Perceptual simultaneity range as a function of frequency separation for two pure tones

Satoshi Okazaki1,* and Makoto Ichikawa2,†

1Graduate School of Advanced Integration Science, Chiba University, 1–33 Yayoi-cho, Inage-ku, Chiba, 263–8522 Japan
2Faculty of Letters, Chiba University, 1–33 Yayoi-cho, Inage-ku, Chiba, 263–8522 Japan

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Abstract: This paper provides a phenomenological quantitative function of the perceptual simultaneity range (PSR) in terms of the frequency separation and a possible explanation. The PSR for two pure tones was measured with the frequency separation between the tones from 0.07 to 4.09 octaves with the lower frequency fixed at 200 Hz. In this study, listeners judged the simultaneity of the tones using the perceptual synchrony–asynchrony cue while the possible use of the perceptual fusion–separation cue (“oneness” or “twoness”) was eliminated. Results show that the PSR plotted against the frequency separation can be fitted to two segmented linear regression lines, one decreasing for small frequency separation and the other increasing for large frequency separation. These regression lines intersect around the critical bandwidth. Results also show no effects of the frequency separation on the singular interval or points, such as tonal consonance, musical consonance, and harmonic relations. These results suggest that the perception of simultaneity is mainly determined by the peripheral representation of the tone distance. We propose a possible explanation for the behavior of the PSR for small frequency separation by considering the mechanics of basilar membrane motion. However, the explanation for the behavior for large frequency separation is still unclear.

Keywords: Perceptual simultaneity, Perceptual fusion, Consonance, Harmonic relation, Basilar membrane motion

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1. INTRODUCTION

Regarding the temporal aspects of human auditory processing, the perception of simultaneity for sounds is a very basic function for understanding auditory events and has been studied in several research contexts (e.g., to explain note-onset synchrony in music [1,2], the voice onset time in speech [3,4], and the psychoacoustics of synchrony perception [5,6]). However, previous studies investigating the basis for the perception of simultaneity for sounds [4–7] have not shed light on its underlying mechanism or even its phenomenological behaviors. Therefore, knowledge about the perception of simultaneity for sounds is limited to the fact that it is easy to hear the asynchrony of sounds with a separation of 10 ms order. Although there are many factors that may affect the perception of simultaneity, the list of such factors is incomplete. In this study, we investigated the effects of one of the candidate factors, which is an inherent property of tonal sounds: the frequency separation between pure tones.

The perceptual simultaneity range (PSR) has been measured in several studies; in this range, a listener perceives two asynchronous tones as simultaneous regardless of their physical asynchrony. These studies used two pure tones with the frequency separation of the tones as the independent variable [4–7] to determine whether the PSR of two pure tones varies with the frequency separation between them (Figure 1 shows a schematic spectrogram of the stimuli used in the present paper and previous studies). These studies used two pure tones with the frequency separation of the tones as the independent variable [4–7] to determine whether the PSR of two pure tones varies with the frequency separation between them. However, even with the results of these previous studies, whether and how the frequency separation affects the PSR remain unclear. The difficulty in establishing the effect of frequency separation on the PSR arises from the following...
problems. (i) The results of previous studies are inconsistent. That is, Parker [4] and Micheyl et al. [7] reported that the PSR for two pure tones increased concomitantly with increasing frequency separation, whereas Sinico [5] and Wojtczak et al. [6] reported non-systematic effects or no effect of the frequency separation on the PSR for two pure tones. (ii) Previous studies provided no information about the slope and intercept of the PSR as a function of frequency separation. (iii) In previous studies, a small number of frequency separation conditions within a limited range were mostly examined: the frequency separation in Parker [4] and Micheyl et al. [7] ranged from 0.42 to 2.32 octaves, while that in Wojtczak et al. [6] ranged from 2.00 to 4.58 octaves and that in Sinico [5] ranged from 0.17 to 0.58 octaves. The latter two problems make it difficult to compare the significance of the different results (the first problem) of the previous studies. To summarize, the currently available data are insufficient to establish the effect of frequency separation on the PSR.

To overcome the above problems and to clarify the phenomenological nature of perceptual simultaneity, in this study, we investigated the PSR in a wide range of frequency separation conditions. The PSR was measured using two pure tones as in previous studies. The fragmented and inconsistent results in the previous studies are reconciled in this paper. A possible underlying mechanism is also discussed.

1.1. Singular Effects of Frequency Separation

In the continuum of frequency separation, there are some special intervals or points that affect human auditory perception. Such singular factors in frequency separation are tonal consonance, musical consonance, and harmonic relations. The contribution of these factors to the PSR was examined in this paper. Tonal consonance, which refers to a very basic sensory experience of consonance [5], appears in the case of small frequency separation. When the frequency separation is 0–0.25 (unit: critical bandwidth), the tonal consonance decreases, and then increases to a maximum (zero dissonance) when the frequency separation is 1.2 (Fig. 2). To examine the effect of the tonal consonance on the PSR, We collected data at the characteristic frequency separations of the consonance curve (highest, lowest, and middle consonance points; black dots in Fig. 2) and examined whether the PSR reflects the curvature. In music theory, musical consonance appears at frequency separation of simple integer fractions of an octave. The most consonant frequency separation is defined to be an octave and this octave separation is also an example of a harmonic relation. Harmonic relations appear at frequency separations of integer multiples of the lowest tone frequency. To examine the effects of both musical consonance and harmonic relations on the PSR, we collected data at the frequency separation of exact octaves (consonant and harmonic) and the semitone above from exact octaves (dissonant and inharmonic).

1.2. Ambiguity of Simultaneity Judgment

In the previous studies [4–7], it was implicitly assumed that only a single boundary exists across which a listener changes the synchronous–asynchronous judgment. This assumption is questionable in light of research investigating the perception of temporal order. Several papers have reported that two perceptual boundaries exist, beyond which a listener can identify the relative timing of two tones [10–13]. The first boundary, which appears at a very short onset asynchrony between the tones, demarcates the perceptual fusion (“oneness”) and perceptual separation (“twoness”) of the tones. Below this “fusion boundary,” a listener perceives two tones as a fused sound and cannot perceive the relative timing of the tones. Nevertheless, a listener might judge the tones to be simultaneous. Beyond the fusion boundary, a listener perceives two separate tones but still does not perceive their asynchrony. Using this perceptual separation as a cue for physical asynchrony, the listener might judge the tones as asynchronous, even without the perception of asynchrony. The second boundary, which appears at a larger tone asynchrony, demarcates the perceptual simultaneity and perceptual asynchrony of the tones. Beyond this “simultaneity boundary,” the
listener perceives two asynchronous tones. Therefore, a listener can judge the relative timing of the tones on the basis of the perception of asynchrony. These two types of “simultaneity judgment” of listeners were reported in a previous paper [14] by considering a few cases and is again examined in the present paper. To elucidate the relation between the PSR and the frequency separation for two tones, only the simultaneity boundary should be extracted from the measurement of the PSR. To avoid the contamination of judgment of perceptual simultaneity with judgment of perceptual fusion by such an ambiguity, we modified the listener’s possible choices: after the presentation of a stimulus, the listener was first asked to judge whether a single fused sound or two separate tones were heard. Only if the listener heard two separate tones was the listener asked to judge whether the two tones were simultaneous or not. This procedure covers all the possible situations described above and therefore is able to distinguish simultaneity judgments based on perceptual simultaneity and perceptual fusion.

2. METHOD

2.1. Listeners

We examined 15 listener participants (four females and 11 males, 20–51 years of age; one was the first author). All listeners reported having normal hearing. Each listener made judgments of 4–12 conditions of frequency separation (9–12 listeners per condition).

2.2. Stimuli

As shown in Fig. 1, the stimuli consisted of two pure tones with onset asynchrony ($\Delta t$) and frequency separation ($\Delta f$) between them. The frequency separations presented were 0.07, 0.18, 0.34, 0.70, 1.00, 1.09, 2.00, 2.09, 3.00, 3.09, 4.00, and 4.09 octaves. The first four frequency separations correspond to the characteristic points of the tonal consonance curve (Fig. 2). The latter frequency separations are either exact octaves (consonant and harmonic) or the semitone above from exact octaves (dissonant and inharmonic). The lower tone frequency was fixed at 200 Hz because the effect of the lower tone frequency on perceptual simultaneity is unknown (however, preliminary studies by the authors suggested that the effect of the lower tone frequency is sufficiently small to be undetected by the listener). The higher tone frequency was varied between 210 and 3,413 Hz.

The loudness of each frequency tone was matched to that of a 65 dB, 1,000 Hz pure tone for each listener by the following method of adjustment. In each trial, the test tone and standard tone were presented repeatedly. The listener adjusted the intensity of the test tone so that it had equal loudness to the standard tone. The initial intensity (low or high) of the test tone and the presentation order of the test and standard tones were counterbalanced. Each frequency condition was presented 12 times in random order with no feedback. This loudness-matching task was performed because a difference in loudness between the two tones makes it difficult for a listener to detect asynchrony [15].

The tone-onset asynchronies ($\Delta t$ in Fig. 1) presented were ±0, 2, 4, 7, 14, 27, 52, and 100 ms (equal spacing in a log scale [16]; positive asynchronies indicate that the tone with lower frequency preceded the tone with higher frequency while negative asynchronies indicate that the tone with lower frequency followed the tone with higher frequency). The two tones were always terminated at the same time. This prevented the listener from using the offset difference as a cue of simultaneity. The duration of the following tone was 300 ms, whereas that of the preceding tone was lengthened by the absolute value of the onset asynchrony (300 ms + onset asynchrony). The duration of 300 ms was sufficient to prevent the tone loudness from changing owing to the variation of the tone duration [17]. Each tone was tapered with a rise–fall time of 15 ms by the cosine function to avoid spectral splatter at the tone onset and offset.

2.3. Apparatus

Pure tones were generated in MATLAB on a computer (Apple MacBook Air, 11-inch, Mid 2012; Apple Inc.) with a 44.1 kHz sampling rate and 16-bit resolution. The tones were presented diotically using a headphone (MDR-1RMK2; Sony Corp.) with an audio interface (Scarlett 2i2; Focusrite plc.). Listeners were seated in a soundproof room (FKS20-12; Kawai).

2.4. Procedure

In each trial, after the presentation of two-tone stimuli (Fig. 1), listeners were first asked to judge whether the two tones were fused or separated. Only if they judged that the tones were separated were they asked to judge whether the two tones were simultaneous or not. The trial was finished if they judged that the tones were fused. This procedure was intended to prevent listeners from judging simultaneity based on the perceptual fusion cue. Each condition (15 $\Delta t \times 4 \Delta f$) was presented 10 times in random order. Listeners had no feedback or time pressure for their judgment. Before the test session, listeners had a training session (28 trials) with no feedback. The tasks were completed in about an hour.

3. RESULTS

Data from 17 out of 18,600 trials were discarded because of response errors (hitting incorrect keys). For each frequency separation condition for each listener, the frequency distribution of the judgments for perceptual fusion (a single fused sound was heard) and perceptual
simultaneity (two separate tones were heard) was obtained for different values of tone asynchrony.

Figure 3 shows the mean frequency distribution of the judgment of fusion and simultaneity. Each bar in each panel corresponds to onset asynchronies of −100, −52, −27, −14, −7, −4, −2, 0, 2, 4, 7, 14, 27, 52, and 100 ms from left to right. The number of listeners is 10 for Δf = 0.07, 0.18, 0.34, and 0.70 octaves; 12 for Δf = 1.00, 1.09, 3.00, and 3.09 octaves; and 9 for Δf = 2.00, 2.09, 4.00, and 4.09 octaves.

Figure 4 presents examples of results (a linear replot of Fig. 3, Δf = 2 octaves) showing the synchrony–asynchrony boundary. Filled and open boxes respectively correspond to the frequency of the fusional judgment and the sum of the frequencies of the fusional judgment and simultaneity judgment as in Fig. 3. For the present experi-
ment, the perceptual synchrony–asynchrony boundary is derived from the summed frequencies (curve with open boxes). Previously obtained perceptual synchrony–asynchrony boundaries are also drawn as dashed curves (the boundaries in [4] and [6] are respectively indicated by “P” and “W” in Fig. 4). At most only two data with negative \( \Delta t \) are currently comparable. Although the synchrony–asynchrony boundaries were obtained under considerably different conditions (e.g., [4]: \( \Delta f = 2.2 \) octaves, 78 dB, 600 ms duration, 10 ms linear taper; [6]: \( \Delta f = 2 \) octaves, 85 dB, 40 ms duration, 10 ms cosine taper), we successfully elicited a simultaneity-judgment-like response (rise from 0 to nearly 100% at around \( \Delta t = 0 \)) similar to that in the previous studies, despite the new experimental procedure.

The observed standard deviation (SD) of the frequency distribution was used as an index for the PSR at each frequency separation for each listener. The SDs are shown as a function of frequency separation in Fig. 5. The first four points of the function (frequency separation of 0.7 octave or less) clearly showed no relation to the consonance curve (mid-low-mid-high transition as in Fig. 2). Also, the latter points (frequency separation of 1 or more octave) showed no or slight differences between the exact-octave conditions (1, 2, 3, and 4 octaves) and semitone above conditions (1.09, 2.09, 3.09, and 4.09 octaves). The function of the PSR is nonmonotonic, consisting of two functions: a descending left part for small frequency separations and an ascending right part for large frequency separations. Therefore, these data were divided into two segments, each of which was subjected to linear regression. The point of division was found using the least-squares method [21]. The resulting regression lines are drawn as a solid curve in Fig. 5. The slope for the left part is steep, whereas that for the right part is very gradual. These slopes diverged significantly from zero (left part: \( \beta = -111.1, t(18) = -3.222, p = 0.005, r = 0.605 \); right part: \( \beta = 1.616, t(102) = 3.243, p = 0.002, r = 0.306 \)). The intersection of these lines was estimated to be at 0.26 octaves (dashed line in Fig. 5).

To investigate the generality of the results for the SD, the 50% threshold for simultaneity judgment was used as another index and it was examined how both thresholds vary with the frequency separation. To estimate the 50% threshold at each frequency separation for each listener, the logistic function was fitted to each side (zero or negative asynchrony, and zero or positive asynchrony) of the frequency distribution using the maximum likelihood method. To get the extremes of the distribution close to zero, a nominal value of \( \pm 193 \) ms with no occurrence of simultaneous judgment was extrapolated. The range of 50% thresholds and the two segmented regression lines, which were derived in the same manner as for the SD, are depicted in Fig. 6. The intersection of these lines was estimated to be at 0.26 octaves (dashed line in Fig. 6). This value coincided with that for the SD. In summary, the PSR as a function of frequency separation was similar when the SD and the 50% threshold were used as indices.

4. DISCUSSION

The present results demonstrate that the PSR for two pure tones can be expressed by the two segmented regression lines as a function of the frequency separation of the tones. As the frequency separation increases, the PSR decreases abruptly up to the intersection between the two regression lines. It then increases gradually above the intersection. The intersection of these lines is around the critical bandwidth (0.26 octaves = 0.81 ERBs [equivalent rectangular bandwidths] from 200 Hz [22]). Because the critical bandwidth is determined by the distance along the cochlear basilar membrane, this result indicates that the mechanics of the basilar membrane motion (BMM) are involved in the perception of simultaneity as discussed below.
Also, the present results revealed that the PSR is not affected by tonal consonance, musical consonance, or harmonic relations. In particular, the tonal consonance is determined at an early auditory processing stage of the cochlea. Therefore, it is possible that the perception of simultaneity is also determined at an early peripheral stage of the auditory pathway similarly to the tonal consonance. This possibility is consistent with the notion described above that the basilar membrane, which is the earliest peripheral stage of auditory pathway, is involved in the perceptual processing of simultaneity.

### 4.1. Possible Explanation for Results

The two-segmented function of the PSR is partially explainable as follows. First, the function of the PSR decreases steeply below the intersection. This function might be explained by the overlap of the range of BMM for two pure tones in the cochlea. A tone entering the cochlea causes BMM with a certain range around the site on the membrane. The distance of the site from the basal end of the cochlea is determined by the frequency. The ranges of BMM for two tones overlap when the frequency separation between them is small. When two asynchronous pure tones enter the cochlea, if their frequency separation is reasonably small, then the preceding tone should also trigger BMM at the site corresponding to the following tone frequency. Therefore, the BMM onsets at the sites for the preceding tone and following tone are simultaneous irrespective of the tones’ asynchrony. This should result in a wide PSR for tones with small frequency separation.

Second, above the intersection, the simultaneity function shows a gradual increase in the PSR at large frequency separation. However, we could not find a possible explanation for such behavior in the auditory system. Further phenomenological data, such as for various lower tone frequencies, may make it possible to determine the underlying mechanism in the future.

### 4.2. Interpretation of Previous Studies

The present results can explain the discrepancies among the results of earlier studies. First, Parker [4] and Micheyl et al. [7] found that the PSR of two pure tones increased with increasing frequency separation of the two tones. These studies used frequency separation of 0.42–2.32 octaves in experiments. In this range, the present results show an increase in the PSR with increasing frequency separation. This increase in the PSR is consistent with the results reported by Parker [4] and Micheyl et al. [7].

Second, Wojtczak et al. [6] found that the PSR of two pure tones is constant irrespective of the frequency separation in the range of 2.00–4.58 octaves. According to the discussion of Wojtczak et al., the discrepancy in the effect of frequency separation among the studies results from a cochlear within-channel cue. The cochlear within-channel cue is explainable as follows. The ranges of BMM for two pure tones overlap when the frequency separation between the tones is small. In this overlapping range, the BMM induced by the preceding tone fluctuates with the arrival of the following tone. This fluctuation is a valid cue for the tones’ asynchrony and for comparing the timing of the tones. Wojtczak et al. argued that the within-channel cue is available only when the frequency separation between the tones is small, and the absence of the within-channel cue for large frequency separations causes the flat function of the PSR. Indeed, Parker [4] and Micheyl et al. [7] used frequency separations of less than 2.32 octaves, for which a listener can use the within-channel cue. Wojtczak et al. [6] used large frequency separations in addition to a noise masker to prevent the potential availability of the within-channel cue for even such large frequency separations. The results of Parker [4], Micheyl et al. [7], Wojtczak et al. [6], and the present study for large frequency separations are consistent with the explanation of the within-channel cue. However, this explanation cannot predict the increase in the PSR for small frequency separations (below the intersection) in this study. From a theoretical viewpoint, it is still possible that the within-channel cue determines the increase in the PSR for relatively large frequency separations. Before further theoretical discussion, it should be noted that the increase in the PSR for large frequency separations is small. Therefore, it is possible that Wojtczak et al. failed to detect such a small effect. In line with this, Wojtczak et al. did not rule out the variability that arose from the ambiguity of the simultaneity judgment. Also, the flat function reported by Wojtczak et al. was derived from statistical analysis with $H_0 = \text{flat}$ and $\alpha = 0.05$. Such a situation easily causes a type II error (the conclusion that the function is flat). Furthermore, the statistical power of Wojtczak et al.’s analysis might have been lower than that in the present study because of the smaller sample size, fewer $\Delta f$ conditions within a narrower range, and the application of ANOVA instead of linear regression analysis.

Third, Sinico [5] was unable to find any systematic change in the PSR for a small frequency separations of 0.17–0.58 octaves. This range includes the intersection in the present study, and the two functions with opposite gradients describing the PSR. Because Sinico used only four frequency separation conditions, a systematic change would have been difficult to detect. Moreover, in this range, the perceptual fusion cue and perceptual synchrony cue are in competition because a small frequency separation would cause perceptual fusion. The ambiguity of the simultaneity judgment might increase the deviation of the data.
4.3. Validity of the Data

The present data were obtained from an improved simultaneity judgment task. As noted in the introduction, the results of the conventional simultaneity judgment task may have been contaminated because of the ambiguity of “simultaneity”: the judgment of simultaneity may have been performed using the perceptual fusion cue or the simultaneity cue itself. The present procedure successfully discriminated between judgment based on the perceptual simultaneity and that based on perceptual fusion cue.

The present data for perceptual fusion give rise to doubt about the validity of the previous data. The present results clearly showed a high frequency of judgment for perceptual fusion for less than three octaves of frequency separation. This result indicates the existence of a perceptual fusion cue for this range of frequency separation. Once a listener judged “synchrony” based on the perceptual fusion cue, there was no opportunity to judge the perceptual simultaneity itself in the conventional simultaneity judgment task. If this occurs in some trials, a part of the data obtained from the experiment solely represents the perception of fusion. Therefore, the data [4–7] obtained from the conventional task might potentially be based on a mixture of perceptual simultaneity and fusion. This would make it difficult to uncover the systematic behavior of perceptual simultaneity. In line with this, two of the four previous studies failed to find a systematic variation of the perceptual simultaneity as a function of frequency separation. It should also be noted that Wojtczak et al. [6], who failed to find a systematic variation, gave a special instruction to listeners to judge simultaneity by using the most effective cue for each individual. This instruction might have removed the homogeneity of listeners’ usage of the perceptual fusion cue and simultaneity cue. If so, a systematic variation of perceptual simultaneity would have been more difficult to find owing to the variation of the listeners’ judgment.

The present data for perceptual simultaneity are basically free from the contamination effect of perceptual fusion. Therefore, the data allow the more precise description of the behavior of the perception of simultaneity than the possibly contaminated data in [4–7]. The perception of simultaneity of tones has been used to formulate hypotheses and theories in several research areas, such as music and speech. The details of the present phenomenological nature of the perception of simultaneity are expected to promote the development of such hypotheses and theories in future.

NOTES

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REFERENCES

[1] J. Vos, “Perceptual separation of simultaneous complex tones: The effect of slightly asynchronous onsets,” Acta Acust., 3, 405–416 (1995).
[2] D. Huron, “Asynchronous preparation of tonally fused intervals in polyphonic music,” Empir. Musicol. Rev., 3, 11–21 (2008).
[3] D. B. Pisoni, “Identification and discrimination of the relative onset time of two component tones: Implications for voicing perception in stops,” J. Acoust. Soc. Am., 61, 1352–1361 (1977).
[4] E. M. Parker, “Auditory constraints on the perception of voice-onset time: The influence of lower tone frequency on judgments of tone-onset simultaneity,” J. Acoust. Soc. Am., 83, 1597–1607 (1988).
[5] M. Sinico, “Influence of bichord interval on perception of simultaneity,” Percept. Mot. Skills, 99, 937–944 (2004).
[6] M. Wojtczak, J. A. Beim, C. Micheyl and A. J. Oxenham, “Perception of across-frequency asynchrony and the role of cochlear delays,” J. Acoust. Soc. Am., 131, 363–377 (2012).
[7] C. Micheyl, C. Hunter and A. J. Oxenham, “Auditory stream segregation and the perception of across-frequency synchrony,” J. Exp. Psychol. Hum. Percept. Perform., 36, 1029–1039 (2010).
[8] R. Plomp and W. J. M. Levelt, “Tonal consonance and critical bandwidth,” J. Acoust. Soc. Am., 38, 548–560 (1965).
[9] R. Parnicutt, “Parnicutt’s implementation of Hutchinson & Knoppoff (1978),” http://www.uni-graz.at/richard.parnicutt/rough1doc.html.
[10] I. J. Hirsh, “Temporal order and auditory perception,” in Sensation and Measurement: Papers in Honor of SS Stevens, H. R. Moskowitz, B. Scharf and J. C. Stevens, Eds. (Reidel, Dordrecht, 1974), pp. 251–258.
[11] H. Babkoff, “Dichotic temporal interactions: Fusion and temporal order,” Percept. Psychophys., 18, 267–272 (1975).
[12] G. M. Corso, “Auditory temporal order and perceived fusion–nonfusion,” Percept. Psychophys., 28, 465–470 (1980).
[13] P. L. Divenyi, “The times of Ira Hirsh,” J. Acoust. Soc. Am., 111, 2401–2401 (2002).
[14] S. Okazaki and M. Ichikawa, “Perceptual fusion and simultaneity for auditory stimuli,” Proc. 15th Int. Conf. Music Percept. Cognit., pp. 316–319 (2014).
[15] W. Goebel and R. Parnicutt, “The influence of relative intensity on the perception of onset asynchronies,” Proc. 7th Int. Conf. Music Percept. Cognit., pp. 613–616 (2002).
[16] E. Aiba, “Synchrony judgment of multiple overlapped sounds: Perception of unification and separation,” Ph.D. thesis, Kyoto City University of Arts (2009) (in Japanese).
[17] M. Florentine, A. N. Popper and R. F. Richard, Loudness (Springer, New York, 2011), p. 233.
[18] R. Plomp, “The ear as a frequency analyzer,” J. Acoust. Soc. Am., 36, 1628–1636 (1964).
[19] R. Plomp and A. M. Mimpen, “The ear as a frequency analyzer. II,” J. Acoust. Soc. Am., 43, 764–767 (1968).
[20] L. Demany and C. Semal, “Dichotic fusion of two tones one octave apart: Evidence for internal octave templates,” J. Acoust. Soc. Am., 83, 687–695 (1988).
[21] R. S. Bogartz, “A least squares method for fitting intercepting line segments to a set of data points,” Psychol. Bull., 70, 749–755 (1968).
[22] B. R. Glasberg and B. C. Moore, “Derivation of auditory filter shapes from notched-noise data,” Hear. Res., 47, 103–138 (1990).
Satoshi Okazaki  received his B.A. and M.A. from Chiba University in 2013 and 2015, respectively. He is currently a Ph.D. candidate at Chiba University and a research fellow of JSPS. He is a member of ASJ, ASA, JPA, and JPS.

Makoto Ichikawa  received his B.A., M.A., and Ph.D. from Osaka City University in 1988, 1990, and 1994, respectively. He is a professor at the Department of Psychology of Chiba University. His areas of interest include spatial and temporal aspects of human perception, cross-modal processing in perception and cognition, and plasticity in perception and cognition. He is a member of JSKE, ARVO, VSS, JPA, JPS, VSJ, JSCP, and Japanese Society for Time Studies.