Hearing thresholds for low-frequency complex tones of less than 150 Hz

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Hearing thresholds for low-frequency complex tones were measured to investigate effects of intensity and frequency differences between components and effects of the number of components on the detection of complexes. Complex tones comprised two tones, geometrically centered at 60 Hz, with frequency differences of 30, 60, 90, or 120 Hz. Sound pressure levels of the two tones were set to equal intensity or to equal sensation level. Additional threshold measurements were conducted for complex tones comprising 2–6 components at 25–145 Hz. A complex signal with multiple tones was detectable even if the levels of individual components were below the threshold. The improvement of complex signal detection varied greatly with the level difference and number of tones. Threshold levels for complex tones (in terms of level per component) decreased as the number of tones increased. Complex tones whose components have mutually similar frequencies were more detectable than those with separated components.

1. INTRODUCTION

Surveys of low-frequency sounds have revealed that noise problems are often caused by a noise occurring in the region of the hearing threshold [1]; in most cases, a noise at very low levels, which is generally regarded as acceptable, caused the complaint [2]. These facts suggests that in real life situations some people may detect a low-frequency sound at a level below the threshold of hearing as measured for single pure tones using the conventional procedure.

Hearing thresholds of sounds higher than 20 Hz [3] and lower than 20 Hz [4] have been measured for pure tones. However, sounds we generally encounter in our daily lives are not pure tones; they are combinations of tonal components and random noises. Field measurements of low-frequency noise often reveal several low-frequency harmonic or inharmonic tonal components [1,5,6]. The hearing characteristics for such low-frequency complexes might be affected by their frequency separation and the number of components.

Several studies have investigated detection phenomena of complex tones and band noises by measuring thresholds. Most investigations [7–14] have revealed that thresholds of complex tones and band noises (in terms of the level per component or spectrum level) were lower than those of pure tones: complex tones are detectable even if their individual components are not audible. However, most empirical data related to thresholds for complex signals are for middle-frequency and higher-frequency sounds. In the low-frequency region, threshold and loudness characteristics differ greatly from those of the higher-frequency region. Bandwidths of auditory filters around 100 Hz are narrower (35 or 60 Hz) than those in the higher-frequency region [15–17], but those less than 100 Hz are still ambiguous because of a lack of empirical data [16]. Furthermore, loudness and thresholds for low-frequency sounds varied greatly with frequency. Therefore, the need exists to clarify the detection characteristics for complex signals in the low-frequency region.

Several studies have investigated thresholds for low-frequency complex tones [2,18] and noises [19]. Their results were consistent with those of the studies described above for middle-frequency and high-frequency sounds. However, in their studies [2,18], the bandwidths of complex tones (frequency difference between highest and lowest tone) were narrow, less than 50 Hz. Therefore, the effects of frequency difference between tones related to auditory filters on detection have not been described.

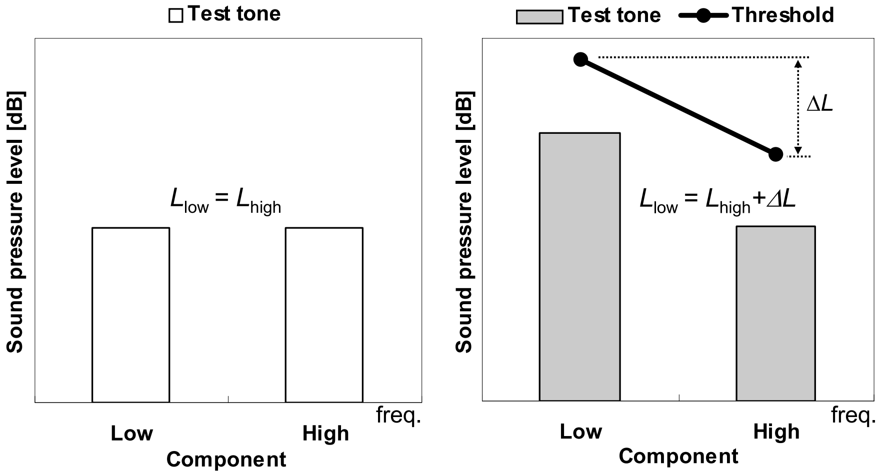
This study was undertaken to investigate the effects of intensity and frequency differences between components and the number of components on detection of the complexes which have wider bandwidths than those examined in previous studies. This study measured hearing thresholds for complexes with two tones that were centered geometrically on 60 Hz and which have various frequency differences (bandwidths). Thresholds for complexes comprising 2–6 tones from the 25–145 Hz range were also measured.

2. EXPERIMENT-1

2.1 METHOD

2.1.1 Stimuli

Hearing threshold measurements for pure tones with frequencies of 25, 30, 37, 47, 77, 97, 120, and 145 Hz were first conducted to obtain reference values for the sensation level, which was a relative level to the threshold, for each subject. These pure tones were used to produce complex tones comprising two tones: they were centered geometrically on 60 Hz and had frequency differences (Δf, bandwidth) of 30 (47 and 77 Hz), 60 (37 and 97 Hz), 90 (30 and 120 Hz), or 120 Hz (25 and 145 Hz). All the tone pairs started with zero phase difference. Then, the second threshold measurement was conducted for the two-tone complexes with a center frequency of 60 Hz. Figure 1 shows that the sound pressure levels of two tones were set to equal intensity or to equal sensation levels (*SL*s) for individual listeners. For equal sensation levels, the



(a) Equal intensity (b) Equal sensation level

Figure 1. Settings of sound pressure levels of paired components. Equal sensation levels were determined based on thresholds for individual components.

complex tones retained the threshold level difference between two tones during threshold measurement. Therefore, the two tones of complexes had an identical level in terms of detection; thresholds of the tones were independent of frequency. However, the equal intensity indicates only an equal sound pressure level of two tones. The tone duration was 2,000 ms including a rise–fall time of 150 ms. Signals were generated digitally using a personal computer with a sampling frequency of 44.1 kHz with 24-bit resolution.

2.1.2 Procedure

The bracketing method [20] was used to estimate the hearing threshold level. Test tones were presented to the subject repeatedly, their level being varied by 5 dB. The interval between test tones was changed randomly from 1,000 ms to 2,000 ms at every presentation. Subjects were instructed to press a key when they detected a target tone. Five successive runs were conducted four times for each stimulus. The first run was always an ascending series for familiarization and was excluded from the threshold calculation. Consequently, 16 measurement values of threshold were obtained for each stimulus. The median of 16 measurement values was calculated as the threshold level for each subject and complex. The mean and standard deviation of six subjects' thresholds were also obtained.

2.1.3 Apparatus

Measurements were conducted in a low-frequency-sound pressure-field chamber at AIST. The internal dimensions were 2.5 m (W) × 3.5 m (D) × 2.6 m (H). The A-weighted sound pressure level of background noise was about 11 dB at the listener's position, the midpoint of the listener's two ears. The one-third-octave band level of the noise was lower than the normative threshold value [3] by more than 10 dB in the measured frequency range. Stimuli were generated using a D/A converter (UA-1000; Roland Corp.) and fed into a 16-channel sound reproduction system with power amplifiers (IP-300D; TOA Corp.). The tones were presented to listeners via 16 loudspeakers (46 cm diameter, HLS46S-8; TOA Corp.), which were mounted on a vertical wall of the chamber in a two-dimensional four-by-four array. A listener's chair was set 3.15 m distant from the speaker array. The listener sat on the chair, facing the loudspeakers.

2.1.4 Subjects

Four male and two female subjects (35–63 years old; two in their 30s, three in their 40s, and one in his 60s) with normal hearing took part in the experiment. None had any history of hearing difficulty. Each had had many prior experiences with psychoacoustic tasks.

2.2 RESULTS

Thresholds of pure tones for each subject and ISO 389-7 [3] are presented in Fig. 2. The ISO values at frequencies where the international standard does not provide a normative threshold level were derived by linearly interpolating the threshold levels at adjacent frequencies in the standard.

In most cases, thresholds of pure tones were higher than the ISO values, but the level differences were never more than 10 dB. The threshold for S1 was higher at 120 Hz by 13 dB and for S6 was lower at 25 Hz and 30 Hz by about 10 dB than the values listed in ISO 389-7. The threshold for the test tone as a function of frequency was correlated significantly with the ISO threshold ($p<0.01$).

Figure 3 shows threshold levels for two-tone complexes whose components were at an equal intensity. Thresholds in terms of sensation level in decibels on the ordinate indicate the difference in threshold levels between the complex and the pure tone, as obtained by

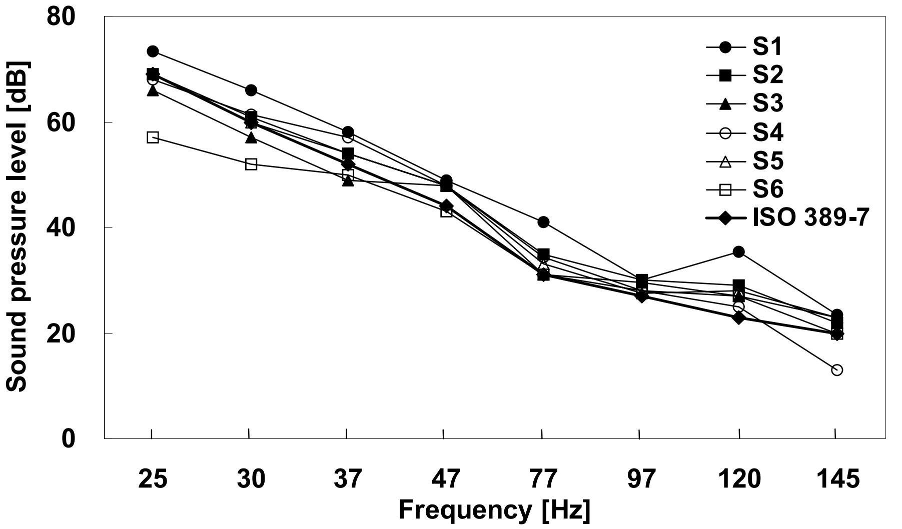


Figure 2. Thresholds for pure tones for each subject (S1-6) and ISO 389-7.

subtracting the threshold level for the pure tone with the same frequency as the higher component from that of the higher component in the complex.

As depicted in Fig. 3, the threshold level differences between the higher component of complex tones and the pure tone with the same frequency as the higher component were less than 1 dB on average; the differences were not indicated as statistically significant ($p > 0.05$) by paired t-tests. Furthermore, analysis of variance revealed no significant difference between complexes ($F = 2.51$, $df = 3, 20$, $p > 0.05$), which indicates that the threshold for the complex with two tones of equal intensity was determined by the higher components, which were at a much higher sensation level than the lower component.

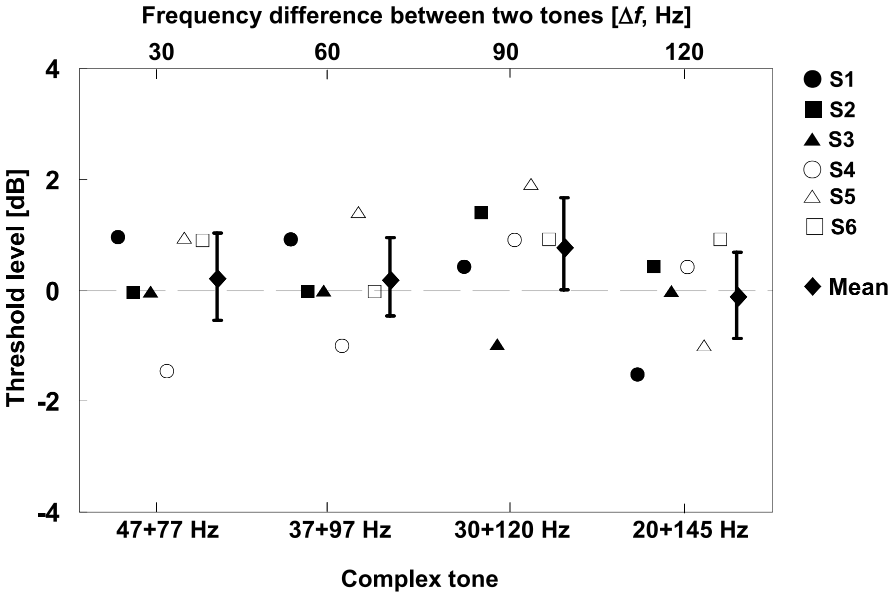


Figure 3. Threshold levels for two-tone complexes whose components were at an equal intensity for each subject (S1-6). Error bars show 95% confidence intervals for the mean. The threshold level on the ordinate was obtained by subtracting the threshold level for a pure tone with the same frequency as the higher component from that of the higher component in the complex.

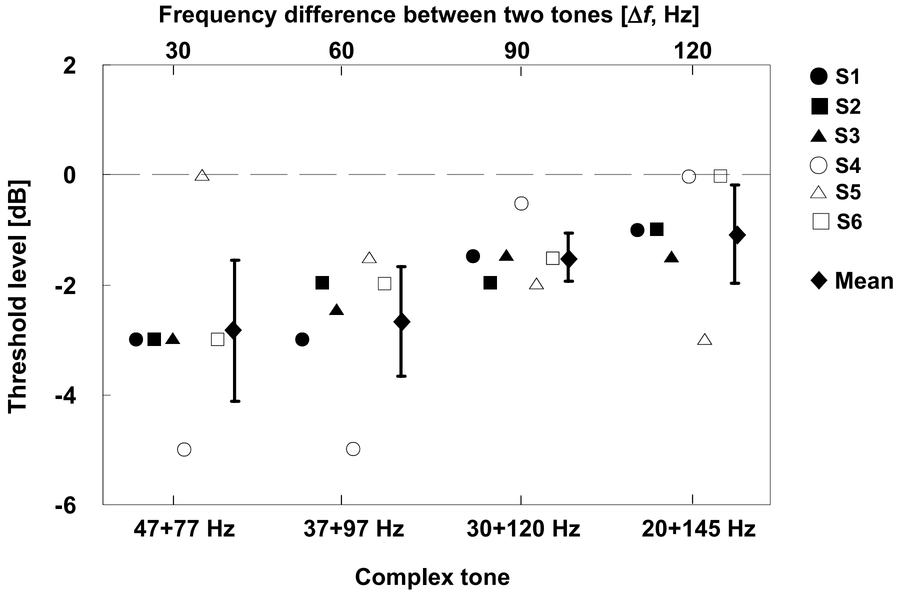


Figure 4. *Threshold levels for two-tone complexes whose components were at an equal sensation level for each subject (S1-6). Error bars show the 95% confidence intervals for the mean. The threshold level on the ordinate was obtained by subtracting the threshold level for a pure tone from that of a component in the complex.*

Figure 4 presents threshold levels for two-tone complexes whose components were at an equal sensation level. Thresholds for most complexes were lower than those for the single components of the complexes. The difference in average thresholds between the complex and the single component was statistically significant for each complex ($p < 0.05$ by paired t-test). Average thresholds of complex (in terms of the level of a component) were lower by about 3 dB than those of pure tones for 47 + 77 Hz and 37 + 97 Hz complexes, and were lower by about 1.5 dB for 30 + 120 Hz and 20+145 Hz complexes, which shows that the complex tone is detectable even if each component is 1.5–3 dB below its threshold in isolation.

3. EXPERIMENT-2

3.1 METHOD

Additional threshold measurements were conducted for complexes comprising 2–6 tones in the 25–145 Hz range. Table I shows composition and bandwidth (Δ*f*, frequency difference between highest and lowest tone) of the complex tones. Test stimuli were five complexes of 25 + 47 Hz, 25 + 47 + 77 Hz, 25 + 47 + 77 + 97 Hz, 25 + 47 + 77 + 97 + 120 Hz, and 25 + 47 + 77+ 97 + 120 + 145 Hz. The bandwidths

Table 1 Composition and bandwidth (Df) of the complex tones

Complex tone		Single tone (Hz)					
	Bandwidth (Δ*f*, Hz)	25	47	77	97	120	145
25-47	22	○	○				
25-77	52	○	○	○			
25-97	72	○	○	○	○		
25-120	95	○	○	○	○	○	
25-145	120	○	○	○	○	○	○

(Δf) of stimuli were, respectively, 22, 52, 72, 95, and 120 Hz. Sound pressure levels of all components for each stimulus were also set to equal sensation levels. Other details such as the procedure and apparatus were identical to those in Experiment-1. Six subjects in Experiment-1 also participated in Experiment-2.

3.2 RESULTS

Figure 5 shows threshold levels for complex tones as a function of the number of tones when the components in the complex were at an equal sensation level. The frequency difference between the lowest and highest tone is also shown on the abscissa of Fig. 5. As presented there, the difference at threshold level between complex and pure tones was statistically significant for each complex ($p < 0.05$, by the paired t-test). The average threshold for complex (in terms of level of a component) was lower by about 4 dB than those of pure tone for the 25–47 Hz and 25–77 Hz complex, by about 5.5 dB for 20–97 Hz and 20–120 Hz complex, and by about 7 dB for 25–145 Hz complex. These results also indicate that people can detect the complex with tones that are lower by 4–7 dB than the threshold in isolation. Figure 5 also shows that as the number of tones increased, the threshold levels for complex the tone (in terms of level per component) decreased for most subjects.

4. DISCUSSION

When two tones were set to be equal in intensity, their threshold level did not significantly differ from that of single tone having the same frequency as the higher-frequency tone in the pair. Therefore, detection of complexes was determined by the higher-frequency components. However, when two or more tones at an equal sensation level

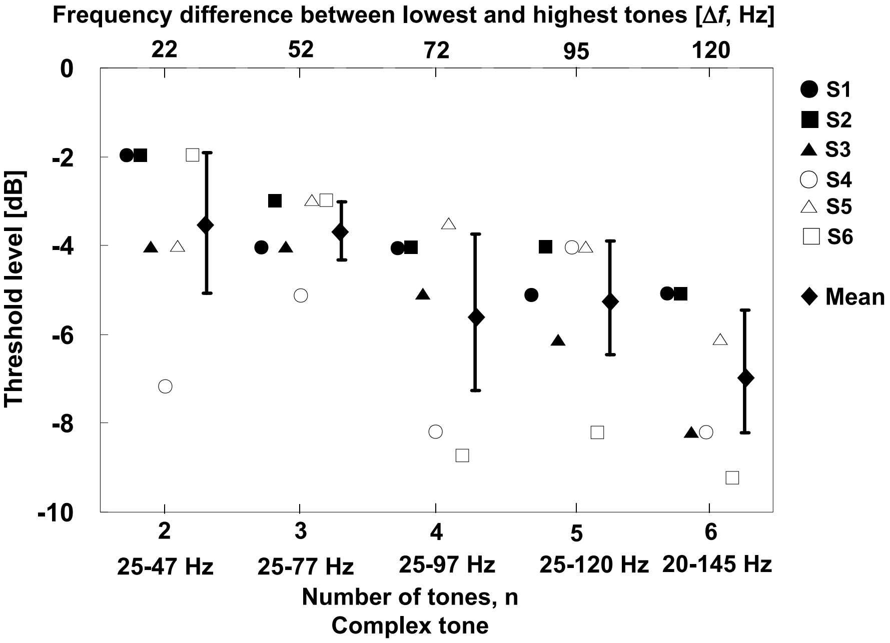


Figure 5. *Threshold levels for complex tones as the number of tones for each subject (S1-6) when the components in the complex were at an equal sensation level. The frequency difference between the lowest and highest tones is also shown on the upper abscissa. The error bars show the 95% confidence interval for the mean. Thresholds on the ordinate were obtained by subtracting the threshold level for a pure tone from that of a component in the complex.*

were separated in the range of a 22–120 Hz frequency difference, thresholds for complexes were significantly lower than those of the component by 1.5–3 dB (see Fig. 6). This improvement in the detection of complexes is consistent with the findings of previous studies not only for middle and high-frequency sounds [7–14] but also for low-frequency sounds below 100 Hz [2,18]. The two results described above indicate that the level difference between two tones strongly influences detection of the complex. In other words, more detectable components between two tones become a main determinant of the detection of the complex. Therefore, the threshold (in terms of level per component) of the complex does not decrease but is instead rather similar to that for more detectable tones. However, for two tones that were equally detectable or had equal sensation levels, the complex detection improved because the probability for detecting two tones increases. Results also show that the threshold for the two-tone complex varied with frequency differences between tones. Thresholds for

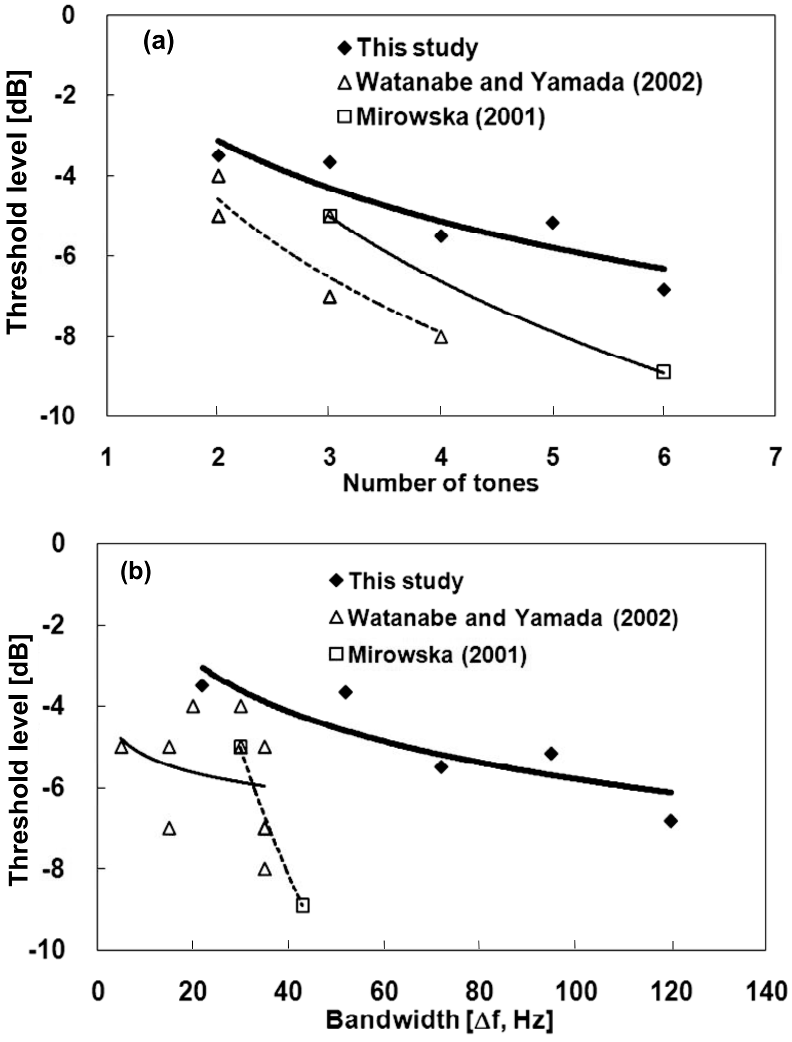


Figure 6. *Threshold levels for complex tones as a function of (a) number of tones and (b) the bandwidth (frequency difference between lowest and highest tone) when components in the complex were at an equal sensation level. Diamonds indicate the mean in the Fig. 5. Lines in figures show the best-fit curves obtained using the method of least squares.*

complexes with a narrower frequency difference (30 and 60 Hz) were slightly lower than those for the other complexes.

These data also show that the threshold levels for complex tones (in terms of the level per component) decreased as the number of tones increased, which is in agreement with results of previous studies [2,18]. Figure 6 portrays threshold levels for complexes as a function of the number of tones and the bandwidth (the frequency difference between the lowest and highest tones) along with data of previous studies [2,18] when components in a complex were at an equal sensation level. Because Watanabe and Yamada [18] did not report threshold levels in terms of the level per component, but the overall level of the complex, the values in Figure 6 of their study were recalculated, assuming that the intensity difference between tones at threshold level of complex was greater than 10 dB. Figure 6(a) shows the results. The threshold levels for complex tones (in terms of level per component) decreased as the number of tones increased. The thresholds of the present study were much higher than those reported in the other two studies. As depicted in Fig. 6(b), bandwidths of complexes for both previous studies were less than 50 Hz, which is similar to the estimated auditory filter bandwidth 35 or 65 Hz [15–17], indicating that a complex with components located near each other in frequency is more detectable than that with components that have more widely separated frequencies.

Figure 6 also shows that the thresholds obtained in the present study and those in Mirowska's study [2] are highly correlated not only with the number of tones but also with bandwidth. This is true because the bandwidth increased concomitantly with increasing number in the two earlier studies. However, the thresholds in Watanabe and Yamada's study [18] correlated with the number of tones well, but not with the bandwidth at all, which indicates that the number of components has a much stronger influence on detection of the tone complex than the frequency difference among tones. This result is also indicated clearly in the results of this study.

Figure 7 shows threshold levels for (a) two tone complexes and (b) two-or-more-tone complexes as a function of the bandwidth when components in a complex were at an equal sensation level in this study. When frequency differences (bandwidths) among components are similar, thresholds (in terms of level per component) for complexes with more than two tones were much lower than those of two-tone complexes, which indicates that, as more tones are found in spectral analysis of low-frequency noise, the hearing threshold for the signal might become lower.

In this study, the threshold levels for complex tones (in terms of the level per component) decreased as the number of tones increased when components in a complex tone were at an equal sensation level. Those might be caused by the function of our auditory system that works as if it could integrate the energy of input sound within a limited range of frequency. The hearing threshold for the complex was found to be determined by the energy summed over the components when the components fall within the bandwidth of an auditory filter [8]. However, this study also found that when two tones were set to be equal in intensity, detection of two-tone complex was determined by the energy of higher-frequency component, but not the energy summed over the components. This is due to the fact that threshold level of higher-frequency component was much lower than that of lower-frequency component. These contrary results indicate that further

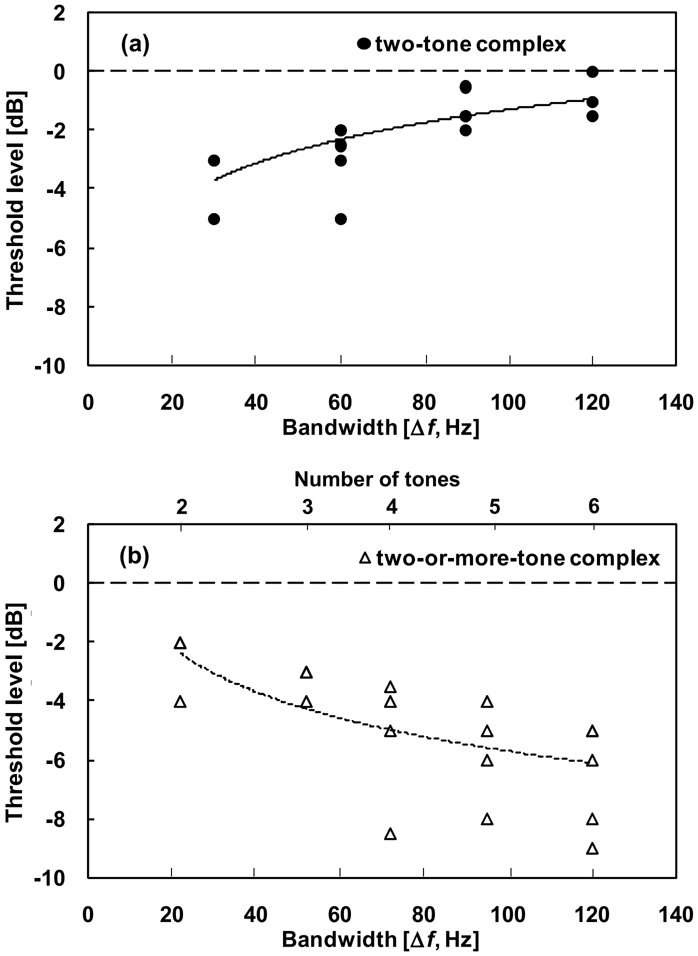


Figure 7. *Threshold levels for (a) two tone complexes and (b) two-or-more-tone complexes as a function of the bandwidth when components in the complex were at an equal sensation level. The number of tones is also shown on the abscissa of Fig. 7(b). All data of subjects are shown except for those of subject-5 (S5) for two-tone complex and the subject-4 (S4) for two-or-more-tone complex, whose data showed very low correlation with others, as shown in Figs. 4 and 5. Lines in figures show the best-fit curves obtained using the method of least squares.*

investigations should be conducted to clarify detection mechanism of low-frequency complex in the future.

5. CONCLUSIONS

To investigate the effects of intensity and frequency difference between components and the number of components on detection of the complexes, hearing thresholds for low-frequency complex tones were measured. Threshold measurements revealed the following.

- Complexes comprising two or more tones in the low-frequency region of less than 150 Hz were detectable even when the sound level of each component was lower than its threshold level.
- Improvement in the detection of the complex signal varied greatly with the sound level difference between tones and the number of tones.
- Threshold levels for a complex tone (in terms of level per component) decreased when the number of tones increased.
- Complex tones with mutually

similar components (in terms of frequency) were more detectable than those with widely separated components.

These data will help elucidate the detection of low-frequency noises in field investigations, which typically assess various combinations of sound levels, frequency separations, and numbers of tones.

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LANDLORDS TO PAY FOR ROWDY TENANTS

Previously, landlords who crammed partying backpackers and students into houses and apartments could ignore complaints about noise, passing them back to tenants who changed so often no one could be held responsible. But in a game-changing move, a noise-abatement order has been served on the owners, rather than their tenants, of a Double Bay (Canberra, Australia) apartment. The downstairs neighbours had complained for years of noise and disturbance. Anyone breaching a noise-abatement order can face fines of up to $5500 as well as charges of contempt of court that could lead to jail terms. For Jean Whittlam, 71, and her son Anthony, 41, the noise-abatement order marks the end of a five-year battle with the owners of the apartment above their flat in New South Head Road, Double Bay. ''We've been told this is the first time anything like this has ever happened," said Mr Whittlam, who said the upstairs flat had been run as a backpacker flophouse. ''It's great ... It gives all of us hope." Landlords John and Sarah Hanna, who own more than 100 properties in the eastern suburbs, denied the allegation. However, Jean Whittlam claimed in court that the tenants were often shouting and singing at night, slamming doors, playing soccer at 2am, swearing, partying and playing loud music. The Hanna's lawyer disputed that the owners could limit the noise because they did not live in the apartment, but the magistrate, Harriet Grahame, ruled they were responsible because they could control who they leased the apartment to, for how long and, if necessary, make physical changes to the property to decrease noise. Colin Grace, of Grace Lawyers, whose firm represented the Whittlams, said this was a landmark decision. ''It means if a landlord has been told about a problem with their tenants but does nothing about it they effectively 'adopt' the problem and are responsible for it." Recent changes in the tenancy laws allowing landlords to demand written consent before tenants can sublet mean owners have even less excuse for not knowing who lives in a property.

WHITTINGTON HIGH-SPEED RAIL CAMPAIGNERS IN NOISE PROTEST

Protesters against the proposed high-speed rail link have been simulating the noise they think the trains would make in a Staffordshire village. The village of Whittington near Lichfield lies on the planned route of the link between London and Birmingham. Residents used speakers to play the sound of a French high-speed train, with noise levels reaching 95 decibels. Transport Secretary Philip Hammond alleged the line, known as HS2, would mean a £44bn boost for the UK economy. Campaigners in Whittington said the noise protest demonstrated some of the sound levels that would be heard in the village, carried on a prevailing wind, equivalent to the 95 decibels of a jet aircraft taking off.

NOISE COSTS CORSHAM STONE FIRM £20,000

A business which breached a notice ordering it to reduce its noise levels has been punished with a maximum fine after Wiltshire Council prosecuted it. Sulis Architectural Ltd, which operates from The Stone Yard, Potley Lane, Corsham, was found guilty at Chippenham Magistrates Court of breaching a noise abatement notice issued by Wiltshire Council. The company, which did not appear at the hearing, was fined the maximum possible penalty, £20,000, and ordered to pay £850 costs to the council.

NOISE POLLUTION IN BEIJING REACHES NEW HIGHS

As Beijing’s noise pollution continue to grow day by day, especially within the crowded Second, Third and Fourth Rings Roads, the government is pushing hard to introduce effective legislation. The Beijing Municipal Environmental Protection Bureau has just issued a report proposing to begin research on how to combat increasingly alarming levels of noise pollution, including prohibiting the use of engines that do not meet reasonable sound standards. Beijing has seen an increase on the whole of up to 1 to 2.3 decibels across the city. Wang Chunlin, head of the Municipal Environmental Protection Bureau, said that as the city tends to grow and develop, increasing sound pollution becomes a more and more serious question that affects all parts of life. City residents have taken their own steps to reduce the effects, with some paying for installation of sound-insulating windows. On the topic of restriction of certain engines, Mr. Wang said that cars which are flagged for breaking the sound limits may be prohibited from driving, a measure which he added “has no international precedent”.