JUDGMENT OF PERCEPTUAL SYNCHRONY BETWEEN TWO PULSES AND ITS RELATION TO THE COCHLEAR DELAYS

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Abstract

This study investigates whether the delay caused in the course of wave propagation along the basilar membrane of the cochlea (the cochlear delay) significantly affects the perceptual judgment of the synchronization of two sounds. An experiment was conducted to detect asynchrony using two types of short chirp against a pulse. A compensatory delay chirp was designed for the peaks of the basilar membrane motion to be aligned. An enhanced delay chirp had an enhanced delay pattern that follows the assumed cochlear delay. The pulse had a cosine phase relation, and as a result, it had an intrinsic cochlear delay at the auditory peripheral. The result suggests that the auditory system tends to be more "tolerant" when the lower components arrive after the higher components, as happens for a pulse.

This study investigates whether the delay caused in the course of wave propagation along the basilar membrane of the cochlea (referred as to the cochlear delay) significantly affects the perceptual judgment of synchronization.

Onset synchrony is widely assumed to be an important cue for perceptual unification as a single tone. However, even if all the components physically begin exactly and simultaneously, their temporal relation might not be preserved at the cochlear level. This is called the cochlear delay.

Cochlear Delay

The cochlear delay shifts the arrival of lower components slightly but systematically behind the higher components. The cause of the delay is based on the mechanical filtering of the basilar membrane, which functions as a transmission line filter bank. In this filter bank, the higher components of an input wave excite the basal side (closer to the oval window), while the lower components excite the apical side. Due to the time delay required for this transmission, the lower components reach the place where maximum vibration occurs later than the higher components. Therefore, even if the components begin simultaneously, their temporal relation is not preserved at the cochlear level.

In the current study, two types of short chirp and a pulse were used as experimental stimuli to investigate whether cochlear delay imposes a systematic bias in judging the perceptual synchrony of two sounds.

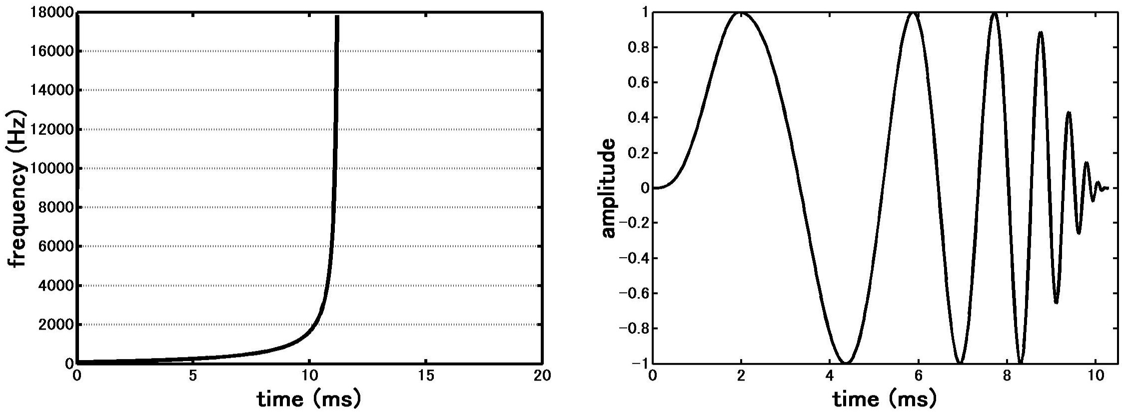

Fig. 1 Increasing frequency pattern (chirp pattern) of compensatory delay condition (left panel) and waveform of chirp with compensatory delay (right panel).

Two Types of Chirp and a Pulse

An experiment investigated whether cochlear delay affects the detection of asynchrony between two sound objects using two types of short chirp and a pulse: (a) a chirp with compensatory delay, (b) a chirp with enhanced delay, and (c) a pulse (with intrinsic cochlear delay). A chirp on the compensatory delay condition instantaneously increased its frequency to compensate for the cochlear delay. The increasing frequency pattern was calculated based on the model proposed by Dau *et al.* (2000). In this compensatory condition, the increasing frequency pattern was designed to "cancel out" the cochlear delay. Accordingly, it can be assumed that excitation along the basilar membrane arises simultaneously so that all the places along the basilar membrane reach maximum amplitude at the same moment. The left panel of Figure 1 shows the increasing frequency pattern of the compensatory delay condition. The right panel of Figure 1 shows the waveform of the chirp with compensatory delay. Enhanced delay condition was generated using the reversed temporal relation of the compensatory delay condition. These two chirps were increased from 100 to 10400 Hz or decreased from 10400 to 100 Hz, and tapered with a raised cosine wave of 100 Hz. Adding to these two experimental conditions, a pulse on the intrinsic cochlear delay condition was prepared where no delay was imposed. The pulse was also lowpass filtered with a cut-off frequency of 10400 Hz.

Experiment

The experimental task was to detect onset asynchrony between the sounds by a two interval, two-alternative forced choice (2I2AFC) task. In each trial, one interval contained a synchronous sound pair, and the other interval contained an asynchronous pair. The order was randomized. Participants were required to judge the synchrony of two sounds in the following conditions: (a) compensatory delay, (b) intrinsic cochlear delay, and (c) enhanced delay. The time lag between the two sounds of asynchronous stimuli (delay time) was changed in every trial, and then the thresholds of the two types of short chirp and the pulse were measured. The delay time was set at 0.2, 0.3, 0.5, 0.8, 1.3, 2.0, and 3.2 ms at intervals that were approximately equal on a logarithmic scale. Therefore, the thresholds were estimated from seven points of psychometric function. Judging the synchronous pair, which resulted in 75% correct responses, was considered the threshold. Figure 2 shows an example of stimuli presentation.

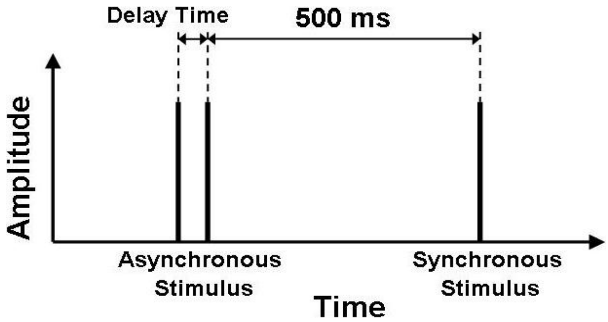

Fig. 2 Example of stimuli presentation by pulse. Here, second interval contains the "synchronous" pair and should be chosen as "correct."

The number of stimulus type combinations was 42 (three type-sounds, seven delay-times, and two orders of correct answers). The participants repeated each 10 times, so the total number of trials was 420. Feedback was provided after each trial. The level of stimuli was approximately 75 dB SPL and varied from +6 to -6 dB stimulus by stimulus to prevent participants from using loudness differences as a cue.

Equipment and Listeners

The stimuli were generated digitally and controlled by a digital signal processor, Kyma (Symbolic Sound), and diotically presented to participants through headphones (SENNHEISER HD 600) connected to an amplifier (Luxman P-1). Five participants with normal hearing from 21 to 29 years old were seated in a sound-treated room (YAMAHA AVITECS) and paid for their participation.

Result

The ratio of correct choices increased as delay time increased, which confirmed that participants performed the task using the onset asynchrony for the detection cue, as we intended. Table 1 shows the estimated thresholds by all sound conditions. As shown in this table, the threshold of the compensatory delay condition is the highest. An analysis of variance (ANOVA) was performed where the condition of sounds was treated as the main factor and participants were treated as a random effect. The ANOVA results were significant [$F(2, 8) = 5.9737$, $p<0.0259$]. The threshold of the enhanced delay condition was perceived as more similar to a pulse than the compensatory delay condition.

Discussion

The threshold of the compensatory delay condition was the highest, suggesting that the accuracy of the synchrony judgment did not improve even if the cochlear delay was

Table 2. Estimated thresholds by condition.

Type of Sounds	Threshold (ms)
(a) compensatory	2.0
(b) enhanced	1.3
(c) intrinsic	0.8

compensated for. On the contrary, such a compensatory operation appeared to complicated synchrony judgment. The result that the threshold of the enhanced delay condition was perceived as more similar to a pulse than the compensatory delay condition means that the enhanced delay condition is more similar to the intrinsic cochlear delay condition for the auditory system. This may be one reason that in both conditions the lower frequencies reach the corresponding place later than the higher frequencies.

The observed result among the three conditions was in accordance with the result by Uppenkamp *et al.* (2001), who asked their listeners how “pulse-like” test stimuli sounded using a simple pulse (with intrinsic delay), an up-chirp (with compensatory delay), and a down-chirp (with enhanced delay). Their results indicated that down-chirp was perceived as more similar to a simple pulse than up-chirp. This corresponds to our results. Uppenkamp *et al*. explained their results on the basis of an additional temporal integration mechanism at a higher stage of auditory processing that effectively removes phase differences between channels.

Additionally, our previous experimental results regarding the accuracy of the synchrony judgment of two complex tones indicated a similar tendency (Aiba and Tsuzaki 2007). The experimental procedure was almost the same as this experiment with two types of short chirp and a pulse. However, listeners judged the synchrony of two complex tones that also had three types, as in the current experiment. Each complex tone was composed of 30 sinusoids, and the onset time relation of 30 sinusoidal components was altered following the increasing frequency pattern by Dau *et al.* of the three types of complex tones. As a result, the threshold of the compensatory delay condition was the highest and the thresholds of the enhanced delay condition and the intrinsic cochlear delay condition were almost the same level. This result also shows a certain level of similarity.

Conclusion

Alignment of the excitation peak along the basilar membrane did not make more accurate the perceptual judgment of synchronization. On the contrary, it tended to deteriorate judgment compared to the simple pulse where the intrinsic cochlea delay remained. The auditory system appeared more “tolerant” of the delay following the intrinsic, natural direction, i.e., the cochlear delay.

Acknowledgements

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