envelopes (Cariani and Delgutte 1996). From a viewpoint of the missing fundamental or pitch of complex components judged by human perception, the running ACF must be processed in the frequency components below about 5 kHz and the fundamental frequency below 1200 Hz (Inoue et al. 2001).

As we have discussed, evidence shows that there exist correlates of the interaural correlation magnitude IACC in neural activity at the level of the brainstem and midbrain (Ando 1998, 2009). The interaural crosscorrelation mechanism exists at the level of the superior olive and the inferior colliculus. It is concluded that the output signal of the interaural crosscorrelation mechanism that computes the IACC is predominantly connected to the right hemisphere. Representation of sound-pressure level (SPL) may also be preferentially processed in the right hemisphere. Sound-pressure level can be expressed in terms of a geometrical average of the ACFs for the two ears at the origin of time ( $\sigma = 0$ ), and changes in sound-pressure level produce changes in neuronal response latencies that appear at the level of the inferior colliculus.

Based on the model, temporal and spatial percepts (Ando et al. 1999; Ando 2002, 2009) and subjective attributes of sound fields in terms of processes occurring in the auditory pathways as well as the specialization of the two cerebral hemispheres will be described.

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