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Delving into Hearing Threshold of the Delay Gap of Initial Reflection in a Room by Using the Response of Cortical Brainwaves

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Abstract: In this study, the apparent variation ranges of acoustical parameters were investigated in a concert hall. The initial time delay gap (ITDG) was evaluated in terms of its just noticeable difference (JND) through two instruments, the cello and the trumpet. Even though the IDTG values were prolonged over the measurements and were not significantly varied, an ITDG range of 22–220 ms in increments of 91 steps was produced electro-acoustically in an anechoic chamber. The result of *JNDc* (Δgap/gap) was rated by 50% "different" judgement ranges for the cello and trumpet tracks, respectively. The effective duration of the autocorrection function (ACF) of the continuous brainwaves (CBWs) within the alpha (8–13 Hz) frequency range in the left hemisphere responding to 91-step ITDG increments revealed that the continuous ratios of τe_min ((τe_min_rear − τe_min_front)/τe_min_front) of CBWs were constantly on the trumpet. Furthermore, a homologous period of resonance between the subjective *JNDc* and τe values of the ACF of CBWs in the alpha range allowed us to conclude that the subjective JND of the ITDG in a room was related to the $W_{_IACC}$ value of the interaural cross-correlation function, which reflected the characteristics of source signals themselves and aroused the activities of the brain in the right hemisphere ($p < 0.01$). The dry sources of sound stimuli were first used to link the psychological preference and the neurophysiological activation of the room acoustics.

Keywords: initial time delay gap; just noticeable difference; autocorrection function; continuous brainwaves

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1. Introduction

Just noticeable difference (JND) values are available for most acoustical parameters currently used in practice. However, they have been determined with reference to conditions typically encountered in concert halls and in rooms for instrumental recitals, covering a range of initial time delay gaps (ITDG) spanning from 35 ms to 200 ms, which are beneficial if they arrive in sequency, each one succeeding the previous one with decreasing intensity. It is such a decreasing sequency that gives the important attributes of EDT and T60. But any one of those reflections can become an echo if its intensity is greater than the reflections immediately surrounding it. An echo is defined as a long ITDG of reflection, sufficiently loud to become annoying to a listener. The musical instrument that most often produces an echo in a concert hall is the trumpet because of its piercing staccato tones and because its bell directs its sound onto whatever surface is available to return the echo. The prediction of whether a reflection will be audible as an echo is not simple. Studies of brain activities in human time perception may reveal the coding in the central nervous system and specialization in the processing of temporal information management [1–6] under Weber's Threshold Law, which considers our psychological judgement and accounts for the most relevant characteristics of the decision-making-related neural activity, as confirmed by Deco et al. [7]. The objective of this study is to give an integrative approach to the time

sense and to focus on the relationship between subjective ITDG differentiation and the responses of the human brain.

1.1. Brainwaves and Sound Field

In view of earlier studies on continuous brainwaves (CBW) [1–9], we shall begin our discussion from the fundamental concept of the initial time delay gap (ITDG) in a sound field, which is the time difference between the arrival of the first reflection and the direct sound [6]. We regard ITDG as the most sensitive psychological factor for listening to music. In other words, when a faint reverberation is present in a sound field, the brain is able to distinguish whether a listening target is interrupted by excessively delayed reflected energies. This creates a noticeable change in the CBW frequency within the interrupted and uninterrupted regions. We propose that this is entirely caused by changes in the firing frequency of signals transmitted between the relative neurons of the cranial nerves located in different regions of the cortex. For instance, Moriyama and Miyagaya [10] categorized external stimuli as rational or sensible and used each type of stimuli to explore how the left and right hemispheres of the brain responded to a specific characteristic of sound. Soeta and Nakagawa [11] found that the peak amplitude of N1 increased alongside pitch strength. When we investigated through CWB recordings how the ITDG in a sound field affected the vestibulocochlear nerve and then compared the differences, we suggested that this was a result of psychological reactions manifested in our preference for or dislike of something [12]. This study investigated the threshold effect of psychological judgment, and therefore the most obvious responses to ITDG on the cerebral cortex should be classified as a CBW and an auditory-evoked potential (AEP), which is a response that occurs within 500 ms after the arrival of an auditory stimulus [8,9]. Most of these responses are manifested in the transmission potential responses of nerves along the auditory pathway, that is, a sound enters from the ear canal, passes through the eardrum and ossicles, and is then converted into electronic signals (nerve impulses) at the cochlea and transmitted to the two cerebral hemispheres, where a response occurs. Ando, Kang, and Nagamatsu [13] studied the AEP in terms of the slow vertex response (SVR) and revealed that the latency of the N2 peak of an SVR increased in response to changes in the magnitude of the interaural cross-correlation (IACC). They deduced that changes to the IACC caused by auditory nerve signals through the lateral lemniscus on the auditory pathway would produce a latency in the N2 peak. The N2 peak was the most distinguishable peak, produced around 200 ms after a signal entered the ear canal. N1, N2, P1, and P2 were dips and peaks of the waveform in AEP responses, which were suggested by Ichikawa [9], as shown in Figure 1. In addition, Ando, Kang, and Morita [14] found that, within an ideal first reflection of a sound in a sound field, the N2-latencies of SVR were prolonged in both hemispheres, while the P1-N1 amplitude in the left hemisphere was also increased. However, in this study, the continuous cueing method was used for auditory stimuli; hence, we believe that, by using the reflected energy and reflection time difference, "reaction" and "non-reaction" threshold responses can be observed for exceeding 500 ms after a stimulus through CBW recordings.

1.2. The Just Noticeable Difference (JND) of the ITDG of a Sound Field

Weber's Law is regarded as an exemplar in research pertaining to physical environments and psychological responses [15]. Laming [16] regarded it as the most fundamental brain activity examination tool for studying the association between physical stimuli and perceptions. In his discourse on the association between music hall designs and the auditory pathway of the vestibulocochlear nerve, Ando [17] stated that ITDG is the most fundamental physical component in a sound field. Indeed, it is closely associated with the clarity in a sound field. The effective delay time (τe) of the autocorrelation function (ACF) of CBW, a parameter that represents the association between the responses before and after the arrival of a signal, is found to be highly correlated with ITDG [6]. However, subsequent studies did not expound the linear relationship of CBW responses, which explains the lack of a square law-based correlation formula between physical components. To explore this

correlation, this study employed ITDG as a preliminary exploratory medium for exploring this uncharted territory. Romo et al. [18] showed that the activity of neurons in the ventral premotor cortex covaried with a monkey's decisions in a perceptual comparison task regarding the frequency of vibrotactile events. The sign of that difference was the determinant of a correct task performance. Deco et al. [7] confirmed this prediction in behavioural tests of vibrotactile discrimination in humans and proposed a computational explanation of perceptual discrimination that naturally accounts for the emergence of Weber's Law. These results support our experiences of the judgements of word intelligibility by changing the ITDG between the direct and the first reflection in a room. In a previous study, the features of the reactions on the ACF of cortical continuous brainwaves were analyzed [2]. The results revealed that the neurodynamical mechanisms and computational principles responded well with the decision-making process in such a perceptual discrimination task in the brain's metastability.

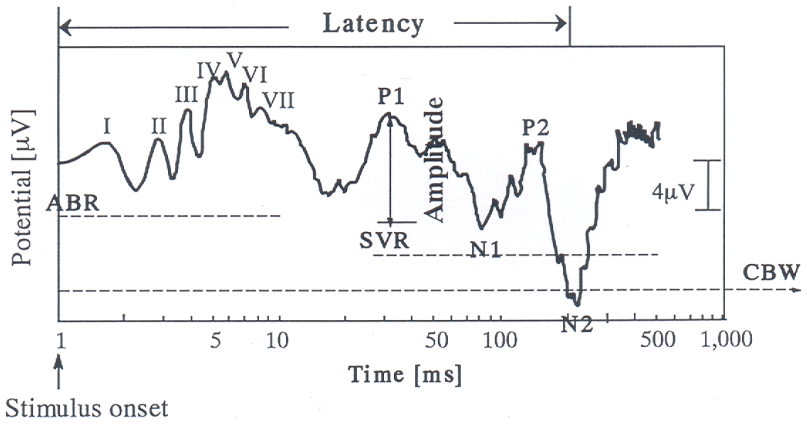


Figure 1. The AEP is a method of gathering the averaging waveform of electroencephalography (EEG) in a section beginning at stimuli onset. The averaging frequency is decided by the magnitude of evoked potential, for example, SVR needs about 50 times average, the ABR needs more than 300 times average for coming to view of I–VII peaks, and the CBW can be recorded through originality.

JND values are available for most acoustical parameters currently used in practice [19]. However, they were determined by referring to conditions that are typically encountered in concert halls and in rooms for speech, covering a reverberation time (T60) range spanning from 0.5 to 2 s. Martellotta [20] proved that JND values were independent of music motifs and showed that the JND in the clarity index was almost independent of T60, varying from 2 to 6 s. Ando [17] also reported that the ITDG was an orthogonal factor with T60, in which it had subjective preference for sound field measures. The proposed research investigates the relationship between the JND of ITDG and the ACF of CBW on the scalp when the subjects are paying attention to two music instruments with ITDG values varying from 22 to 220 ms in a constantly low reverberant room, in which the JND values will act under the sound clarity sensation owing to the ITDG effects and the timbre of stimuli sources.

2. Materials and Methods

Based on the information above, this study was implemented in two stages. According to Weber's Threshold Law, we continuously increased the spatial ITDG (the time difference between the arrival of the initial reflection and the direct sound) of two different instrumental solos. Next, we measured the continuous just noticeable difference (JND) perceived by the subjects in order to compute the threshold of the human ear in relation to continuous changes caused by ITDG. In other words, we measured the point at which a stimulus change can be perceived at the time of detection under different ITDG perceptions. The next stage involved the same instrumental solos, as well as the same cueing method used in the first stage. The subjects had to listen attentively to the performances while their CBWs were being recorded. We analyzed the alpha-wave range (8–13 Hz) of brainwaves,

as well as ACF, to investigate brainwave changes that occurred in response to changes in the ITDG when the human ear was listening to a piece of music. In past studies regarding the statistical attributes of time-varying traffic noise, potential eigenvalues of temporal variations resulting from such factors as earthquake waves were frequently determined using correlation models [21–23]. To evaluate the disturbances caused by the various environmental noises using the normalized ACF (NACF), analysis was applied by Chen [24], too. Lastly, comparative analyses were performed.

2.1. Continuous JND Experiments

2.1.1. Settings of ITDG

The test system used was an artificial simulation of a sound field created within a bright (300 cd on the face of subject) anechoic chamber. Two anechoic music sources were fed to a digital audio editing software (Nuendo V10) to split the dry source of two instrumental solos into two audio tracks. These were fed through various delay units, reverberation units, mixers, and attenuators before being reproduced by a loudspeaker located in front of subjects inside an anechoic chamber. Afterwards, both tracks were synthesized into a single track at an ITDG interval of 22–220 ms. Altogether, this arrangement generated the following: a direct sound, an early reflection whose level was set to 0 dB (referred to as the direct sound with the energy coming from the lateral direction), and an additional short burst with a constant 16 ms lag to the early reflection from an effects unit that smoothened the transition from the early reflection to the reverberation with a decay time set at 0.5 s and level of −3 dB referred to the direct sound (Figure 2), from which a low reverberant and minimum distance decay room was created. The subjects were placed in the front of a loudspeaker at a 1.5 m distance and the listening sound pressure level was 78 dB all over the stimuli. This method has been used before and is well established [25–29]. It allows complete control over the sound field, and the user is able to directly compare different impulse responses.

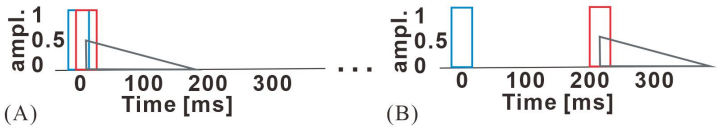


Figure 2. Schematic pictures of the ITDG manipulations of the early part of the impulse responses. (**A**) panel shows the direct sound to the initial reflection with the reverberation component at an ITDG interval of 22 ms and (**B**) panel shows the ITDG interval of 220 ms.

Continuous cueing of ITDG variation was achieved through a single loudspeaker, and preliminary experiments were conducted before investigating the changes to the ITDG in order to understand the JND of the human ear in such stages. This was followed by the production of the final audio cues. According to the preliminary experiments, the dry source of an instrumental solo was not sensitive to changes after being separated into two audio track times. Therefore, the baseline delay time was multiplied by 0.5 increments, that is, 1.25 times (from 22 ms to 27.5 ms), followed by 1.50 times (33 ms), and so on, until an ITDG of 220 ms was achieved as an experimental series. Each gap had to be smaller than the normal JND perceived by the human ear. In total, 91 audio signals were used to bring about the continuous changes, as each sample had a length of 3 s duration, with a 1 s interval between each gap sample. Consequently, one subject had to keep attention to the sound field with around 365 s and respond to their continuous JND cues by touching a key on the chair with an outside lamp, simultaneously. Furthermore, in the following JND experiments, 5 subjects obviously stopped giving responses to continuous cueing of ITDG variation in the middle of experiments, or successively responding to the operating staff after every stimulus, and these data were excluded from the calculation of JND.

2.1.2. Simulation and Material

Based on the information from other studies [30,31], the JND may depend on the characteristics of the motif used to present different sound fields. In addition, Okano [31] reported that the apparent source width (ASW) and loudness in a room are more sensitive to changes in the levels of early reflections among four subjective parameters, since the variation in the physical parameter (1—$IACC_{E3}$) and G values was 7 motifs, respectively. Notably, they fall into a similar range of directivities sent out by the same loudspeakers. Toole [32] considered that low frequencies from most sources radiated mostly omnidirectionally because the wavelengths were longer compared with the size of the source; the directivity index (DI) was nearly zero. The DI can be interpreted as the difference in dB between the on-axis sound and the total radiated sound power, which, in a room, is related to the difference between the direct sound and the reflected sound field. As the frequency increases, so does the directivity of most sources. As the DI increases, the level of direct sound relative to later arriving reflections becomes higher. In present studies, the $W_{_IACC}$ values of many sound sources, including five instruments' recital tracks and a symphony piece, are calculated, which are the width of the interaural cross-correlation function (IACF) defined by the interval of delay time at a value of 0.1 below the IACC [33]. It indicates that the apparent source width (ASW) and the DI would play the part of $W_{_IACC}$ values of sound sources as they are issued by a loudspeaker. The result of the calculation is illustrated in Figure 3, where the cello and trumpet obviously keep the two lowest $W_{_IACC}$ values of all source samples. It means that a sound with a low $W_{_IACC}$ value can be easily reproduced with a domestic cone loudspeaker in the anechoic chamber.

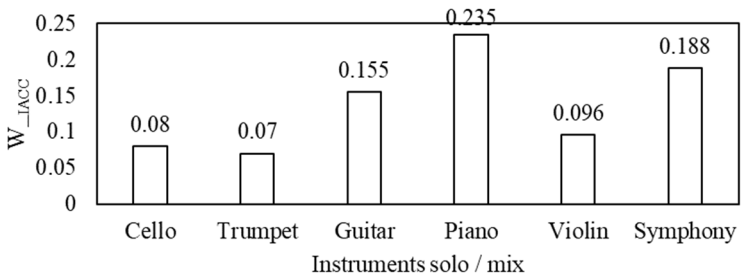


Figure 3. The $W_{_IACC}$ values were calculated by the interaural cross-correlation function for five 3 s pieces of instrumental recital and a symphony for 2 oboes, 2 horns, and strings from Arnold's Sinfornietta, Opus 48, from the beginning of the 3rd movement, which were recorded in an anechoic chamber at the BBC by Burd.

A 3 s segment was cut from each piece of music after it began in order to produce an audio sample for simulation purposes. Therefore, each subject had to listen through 91 continuous audio gaps and record their JND on cue. It took 6 min and 5 s (365 s) for each subject to finish listening to an audio piece. They then rested for at least 10 min before listening to the second piece.

2.1.3. Calculation of Continuous JND

After recording the JND points of 17 subjects, JND was calculated as the ratio of the gap between the sensory points before and after the arrival of a stimulus ($\Delta gap = Gap_2 - Gap_1$) at the second sensory point (Gap_2):

$$JNDc = \frac{Gap_2 - Gap_1}{Gap_2} \quad (1)$$

where *JNDc* represents the subjects' continuous results obtained after 91 gaps ($c = 1, 2, \ldots$). Afterwards, all the *JNDc* and perceived ITDG changes of the 17 subjects were plotted. The JND of a musical piece was defined as the median of all the *JNDc* results of the 17 subjects.

The amount of details regarding training and participant requirements varied across prior studies. In Cox et al. [34], the 7 to 10 subjects were either musicians or regular

concertgoers who all reported to have normal hearing. A total of 10 non-expert listeners with no known hearing problems were used by Bradley et al. [35]. The majority of the studies did not explicitly state how the subjects were trained. In the present study, the preliminary test of JND experiments was provided with the assistance of sound training during this period to allow them to focus on judging the differences in ITDG between the continuous stimuli.

2.2. Recording of Continuous Brainwaves (CBW)

Based on the results of the aforementioned psychological JND experiments in relation to the spatial ITDG, we expect that brainwaves provide the most efficient and direct approach for addressing psychological complexities and simplifying observations of auditory stimuli. The reason behind adopting this approach has been elucidated in our previous studies [1–6] on the effectiveness of EEG in sound field design. Individual differences are the greatest hindrance for sound field components responding to brainwaves. Therefore, it is necessary to adopt an experimental design that involves continuous and repetitive methods for statistical analyses. Therefore, the data of CBW derived by approximately ten participants and the averaged intendency of them is adoptive to the significant level [1–6]. To date, salient components in a sound field, such as T60 and the ITDG of a first reflection and a direct sound, can yield decent correlations through statistical analyses of individual preferences [5,6]. Michelini et al. [8] and Ichikawa [9] consolidated the psychological states and responses manifested through AEPs (auditory evoked potentials) across different frequency ranges. CBWs were recorded at prolonged analysis times and could demonstrate electrophysiological events from the inner ear to the central auditory pathway, which made it possible to record slow components of AEP over 500 ms, such as the response of T60 in an environment. The 8 to 13 Hz range, which corresponds to alpha waves produced when humans are relaxed, is the most suitable state for thought and creation, and the mass generation of these alpha waves can be collected. These auditory impulses of the brain are recorded as CBWs. Meanwhile, the method of brainwave recording is based on the International 10/20 system for placing scalp electrodes to identify the region from where a specific psychological response is emitted [36–38]. When consolidating and reporting on brainwave signals from a statistical perspective, Praetorius, Bodenstein, and Creutzfeldt [39] revealed that the application of spectral analysis would obliterate the characteristics of omnipresent brainwave changes because a spectrum, on average, is merely a single event. In this regard, we used Ando's (Section 5.4.2 in Ref. [17]) auditory pathway model to describe our approach for analyzing the omnipresent temporal characteristics of CBWs.

Similar to experiments on the perceived JND of a spatial ITDG, it was necessary to simultaneously record CBWs through continuous cueing and the auditory stimuli, so as to make preparation for postproduction (as shown in Figure 4). Brainwaves from the cranial nerves were led through the primary electrodes (T3-left, T4-right, 10/20 system), which were correspondingly placed on the scalp. Meanwhile, the reference potential was recorded through the electrodes that were placed on both ear lobes (A1, A2), enabling the recording of cue sound signals via an EEG that used unipolar leads. The reference electrodes were positioned on both the left and right earlobes. The ground electrode was placed on the forehead. The CBW signals were analyzed after passing through a digital bandpass filter with cut-off frequencies (140 dB/octaves lops) of 8–13 Hz: alpha-wave ranges by Galileo Nemus space channel EEG system. Twelve subjects (students with an average age of 18 $\pm$ 1.3 years old), all of whom self-reported as being right-handed and having normal hearing, all participated in the JND experiments before within a time period of less than 24 h. The number of participants demanded that the CBW recordings referred to conventional studies [1–6], and Soeta and et al. [11] employed 7 subjects for the magnetoencephalographic (MEG) investigation, which met the requirements for analyzing CBW with respect to the sound field characteristics. All subjects were prohibited from drinking any alcohol and successive winking in the period of the experiment before the CBW were recorded and refrained from smoking for one hour before their brainwaves were

recorded. They were instructed to concentrate on listening to the music and to differentiate the differences of sound ITDG during the presentation for an experimental series.

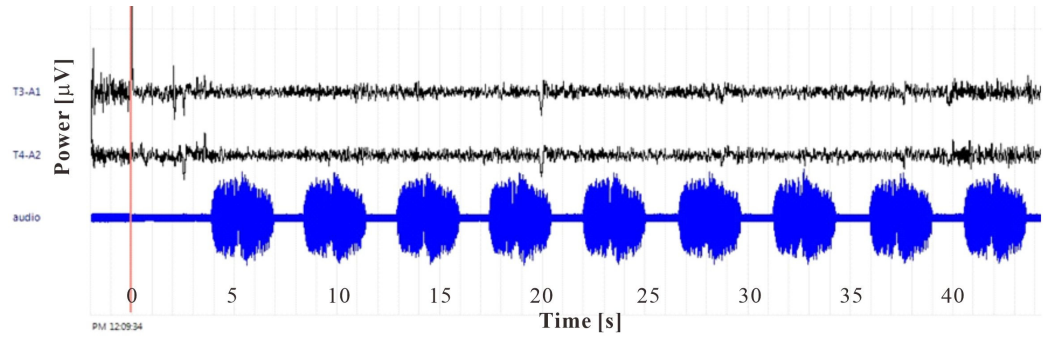


Figure 4. The continuous cues (91 samples) of the trumpet piece (as a trigger) and the alpha-wave signals recorded during the same period.

2.3. Method of CBW Analysis

In line with the aforementioned method of recording brainwaves, the CBW signals were exported as an Excel file using an analog-to-digital (A/D) converter for subsequent analysis. The observation target was alpha waves at an 8 to 13 Hz range, and sampled frequencies were converted from analog to digital at a sampling rate of 100 Hz. Musical signals recorded during the same period were utilized to identify the initial positions of the signals emitted from the T3 and T4 electrodes during a specific period. The integral length (2 T) of ACF of CBW was calculated using an initial position and the succeeding initial position. Afterwards, analyses were performed to calculate the running ACF of a signal. The targets of analysis of this study were calculated based on the experience of previous studies [1–6]. The running ACF was then used to compute the effective delay time (τe, unit in s) of the ACF of each piece of initial data. Thus, the parameters used for calculating the running ACF were as follows: 2 T = 2 s, running step = 3.89 s, τe was defined as the time required for a NACF that had decayed to −5 dB after taking its logarithm to obtain a value from the delay time axis [6].

3. Results

3.1. The Just Noticeable Difference of Initial Reflection in a Sound Field

In this study, there were two dry sources that simulated an instrumental solo: a trumpet piece (Prince of Denmark's March, by Frank Fezishin) and a cello piece (Girolamo Frescobaldi, Toccata, by Arr. Gaspar Cassadó), whereas motifs were set at equal (1—$IACC_{E3}$) and G values along the way. However, the frequency responses were higher than 300 Hz for the trumpet piece, and fluttered at 200 Hz, 400 Hz, . . ., and so on for the cello piece (Figure 5). In addition, the running autocorrelation function (ACF) of the two pieces proposed by Ando (Chapter 3 in [17]) were calculated as shown in Figure 6. The average τe values (ms) of two music pieces were 35.90 ms for trumpet and 46.92 ms for cello. However, the minimum τe values of two pieces were 31.25 ms and 16.24 ms, which were calculated as a function of preferred initial delay time of the music signal in a sound field reported by Ando [27]. According to the settings of amplitude of the first reflection (A1) and reverberation part (AR), total amplitude of reflections (A1 + AR) was equal to 1.5 (as the amplitude of direct sound A0 = 1), so the preferred IDTGs of the two instrumental pieces were estimated as 42.2 ms for cello and 32.3 ms for trumpet, respectively. Table 1 lists the total index of the autocorrelation function (ACF) calculated using both music signal sources.

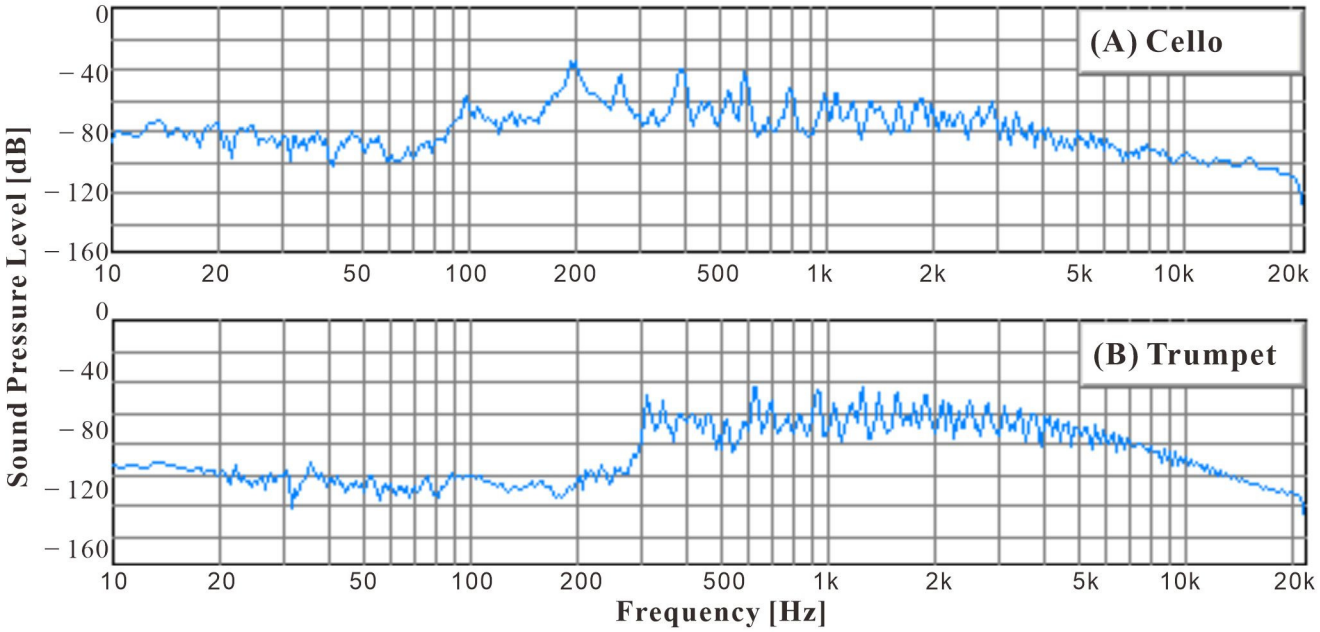


Figure 5. Frequency responses of the (**A**) cello and (**B**) trumpet pieces.

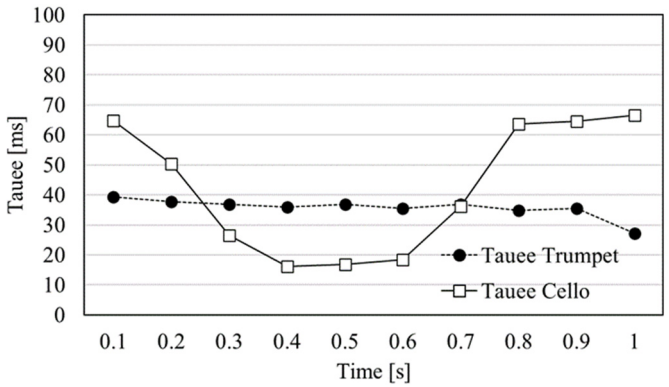


Figure 6. The running ACF of two simulated instrumental music pieces; the integrated period (2 T) was 2 s, while the running step was set at 100 ms.

Table 1. The variable of autocorrelation function (ACF) derived from the music source of cello and trumpet.

Motifs/ Factors	Averaged τe (ms)	τe_min (ms)	Tau_1 (s)	Phi_1 (dB)	$W_{_IACC}$ (ms)	JND	JND of ITDG (ms)	Preferred ITDG (ms)
Cello	46.92	16.24	0.41	0.26	0.08	0.059	7.40 ± 2.75	42.2
Trumpet	35.90	31.25	0.58	0.01	0.07	0.081	10.18 ± 3.52	32.3

Notes: Tau_1, first peak delay gap in the curve of ACF of source signal; Phi_1, first peak value in the curve of ACF of source signal; preferred ITDGs were calculated by short-term τe_min values of the ACF of music source signals (Figure 3) proposed by Ando [32].

According to Figure 7, the perceived ITDG changes of the 17 subjects were lower for the trumpet piece, as indicated by the lower number of *JNDc* points compared with the cello piece. This shows that the ΔGap was often greater for the trumpet piece, and there was a greater difference between the subjects' responses, and it can be known that high-frequency sounds have larger *JNDc* values. This can be explained by the fact that the stimulus was a musical piece; if white noise was used as a stimulus instead, the difference could be significantly reduced. As shown in Figure 7, the results revealed that the *JNDc*

of the cello piece and the trumpet piece were rated approximately 0.059 and 0.081 at a 50% "different" judgement range in most cases, respectively. Additionally, the JND of ITDG of the cello piece was measured as 7.4 ± 2.75 ms, while that of the trumpet was 10.18 ± 3.52 ms in the continuous variations of sound field structures.

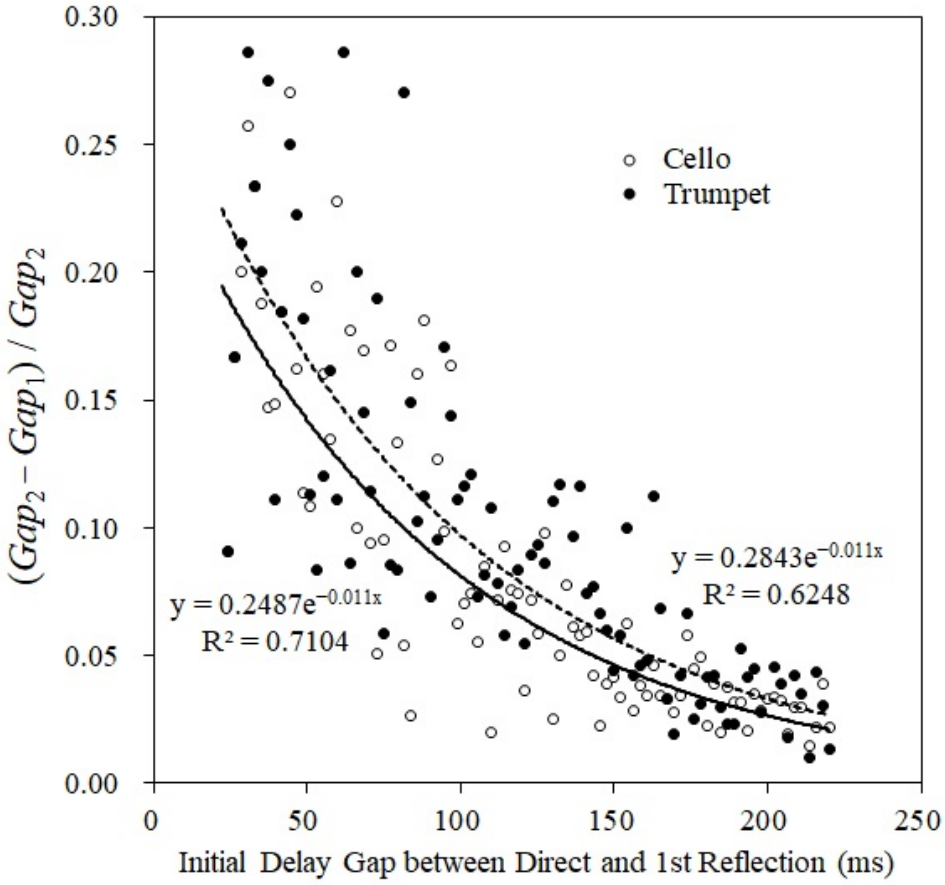


Figure 7. Relationship between all *JNDc* results and ITDG change intervals of the cello and trumpet pieces; the circles denote the averaged responses derived by 17 subjects on *JNDc* at each ITDG interval.

Furthermore, the subjects' perceptions of the spatial ITDG changes of both instrumental solos were significantly different. This finding is reflected in ISO 3382-1 [19], which standardizes the JND of various physical parameters (such as T60 and C80) but lacks a definition for ITDG, mainly because it is difficult to test the range of changes experienced in music halls. This study simulated the changes within the 22 ms to 220 ms range, to provide useful references regarding listener-perceived ITDG for architectural acousticians.

3.2. Analysis of Minimum Value of the Effective Delay Time (τe_min) of the Brainwaves' ACF

Figure 8 illustrates that the averaged τe values of ACF of CBWs on the alpha-wave frequency range correlated well with $W_{_IACC}$ on the T4 (right) electrodes for 12 participants during continuous ITDG cues (91 steps) when the trumpet and cello pieces were played (Sigh Test, Z = 6.92, $p < 0.01$). On the other hand, as shown in Figure 9, the average continuous minimum value of the effective delay time (τe_min) of the ACF of CBWs detected in the left hemispheres (T3) of the 12 subjects in response to the trumpet piece was 0.28 s. This also resulted in a fixed and continuous phase ratio ((τe_min$R$ − τe_min$F$)/τe_min$F$) equal to 0.4, whereas the minimum value of τe was defined as the running minimum value between the two music pieces with respect to the value of *JNDc* at a minimum distance of 20 ms, longer than the duration of JND of two instrumental stimuli. The minimum value of the cello piece occurred at 0.23 s, and the average stage ratio formed in the left hemisphere (T3) was 0.23, which was neither consistent nor continuous and was subsequently diminished.

This finding indicated that the continuous minimum value of the effective delay time of the ACF of CBWs resulted in a fixed continuous phase ratio ((τe_min$R$ − τe_min$F$)/τe_min$F$) equal to 0.11, which to a certain extent, was associated with the JND obtained through psychological tests. However, the existing data comparisons were unable to explain the reason behind this observation.

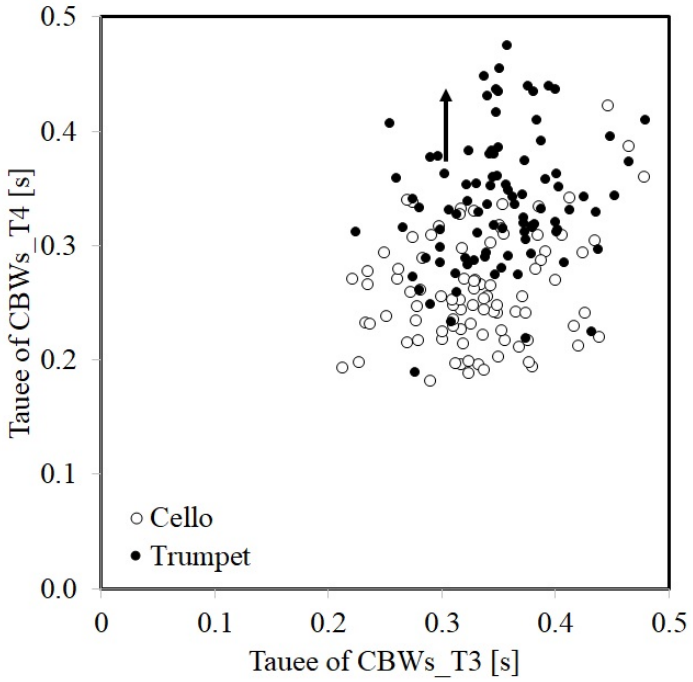


Figure 8. The τe values of ACF of CBWs on the alpha-wave frequency range correlates well with W_IACC on the T4 electrodes for 12 participants during continuous ITDG cues (91 steps) of the trumpet and cello pieces.

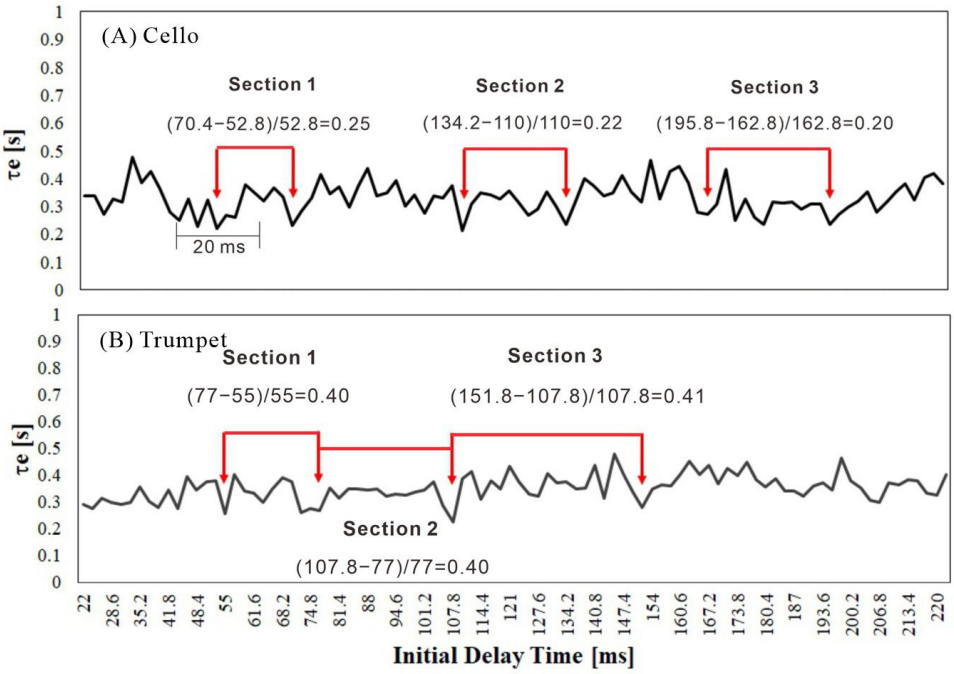


Figure 9. The continuous minimum values of the effective delay time of the ACF of CBWs detected in the left hemisphere in response to the (**A**) cello and (**B**) trumpet pieces. For both music pieces, they were defined as the lowest value after 20 ms from each other.

4. Discussions

The following discusses the comparisons between the subjective responses on the JND decision-making process and the results of calculating the ACF of CBW with respect to the ITDG of a sound field ranging from 22 ms to 220 ms.

4.1. Coordination in Brainwaves and the Subjective JND of ITDG

A design theory proposed by Ando [27] stated that the short-term value of the effective delay time (τe) of the ACF of a stimulus signal was related to the preferred ITDG value in a sound field. The observed relationship between the subjective responses in the JND process and the τe (s) of ACF of CBW in an alpha rhythm range is illustrated in Figure 10. As shown in Figure 11, we found that the subjective responses of the ITDG decision-making process, $JNDc = Gap_2 - Gap_1/Gap_2$, and the τe (s) of ACF of CBW in an alpha rhythm range were in coordination with the various delay simulated orders, starting approximately at 132 ms for the cello piece and 101 ms in the left (T3) hemisphere, as well as 97 ms and 74 ms in the right hemisphere (T4) for both instrumental tracks. This suggests that the first coordinator on delay order was related to the averaged τe (ms) listed in Table 1 for the respective cello and trumpet pieces as well. They were all approximately 2.8 and 2.0 times higher than the values of the average τe (ms) in the left (T3) and right (T4) hemispheres. At that moment, with subjective ITDG judgements, the time gap would be experienced as an echo of a sound field, and, perhaps, the ITDG image of a sound would be changed. In other words, in the subjective responses of ITDG decision making, the subjective judgements of ITDG in a room consisted of two models within a range of 22–220 ms. The subjective responses should have two different models that changed noticeably with respect to ITDG judgements, but the τe (s) of ACF of CBW in the alpha rhythm range were linear and unchangeable.

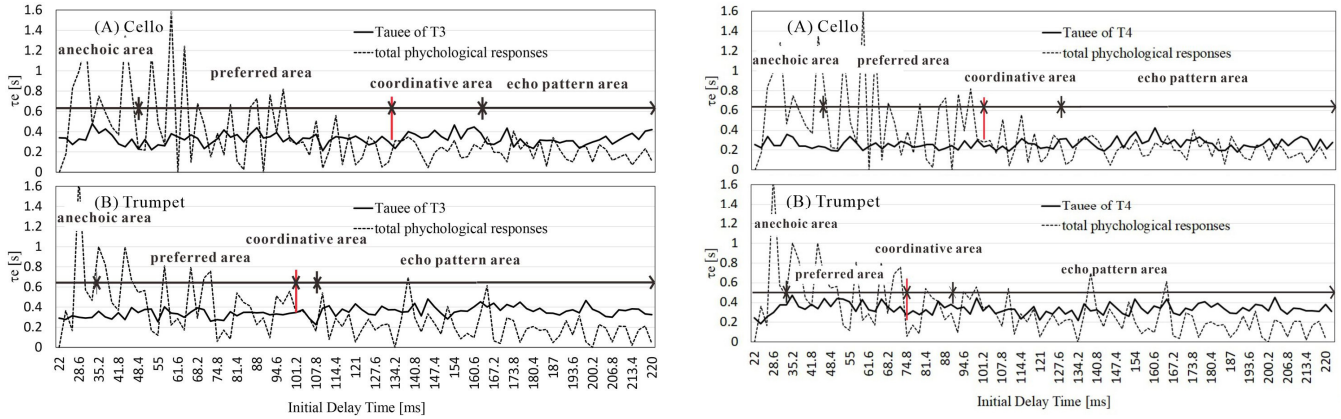


Figure 10. The summation of subjective responses of the decision-making process on ITDG, $JNDc = Gap_2 - Gap_1/Gap_2$, and the τe (s) of ACF of CBW in alpha rhythm range work in coordination with the various delay-simulated orders that started approximately at 132 ms (indexed by red line) for cello (**A**) and 101 ms for trumpet (**B**) in the left (T3) hemisphere, and 97 ms and 74 ms in the right (T4) hemisphere for both instrumental tracks for a period of at least 10 ms. Furthermore, each instrumental track activated a range of preferred ITDG range with respect to the short-term τe_min value of the ACF of the signal sources proposed by Ando [27]. The process of decision-making processes on ITDG involved 4 subjective sound cognitions within 91 running audio signals.

4.2. Subjective JND of ITDG and Auditory Path in the Brain

As shown in Figure 12, the τe_min of the ACF of two instrumental source pieces were evidently functioning with the coordinative beginning point between the subjective ITDG's "different" decision-making process and the τe of the ACF of brainwaves in the alpha range under varying sound field ITDGs in the left and right hemispheres. The coordination period here was indicated by the phenomena shown in Figure 10 and was related to the short-term

τe values of the ACF of music signals in a room [28] for a duration of at least 10 ms. These coordinative characteristics were confirmed in both hemispheres, with a constant delay of 31 ms for the cello piece and 23 ms for the trumpet piece. Therefore, the slope (0.76) in Figure 12 denotes the difference between two instrumental timbres for continuous variation of ITDG sensation in a room, and the function between the τe of the ACF of brainwaves in the alpha range with respect to two instruments (cross axle) shows linear correlation with τe_min of the two musical dry sources.

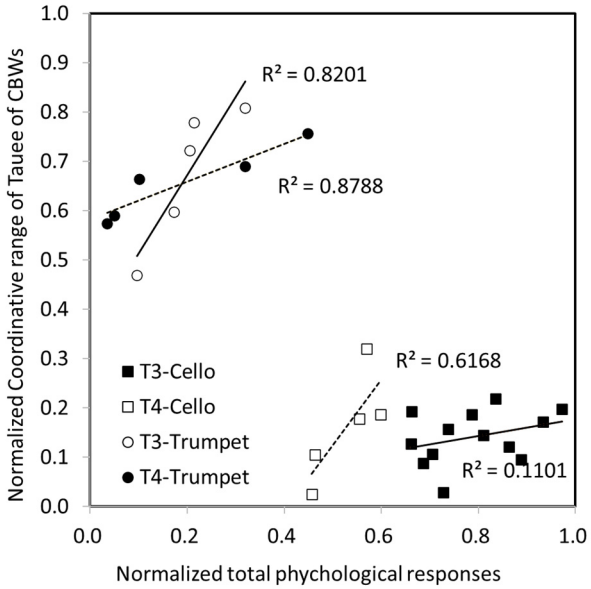


Figure 11. The coordinative period between the normalized summation of subjective responses on ITDG and the normalized τe (s) of ACF of CBW in the alpha rhythm range show well correlation in both hemispheres for the trumpet track, but the lower values for the cello in the different part of range of illustration.

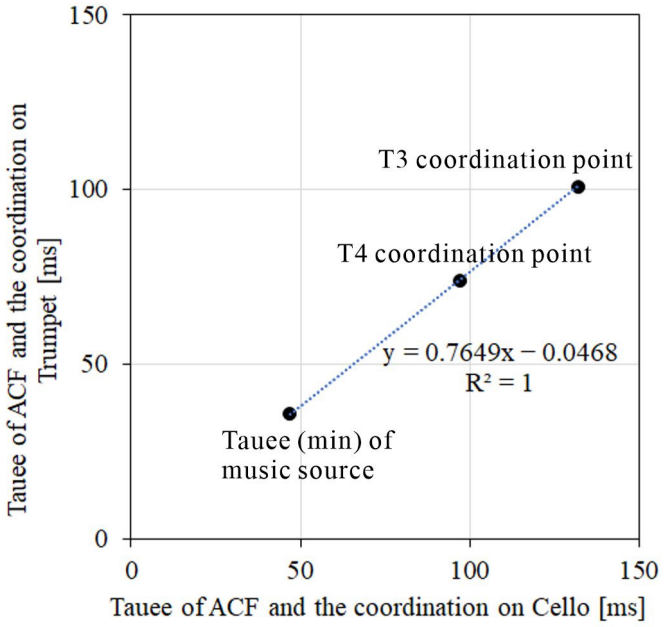


Figure 12. Illustration of the coordination points between the subjective ITDG's "different" decision-making process, with the τe of the ACF of brainwaves in the alpha range for cello and trumpet presented under continuous varying ITDG between the left and right hemispheres. These coordinative characteristics are obviously functioning with the τe (min) of ACF of the instrumental source pieces.

As stated above, the coordinative characteristics between a subjective decision-making process and brainwave activities were obviously functioning with the τe of ACF of the instrumental source pieces in both hemispheres (Figure 12). The T4 (right hemisphere) responses in the brain began coordinating in front of the T3 (left hemisphere) under the varying ITDG for both instrumental pieces along the way. This was not associated with hemispheric specialization in the brain, and this effect was believed to be due to the temporal effect of ITDG sensation in a room that dominated over the left hemisphere. The present findings reconfirmed a conventional study, which found the temporal effect of word intelligibility over the left hemisphere dominated over phonic signals, and ASW affected both left and right spatial consciousness as subjects focused on the variation of ASWs using pure tone (2 kHz) [2]. Based on functional Doppler ultrasonography in MRI as a method to detect brain activity patterns, Floel, Jansen, and Deppe et al. [40] confirmed an atypical hemispheric dominance for visuospatial attention and language. In addition, they found that subjects with an inverted lateralization of language and spatial attention (language right, attention left) recruited left-hemispheric areas during the attention task, homotopic to the areas recruited by control subjects (right-handed subjects) in the right hemisphere. In subjects with lateralization of both language and attention to the right hemisphere, an attentional network was activated in the right hemisphere that was comparable to that of control subjects. Based on their findings, hemispheric dominance of neural processes underlying language and attention is determined not by hemispheric side but by the intra-hemispheric pattern of activation. Decision making in the ITDG room is a perceptual discrimination exercise. Responses in the brain are longer than one minute, and the signal information is recruited to the corpus callosum by the auditory nerve and feed backed.

4.3. JND of ITDG in Concert Hall

Even though ISO3382-1 [19] has announced the JNDs of the physical factors of a concert hall, and Okano [31] has reported that the JNDs in sound fields of concert halls are caused by intensity variations in early reflections, ITDG cognition remains sensitive on account of the sound field structure. Even though Ando [16] reported that the ITDG factor is independent of reverberation time, sound strength (G), and IACC, Bech [41] reported that the JND of ITDG varies with the instrumental timbre for the temporal structure of a source signal. We carefully carried out the initial estimation on JND of ITDG through two simulated source signals. Nevertheless, the IDTG model (Figure 7) fluttered as an exponential function in a transfer response function of the neurodynamical mechanisms. The computational principles underlying the decision-making processes did resemble the conclusions in the vibrotactile discrimination task argued by Deco et al. [7]. The function of *JNDc* on ITDG in a model that varies by the characteristics of source signal is shown below:

$$JNDc = A \cdot e^{-0.011 \cdot ITDG} \quad (2)$$

where A denotes the characteristics of simulated source signals. Here, A is 0.284 for a trumpet and 0.249 for a cello. In addition, the value of $W_{_IACC}$ listed in Table 1 for two instrumental pieces is inversely proportional to A as well. Hence, Equation (2) can be transformed to:

$$JNDc = k \cdot W_{IACC} \cdot e^{-0.011 \cdot ITDG} \quad (3)$$

where *k* is a constant in the relationship of $W_{_IACC}$ in a concert hall, and k ≈ 3.55 for the experimental conditions of the trumpet and the cello in this study.

If the $W_{_IACC}$ value of the source in a concert hall is an effective variable of the ITDG, then this explains why the T4 (right hemisphere) responses in brain coordinated at the beginning in front of the T3 (left hemisphere) responses on the varying ITDGs for both instrumental pieces along the way (Figure 10). Fujii et al. [42] proposed that the $W_{_IACC}$ value of the source in a concert hall is dominated in the right hemisphere, which is specialized as a spatial factor in a concert hall.

Finally, an initial measure of the subjective JND of ITDG in a room is related to the value of $W_{_IACC}$ of IACF, the characteristics of source signals themselves. Okano [31] reported that the ASW and loudness in a room are more sensitive to changes in the levels of early reflections. The ASW is dominated by the $W_{_IACC}$ of IACF, as reported by Nakajima et al. [33]. The fluctuation of the CBWs in the alpha range derived from the scalp using the T3 and T4 electrodes was analyzed by autocorrelation technology for detecting the activities of potential in auditory neurological mechanisms that correspond to repeatedly varying ITDGs in a sound field. Although the results of minimum value of the effective delay time (τe_min) of the ACF of CBWs were unspecified to the concept of "difference" in the JND process, they resulted in a fixed and continuous phase ratio ((τe_minR − τe_minF)/τe_minF) that was equal to 0.4 at T3 as music simulated by the trumpet recital (Figure 9).

5. Conclusions

When observing the step-varying ITDG for the subjective *JNDc* and τe values of ACF of CBWs in the alpha range, a homologous period of resonance (duration longer than 10 ms) was found between both simulated instrumental tracks. The resonance correlated well with the short-term τe_min value of the ACF of the signal sources. In addition, the JND of ITDG of a concert hall corresponding to the brain is rarely studied and discussed. Weber's Law enabled us to detect the decision-making processes that take place in a simple single reflection in a room or an echo cognition on a temporal and spatial specification. Two room models were clearly discriminated in both the subjective and neurological correspondences, owing to the coordinative point in the judging processes. An unexpected finding was the effective variable of the spatial auditory advanced in responses along the way, since the coordinative point was superior in the left hemisphere.

A long-term ITDG decision-making process activated significant neuron activity in both hemispheres, according to hemispheric dominance. The running minimum τe value for the trumpet music piece resulted in a fixed and continuous phase ratio in the left hemisphere and was prolonged ($p < 0.01$) in the right hemisphere simultaneously. Hemispheric specificities were synchronic, but the pattern was different between the two hemispheres.

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Institutional Review Board Statement: Under Taiwan Centers of Disease Control (NO.1010265079) issued on 5 July 2012, regulations on the domain of human body research announced that research data do not include invasion of human body, or probably getting designated personal registration from the public organismic data bank will be excluded from the human body ethics review. The present paper of applsci-2600884 involved brainwaves recordings processes, which were derived by voltage on the human's scalp using electricity conduct glue. The participants were all operated voluntarily. National Science and Technology Council, Taiwan granted one-year periodic financial support and confirmed without ethics investigations need. Ethic Committee Name: National Science and Technology Council, Taiwan. Approval Code: MOST 109-2221-E-324-004. Approval Date: 27 June 2018.

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Abbreviations

The following abbreviations are used in this manuscript:

ITDG	initial time delay gap
JND	just noticeable difference
ACF	autocorrelation function
NACF	normalized ACF
IACF	interaural cross-correlation function
CBW	continuous brainwaves
AEP	auditory evoked potential
SVR	slow vertex response
EEG	electroencephalography
ASW	apparent source width
IACC	gratitude of interaural cross-correlation function

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