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Effect of the bandwidth of high-frequency sounds (>8 kHz) on loudness

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Abstract

The effects of the bandwidth of high-frequency sounds on loudness are investigated. Loudness matches are obtained using a two-interval, adaptive forced-choice procedure converging on the point of subjective equality by following a simple 1-up, 1-down rule. Loudness increases significantly when the sound has a 1/3 octave band compared with smaller bandwidth sounds, confirming the effect of bandwidth of high-frequency sounds.

1. Introduction

Changes in frequency and bandwidth affect the perceived loudness of a stimulus, even when the intensity is constant [1]. Previous studies have concluded that the loudness of a noise remains constant as the bandwidth of the noise increases up to a critical bandwidth (CB). Thereafter, the loudness increases with increasing bandwidth under the same sound pressure conditions [2,3]. Other studies have indicated that the loudness of a sharply filtered noise increases as the filter bandwidth decreases when the bandwidth of the signal is within the CB, suggesting a tonal component to loudness [4,5]. However, the sounds used in the previous studies were of a frequency between 250 and 5200 Hz.

Recently, it has been warned that very high-frequency sound could cause annoyance, tinnitus, headaches, fatigue and even nausea [6]. Some industrial and commercial appliances generate high-frequency sounds (>8 kHz). These include TV converters [7], functional magnetic resonance imagers and associated equipment [8], dental turbines [9], animal repellents [10] and railway noise [11]. The previous studies show existence of high-frequency sounds (>8 kHz); however, they did not investigate the subjective response to high-frequency sounds [7–9,11]. Most of the sounds used in previous psychoacoustic studies were of a frequency below 8 kHz, and only a few systematic reports have investigated how the humans perceive sounds with a frequency above 8 kHz, leaving this a large gap in our understanding of the primary perception of sounds, such as loudness.

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Therefore, this study evaluates the effects of the bandwidth of high-frequency sounds (>8 kHz) on their loudness.

2. Method

Ten normal-hearing subjects (22–37 years old) took part in the experiment. They all had normal audiological status and no history of neurological diseases. Informed consent was obtained from each subject after the nature of the study was explained. The study was approved by the ethics committee of the National Institute of Advanced Industrial Science and Technology (AIST), Japan.

Pure tones, 1/12, 1/6 and 1/3 octave band noise with center frequencies of 8, 12 and 16 kHz were used. Digitally generated white noise with a sampling rate of 48 kHz was used to produce bandpass noise. The duration of the stimuli used during the experiments was 0.5 s, including linear rise and fall ramps of 10 ms. The sounds were digital-to-analog converted with a 16-bit sound card and sampling rate of 48 kHz. The sounds were presented diotically at a sound pressure level (SPL) of 60 dB through insert earphones (Etymotic Research ER-2) with 29-cm plastic tubes and eartips inserted into the ear canals. To produce a flat frequency response at the eardrum for frequencies up to 16 kHz and minimize variability due to earphone placement, the insert earphones were used in this study. The transfer function of the whole setup, which was measured with an ear simulator (Brüel & Kjær Ear Simulator Type 4157) that included a microphone, a preamplifier and an adaptor connected to the eartip, showed bandpass characteristics with a bandwidth from approximately 500 to 5000 Hz. To account for the transfer characteristics of the transmission system, the amplitude of each spectral component was multiplied by a factor compensating for the system's frequency-specific loss in SPL, preserving the original spectral profile of the stimuli.

Loudness matches were obtained using a two-interval, adaptive forced-choice (2AFC) procedure converging on the point of subjective equality (PSE) by following a simple 1-up, 1-down rule [12] in an anechoic and soundproof room. In each trial, the fixed (test) and variable (reference) sounds were presented in a random order with equal, a priori probability, separated by a 500-ms pause. The test sound was a pure tone or bandpass noise and the reference sound was a 1-kHz pure tone. The subject's task was to indicate which sound was louder by pressing a key. For each adaptive track, the overall level of the test sound was fixed at 60 dB SPL and the starting level of the reference sound was 50 dB SPL. The level of the reference sound was controlled by an adaptive procedure: whenever the subject judged the reference sound to be louder than the test, its SPL was lowered by a given amount; whenever the subject judged the test sound to be louder, the SPL of the reference sound was increased by that same amount. The initial step size was 5 dB; after two reversals (that is, changes in the direction of the adaptive track), it was decreased to 2 dB. A total of 12 reversals were collected for each adaptive track; the arithmetic mean of the last four was used to estimate the PSE.

The effects of stimulus parameters (the center frequency and the bandwidth) on the perceived loudness were statistically analyzed by a repeated-measure analysis of variance (ANOVA) with two within-subject factors: center frequency × bandwidth. Where appropriate, probabilities were adjusted by the Greenhouse–Geisser correction. Post-hoc comparisons were carried out using the Newman–Keuls test.

3. Results

Fig. 1 shows the SPL that was required for the 1-kHz pure tone to balance the loudness of the stimuli presented at a SPL of 60 dB in the higher-frequency range (>8 kHz). Perceived loudness decreased with increasing center frequency. The main effects of the center frequency ($F(2, 18) = 43.44$, $p<0.001$) and bandwidth ($F(3, 27) = 9.26$, $\varepsilon = 0.597$, $p<0.005$) on the loudness were significant. The interactions between center frequency and bandwidth were not significant ($F(6, 54) = 1.30$, $p = 0.27$).

4. Discussion and conclusions

Previous research has indicated that perceived loudness remains constant provided the bandwidth of a sound is less than the CB, but that loudness increases with increasing bandwidth if the bandwidth is increased beyond the CB at center frequencies of 500, 1000 and 2000 Hz [2,4]. The CB calculated as a function of center

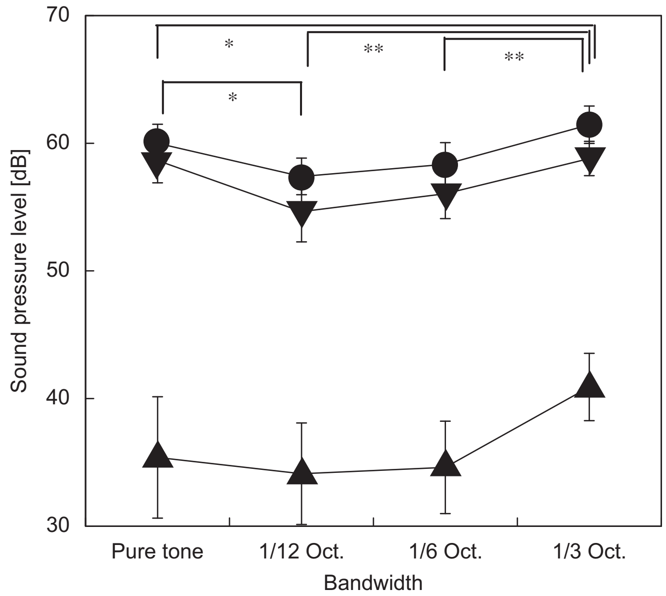

Fig. 1. SPLs for a 1-kHz reference pure tone as a function of bandwidth for (●) 8 kHz, (▼) 12 kHz and (▲) 16 kHz stimuli. The asterisks indicate statistical significance (* $p<0.05$, ** $p<0.01$; post-hoc Newman–Keuls test).

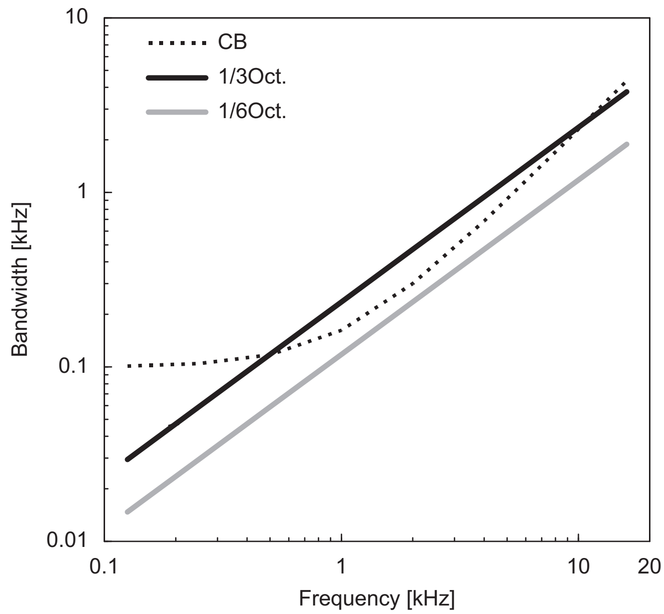

Fig. 2. Comparisons of CB, 1/3 octave and 1/6 octave bandwidths.

frequency [13] is represented by the dotted line in Fig. 2. At a center frequency of 8.5 kHz, loudness increases clearly for a bandwidth larger than 700 Hz, which corresponds to between 1/12 and 1/6 octave bandwidth [14]. In this study, the loudness significantly increased when the bandwidth was 1/3 of an octave compared with smaller bandwidth sounds. The loudness increased more rapidly between 1/6 and 1/3 octave bandwidth than between 1/12 and 1/6 octave bandwidth. This is roughly consistent with the previous finding at a center frequency of 8.5 kHz [14].

In this study, the pure tone judged louder than the 1/12 and 1/6 octave band noise at center frequencies of 8 and 12 kHz. This is consistent with previous findings at center frequencies of 0.25, 0.5, 1 and 2 kHz [4,5]. The increase in loudness of a pure tone might reflect the effect of a tonal component to loudness. At a center frequency of 16 kHz, the loudness of the pure tone was approximately the same as that of the 1/12 and 1/6 octave band noise. This result might be due to audible frequency range. Absolute thresholds increase rapidly for frequencies above 15 kHz [15]. Broader bandwidth sounds include lower frequency components that have lower thresholds. Thus, the effect of a tonal component might be weakened at a center frequency of 16 kHz.

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References

[1] W.A. Yost, *Fundamentals of Hearing; An Introduction*, Academic Press, San Diego, 2000.
[2] E. Zwicker, G. Flottorp, S.S. Stevens, Critical bandwidth in loudness summation, *Journal of the Acoustical Society of America* 29 (1957) 548–557.
[3] B. Scharf, Loudness summation and spectrum shape, *Journal of the Acoustical Society of America* 34 (1962) 228–233.
[4] S. Sato, T. Kitamura, Y. Ando, Loudness of sharply (2068 dB/Octave) filtered noises in relation to the factors extracted from the autocorrelation function, *Journal of Sound and Vibration* 250 (2002) 47–52.
[5] Y. Soeta, T. Maruo, Y. Ando, Annoyance of bandpass filtered noises in relation to the factor extracted from autocorrelation function, *Journal of the Acoustical Society of America* 116 (2004) 3275–3278.
[6] Health Canada, *Guidelines for the Safe Use of Ultrasound: Part II—Industrial and Commercial Applications, Minister of National Health and Welfare, EHDTR-158*, Canadian Communication Group, Ottawa, 1991.
[7] B.W. Lawton, Damage to human hearing by airborne sound of very high frequency or ultrasonic frequency, *Contract Research Report* 343 (2001) (Health and Safety Executive).
[8] M.E. Ravicz, J.R. Melcher, N.Y.S. Kiang, Acoustic noise during functional magnetic resonance imaging, *Journal of Acoustical Society of America* 108 (2000) 1683–1696.
[9] E. Sorainen, E. Rytkönen, High-frequency noise in dentistry, *Journal of Occupational and Environmental Hygiene* 63 (2002) 231–233.
[10] K. Ashihara, K. Kurakata, T. Mizunami, K. Matsushita, Hearing threshold for pure tones above 20 kHz, *Acoustical Science and Technology* 24 (2003) 398–399.
[11] M. Hiroe, High frequency sounds radiated from rails, *Proceedings of the International Congress on Acoustics* IV (2004) 3223–3226.
[12] H. Levitt, Transformed up–down procedures in psychophysics, *Journal of the Acoustical Society of America* 49 (1971) 467–477.
[13] E. Zwicker, E. Terhardt, Analytical expressions for critical-band rate and critical bandwidth as a function of frequency, *Journal of the Acoustical Society of America* 68 (1980) 1523–1525.
[14] H. Fastl, Loudness and masking patterns of narrow noise bands, *Acustica* 33 (1975) 266–271.
[15] L.A. Han, T. Poulsen, Equivalent threshold sound pressure levels for Sennheiser HDA 200 earphone and etymotic research ER-2 insert earphone in the frequency range 125 to 16 kHz, *Scandinavian Audiology* 27 (1998) 105–112.