Illusory Continuity of Intermittent Pure Tone in Binaural Listening and Its Dependency on Interaural Time Difference

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Abstract

Illusory continuity is known as a psychoacoustical phenomenon in hearing; *i.e.* an intermittent pure tone may be perceived as if it was continuous, when it is padded with enough large white noise. There are many researches related to this issue in monaural listening. It is said that such illusory continuity is observed when there is no evidence of discontinuity and level of the white noise is large enough to mask the pure tone. In this paper, we investigated illusory continuity in binaural listening, and measured its threshold levels according to some interaural time differences (ITDs). The ITDs simulate a sense of direction about sound sources and give new information for evidence of discontinuity, which should be expected to promote the illusory continuity. As a result, the threshold level of illusory continuity in binaural listening depended on ITDs between tone target and noise masker. The increase of threshold level was minimum when the target and masker had the same ITD.

1. Introduction

Speech recognition system has become a handy tool for communication amang humans and computers. Such systems should be robust for noise in practical usage. Although many noise reduction systems have been proposed, present systems are not robust enough, especially with nonstationary noise like a burst sound. On the other hand, human has an excellent hearing system that is robust for such noises. Humans can hear a target sound selectively as they like, from many sounds[1]. This ability has a contribution to improving robustness of hearing in noisy environments. Sound source segregation by binaural listening plays an important role in obtaining such an effect.

Illusory continuity is known as a psychoacoustical phenomenon in hearing[2, 3, 4]. For example, a pure tone which is intermittently substituted with white noise of appropriate magnitude is perceived as if it was continuous. Many researches which were concerned with this issue have been reported in monaural listening. One explanation to this phenomenon is that illusory continuity is observed when there is no evidence for discontinuity and the white noise is strong enough to mask the pure tone[2, 3]. In these cases, the differences of duration time and amplitude level between pure tone and white noise are important factor of the explanation. Meanwhile, in binaural listening, there is another possible factor to know the discontinuity; *i.e.* the directions of sound sources. There are two typical ways to control a sense of direction; one is interaural intensity difference(IID), the other interaural time difference(ITD)[5].

In this paper, we investigate illusory continuity of hearing in binaural listening, by introducing some kinds of ITD as an additional information about sound sources for examining a sense of direction[6]. It is observed whether the threshold level of illusory continuity depends on ITDs and becomes minimum when the tone target and noise masker have the same ITD. This ITD dependency of illusory continuity of human hearing is applicable to speech enhancement and noise reduction.

2. Experiments

In this section, we explain about the settings of psychoacoustical experiments to measure threshold level for illusory continuity in binaural listening. First, the design of stimuli and the position of virtual sound sources are considered. Then, the protocol of the experiment is described.

2.1. Stimuli

There are two kinds of stimuli in the experiments, *i.e.* target and masker, as shown in Fig. 1. The target consists of a pure tone of 500 [Hz] and 5 [s] long. In the first part of 1.8 [s] long, the target is continuously presented while it is interrupted every 0.2 [s] by silence of 0.2 [s] long in the latter part. Some 1/3 octave band noises with center frequency of 500 [Hz] are adopted for the masker. They are presented every 0.2 [s] in the silence portion of the target sound. Then the target and masker are presented alternatively eight times every 0.2 [s] in the latter part of stimuli. All components in these stimuli are tapered with a sin window of 10 [ms] long. They are produced with sampling frequency of 20 [kHz] and linearly quantized with 16 [bit].

We suppose that the sound sources are far enough from the subject so that plane waves are arrived and that the shape of the subject's head in horizontal plane is considered to be a circle.

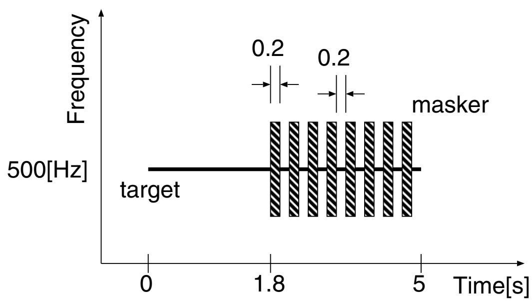


Figure 1: Design of stimuli.

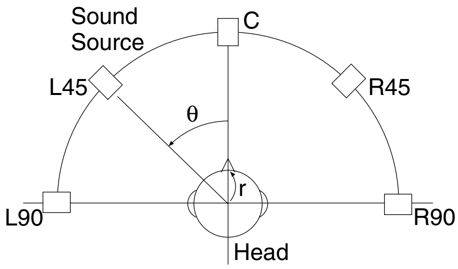


Figure 2: Virtual allocation of sound sources for ITD design (stimuli are presented through a closed headphone in practice.)

Then, the interaural time difference(ITD) corresponding to the direction of a sound source is calculated as follows:

$$\mathrm{ITD} = \frac{r\theta + r\sin\theta}{c}, \quad (1)$$

where $r = 9$ [cm], θ [rad] and $c = 340$ [m/s] denote radius of head, direction of the sound source and velocity of sound, respectively. For the sound from left side, θ is positive. We virtually allocate sound sources in the horizontal plane; *i.e.* θ is one of $\pi/2$, $\pi/4$, 0, $-\pi/4$ and $-\pi/2$ in radian as the direction from left to right. Hereafter, we call the above directions as L90, L45, C, R45 and R90, respectively, as shown in Fig. 2.

In this experiment, appropriate ITD was introduced additively to the target and masker, respectively, according to their directions. Figure 1 illustrates an example of stimuli in the case of $\mathrm{ITD} = 0$. Generally, the target and masker are lateralized according to each ITD, respectively. Hence, there may be gaps and laps in the stimuli when the directions of target and masker is different from each other.

2.2. Experiment 1

In the experiment 1, the same ITD was added to target and masker, respectively, according to the directions L90, L45, C, R45 and R90. In this case, the sounds arrived at each ear are the same except their time axis being shifted for appropriate ITD.

2.3. Experiment 2

In the experiment 2, the directions of target are not always the same as that of masker, while the direction of masker is fixed. Then the sounds arrived at each ear are generally different according to the difference between target's and masker's ITDs, respectively. This experiment consists of three subexperiments 2a, 2b and 2c as follows.

2.3.1. Experiment 2a

In experiment 2a, the ITD of masker was fixed corresponding to the center C, while that of target was varied corresponding to L90, L45, C, R45 and R90, one by one.

2.3.2. Experiment 2b

In experiment 2b, the ITD of masker was fixed corresponding to the right R90, while that of target was varied corresponding to L90, L45, 0, R45 and R90, one by one.

2.3.3. Experiment 2c

In experiment 2c, the ITD of masker was fixed corresponding to the left L90, while that of target was varied corresponding to L90, L45, 0, R45 and R90, one by one.

2.4. Protocol

In the above experiments, we adopted the following same protocol.

Subjects were two males of about 23 years old, with normal-hearing. They had carried out some experiments as training beforehand. They were able to distinguish the lateralization of target and masker according to ITD. The stimuli were presented to the subjects through a closed headphone in a silent room.

The amplitude ratio of masker with respect to target was controlled to measure the threshold level of illusory continuity. The subjects were asked to judge whether the target was perceived completely continuous, amplitude modulated or discontinuous. The threshold level was measured by the method of limits. The next stimulus was presented in 1[s] later after the subject made a judgment.

First, the masker to target amplitude ratio was set to -13 [dB] or -14 [dB] which was enough high for the target to be perceived as completely continuous. The amplitude ratio was decreased by a step of 2 [dB] until the target was perceived as discontinuous. Then the final amplitude ratio was recorded as $R2$ [dB] which was the magnitude level presented. In the middle of this step, when the perceived target was felt like amplitude modulated, the amplitude ratio was also recorded as $R1$ [dB]. Next, the masker to target amplitude ratio was set to -36 [dB] or -37 [dB] which was enough low to perceive the target as discontinuous. The amplitude ratio was increased by a step of 2 [dB] until the target was perceived as completely continuous. Then the final amplitude ratio was recorded as $R4$ [dB]. In the middle of this step, when the perception of the target became amplitude modulated, the amplitude ratio was also recorded as $R3$ [dB].

Each experiment was carried out for a combination of decreasing series $(-13, -15, \ldots, R1, \ldots, R2)$ and increasing series $(-36, -34, \ldots, R3, \ldots, R4)$, or a combination of $(-14, -16, \ldots, R1, \ldots, R2)$ and $(-37, -35, \ldots, R3, \ldots, R4)$, respectively. Finally, the threshold level was calculated by the arithmetic mean of $R1$, $R2$, $R3$ and $R4$.

Experiments 1, 2a, 2b and 2c were achieved in this order. In each experiment, the order to present stimuli with each ITD was random. These four experiments were carried out eight times for each subject.

3. Results

In this section, we describe the results of the above experiments.

3.1. Result of Experiment 1

Figure 3 shows the threshold amplitude ratio versus ITD for a subject in the experiment 1 where the same ITD was added to target and masker. As shown in this figure, the threshold has no significant difference according to the directions L90, L45, C, R45 and R90, by F-test with significance level of 95%. This means that illusory continuity is observed under binaural listening even if ITD exists. And the threshold is independent of ITDs when target and masker have the same ITDs and they are supposed to come from the same direction. The other subject had the same tendency.

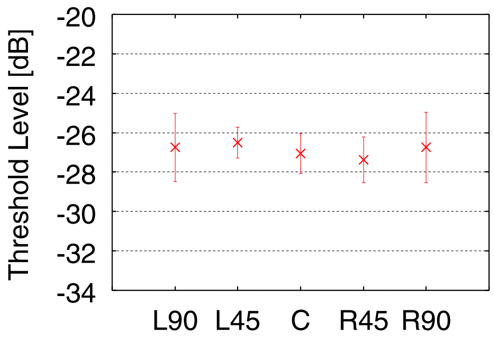


Figure 3: Threshold level v. ITD for a subject in experiment 1. (Directions of target and masker are supposed to be same.)

3.2. Result of Experiment 2

In experiment 2, ITDs of target and masker are not always same. Figure 4 shows the sensation level that is calculated by the difference of individual threshold levels ($R1$, $R2$, $R3$ and $R4$) between experiment 1 and experiment 2, for the same subject in the above subsection 3.1. The sensation level means how large the noise level should be for illusory continuity, comparing to experiment 1. Since the other subjects had the similar tendency, we will show the result only for the subject. Double asterisk ** means that the difference is significant at 99% by Fisher's least significant difference. As shown in these figures, the sensation level varied as a function of the difference of ITDs between target and masker. The sensation level became minimum when the target and masker had the same ITD.

3.2.1. Result of Experiment 2a

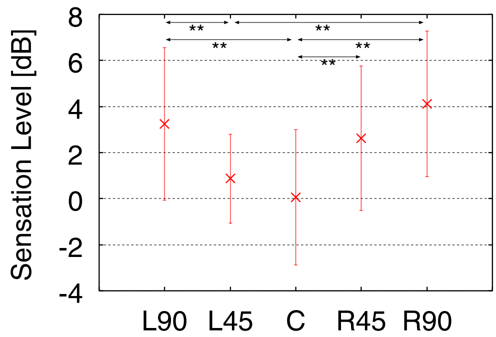
Figure 4(a) indicated the sensation level in experiment 2a where the masker is supposed to be fixed on the center C. The sensation level was clearly minimum when the ITD of target was the same as that of masker.

3.2.2. Result of Experiment 2b

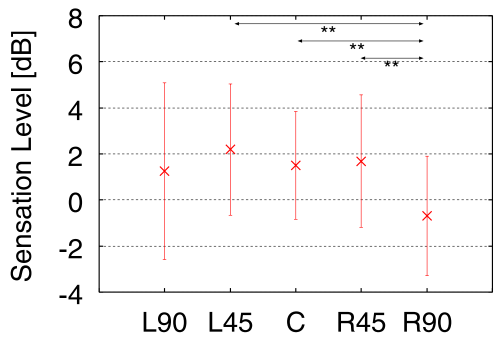
Figure 4(b) showed the sensation level in experiment 2b where the masker is fixed on the right R90. The minimum threshold level was obtained when the ITD of target was the same as that of masker.

3.2.3. Result of Experiment 2c

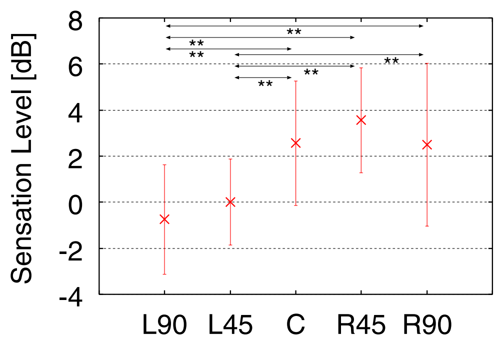
Figure 4(c) depicted the sensation level of experiment 2c where the masker is fixed on the left L90. The threshold level was minimum when the ITD of target was the same as that of masker.



(a) Sensation level in experiment 2a. (Masker is fixed at the center: C.)



(b) Sensation level in experiment 2b. (Masker is fixed at the right: R90.)



(c) Sensation level in experiment 2c. (Masker is fixed at the left: L90.)

Figure 4: Sensation level v. ITD for a subject in experiment 2. (Direction of masker is supposed to be fixed at a direction. The double asterisk ** means that the difference is significant at 99%.)

4. Discussions

The result of experiment 1 leads that illusory continuity is observed in binaural listening independent of ITD although it has been discussed mainly in monaural listening till now. In this case, the sound presented one ear is the time shift version of the other ear, hence there is no difference from the conventional illusory continuity in monaural listening except that the shifted version is presented to the other ear. If we can suppose no interference between both ears, this phenomenon may be explained as conventional; *i.e.* illusory continuity is observed if there is no evidence for discontinuity and it is possible for the white noise to mask the pure tone.

Experiment 2 shows that the sensation level decreases as the difference between ITDs of target and masker decreases. This means that the influence of a sound in binaural listeng is somewhat localized around its own ITD. When the ITDs of target and masker are different, there are gaps and laps in the stimuli. So there is a possibility to have their unexpected influence. In order to check it, we made a further experiment; *i.e.* the stimuli for the left ear was also presented to the right ear instead of the propper ones for right ear, and the threshold level was measured. In this case, the same stimuli may still have gaps and laps, but is presented to both ears like experiment 1. As a result, the obtained sensation level was almost equal to that in experiment 1, and it was considered to be constant. This means that the shorter gaps and laps in the stimuli had no influence on the results of experiment 2.

The results in this experiments will have close relation with binaural masking level difference(MLD)[4, 7]. According to MLD, when masker is located on the center C as in experiment 2a, the targets except from C will be easily perceived because the MLDs are supposed to increase, while the MLD should decrease when target is also located on C. However, it is not so simple in experiments 2b and 2c. Contralateral induction[8, 2] shows the influence on sound perception from one ear to the other. As binaural release of temporal induction[9, 2], it is known that temporal induction is inhibited when interaural phase relations are different between the inducer and inducee. The binaural critical bandwidthand the binaural interference, which is considered as a special case that target and masker is in a same band, will have close relation to our results.

In addition, this possibly suggests that there would exist a direction selective or localized characteristics in audio system and it would be used for integrating information from both ears. If this kind of characteristics exists, the masker from the same direction as a target can most effectively mask the target, and the sensation level becomes minimum when they come from the same direction. It will be applicable for phoneme restoration, speech enhancement and so on.

5. Conclusions

In this paper, we investigated the illusory continuity in binaural listening, by controlling ITD. As a result, illusory continuity was observed in binaural listening and the threshold amplitude ratio between masker and target was dependent on the difference of their ITDs. The sensation level decreased as the difference of ITDs decreased, and was minimum when the ITDs of target and masker were same. These characteristics should be explained not only in peripheral auditory nerve and organ but also higher systems near brain because the information from both ears need to be integrated. The results in this paper are also considered to indicate the locality of the effect of sounds from another direction. Supposing a direction selective filter bank, the qualitative characteristics of this phenomenon are possibly explained. This kind of selectivity to sound source location is applicable for enhancement of speech and reduction of noise for speech processing. More detailed measurements and explanation for this phenomenon are still remained for future works.

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