How high-frequency do children hear?

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ABSTRACT

In industrial fields, sound waves above 20 kHz, known as ultrasonic waves, are widely applied to sensors, medical devices, welding equipment, and cleaning equipment. Recently, high-frequency sound waves around 20 kHz have been used for mouse-repelling devices and youth-repelling machines, and many such devices have been installed in public spaces. These devices generate sound waves that produce a nearby sound pressure level of 100dB or above. Furthermore, such sounds as those of turbines for dental treatment and railways sometimes have very high frequency. Therefore, we are exposed to many high-frequency sound waves in our daily lives. Although some past studies addressed the high-frequency (exceeding 10 kHz) hearing threshold, many of them were conducted on 20 year old adults. Almost nothing is known about the effect of high-frequency sound waves, including ultrasonic waves, on infants and children. Therefore, this study measured pure-tone hearing thresholds for sounds ranging from 1kHz to 32kHz with kindergarteners, primary schoolchildren, and junior high students (ages 6 to 15 years) . The thresholds could be obtained from all children at less than 22 kHz. Even at 26 kHz, threshold levels were lower than 100 dB(SPL) for 40 % of the children.

Keywords: High Frequency Noise, Children,
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1. INTRODUCTION

In industrial fields, sound waves above 20 kHz, known as ultrasonic waves, are widely applied to sensors, medical devices, welding equipment, and cleaning equipment. Recently, high-frequency sound waves around 20 kHz have been used for rodent-repelling devices and youth-repelling machines, and many such devices have been installed in public spaces1. These devices generate sound waves that produce a nearby sound pressure level of 100dB or above. Furthermore, such sounds as those of turbines for dental treatment and railways sometimes have very high frequency1,2. Therefore, we are exposed to many high-frequency sound waves in our daily lives.

Although some past studies addressed the high-frequency (exceeding 10kHzt) hearing threshold, many of them were conducted on 20 year old adults3-5. Almost nothing is known about the effect of high-frequency sound waves, including ultrasonic waves, on infants and children.

Therefore, this study measured pure-tone hearing thresholds for sounds ranging from 1kHz to 32kHz with kindergarteners, primary schoolchildren, and junior high students (ages 6 to 15 years) .

2. MEASUREMENT OF HEARING THRESHOLD

2.1 Stimuli and experimental equipment

Measurement of pure-tone hearing thresholds was conducted in a soundproof room. Frequencies used for sound stimuli were 1 kHz, 2 kHz, 4 kHz, 8 kHz, and from 12 kHz to 32 kHz at intervals of 2 kHz. Sound stimuli consisted of intermittent sounds obtained from a sine wave by applying window-function processing to it with 200 ms of onset, 200 ms offset, and 600 ms of stationary wave; this was presented repeatedly at intervals of one cycle per second. Cosine windows were used for onset and offset. Sound stimuli were prepared as digital signals with a sampling frequency of 96 kHz, and 16 quantifying bits were generated at the USB audio interface (EDIROL, UA-101) after amplitude adjustment using digital processing. The stimuli were then presented using a speaker or super tweeter via an audio amplifier (ACCUPHSE, E212) from the right lateral direction of the participant at a distance of 500 mm from the entrance of the external auditory canal of the left ear (Figure1).

A desk for operation of the mouse was placed in front of the participant, and an LCD display to give instructions was placed 800 mm in front of the participant. Although the pure-tone hearing threshold near frequencies of 2 kHz or 4 kHz sometimes goes below the sound pressure level of 0 dB, the threshold near the frequency of 20 kHz may exceed 90 dB. Because sound stimuli are 16-bit digital signals, the theoretical dynamic range is 98 dB; as a result, measurement of thresholds above the frequency range of 1 kHz to high frequencies above 20 kHz is difficult with only amplitude adjustment using digital processing.

Therefore, measurement of both thresholds below the sound pressure level of 0dB in the low-frequency range and those exceeding the sound pressure level of 90 dB in the low-frequency range was enabled by varying the audio amplifier gain by 30 dB between measurement in the range of 1 kHz to 14 kHz and that in the range of 16 kHz and above. Sound stimuli of 1 kHz to 14 kHz were presented using a speaker (VICTOR, SX-V05), and sound stimuli over 16 kHz were presented using a super tweeter (PIONEER, PT-R100) via a high-pass filter (PIONEER , DN-100). Frequency characteristics of the speaker and super tweeter were measured previously using a 1/4inch microphone(Brüel & Kjær, Type4939) of that sound pressure level is calibrated up to 100 kHz with audio amplifier gain fixed. Therefore, it was possible to determine the presenting sound pressure level at all testing frequencies by simply adjusting the sound pressure level at the hearing positon while emitting a 1 kHz pure tone (continuous tone) from the speaker.

Based on data obtained in the past4,5, it can be assumed that the threshold in the high-frequency band above 20 kHz exceeds a sound pressure level of 80 dB, depending on the case. To measure such a threshold, it is necessary to present a pure tone at a sound pressure of nearly 90 dB. However, when attempting to present a test tone of such a high level, distortion due to the nonlinearity of the speaker may occur in the audible band and may be detected by the participant6.

Therefore, to determine whether or not any detectable sub-harmonic distortion is generated, power spectra of the test tone at a distance of 500 mm in front of the super tweeter were observed.
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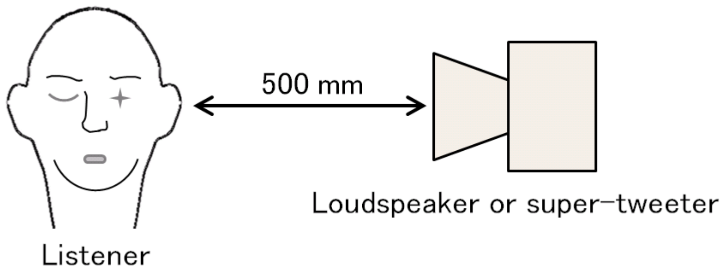


Figure 1 – Listener and sound source:

Acoustic stimuli were presented to the listener through a loudspeaker or super-tweeter that was placed at a distance of 500 mm from the listener's left ear.

2.2 Participants

Participants consisted of twenty-five children aged 6 to 15 years, including eight female children. Prior to the test, informed consent was obtained from all participants and their parents. This test has passed examination by the Ergonomics Experiment Ethical Review Board of the National Institute of Advanced Industrial Science and Technology.

2.3 Procedure

Measurement of pure-tone hearing thresholds was conducted using the method of limits of ascending series. With the method of limits, measured values are apt to be influenced by cognitive bias, such as prediction and belief; the method of constant stimuli or the method of adjustment is often adopted to avoid this bias. However, these methods require several trials to obtain a single measured value and thus require much time. Because the present test involved young children, measurement over a long time was difficult. Thus, we adopted the method of limits, which enables acquisition of the threshold within a short time. To determine whether or not the participant's response was reliable, catch trials were inserted, depending on the circumstances.

First, the participant was given sound stimuli at a sufficiently audible level and then told, "Click the mouse when this sound begins to be audible. Do not move your head during the measurement. Do not worry if no sound is heard at all." Thereafter, measurement was performed using the method of limits with ascending series starting at the non-audible level.

The sound level was increased at 3 dB intervals. Since the participant clicked the mouse when sound stimuli begin to be heard, the level presented at that time was adopted as the measured value. When the mouse was clicked, sound stimuli were presented once more at a level that was 3 dB stronger than the measured value for confirmation; this process was defined as one trial.

To measure thresholds, at least two trials but as many as four to five trials, depending on the circumstances, were repeated at each frequency to confirm reproducibility.

When the participant was a child in the elementary school upper grades or junior high, measurement was conducted with the participant alone in the soundproof room. When the participant was a kindergartener or a lower-grade child and we assumed that measurement with the participant alone would be difficult, measurement was conducted with a parent accompanying the participant in the soundproof room.

3. RESULTS

3.1 Power-spectra of stimuli

If the super tweeter generates any sub-harmonic distortion detectable from the hearing position, it is difficult to judge whether the participant is responding to the sound stimuli or the distortion. Therefore, to investigate how much distortion was generated when sound stimuli were presented, sound stimuli were presented from the super tweeter in the absence of the participant, recorded using a recorder installed 500 mm in front of the super tweeter, and subjected to frequency analysis.

As a result, a non-ignorable level of distortion was sometimes observed when the sound-pressure level neared 100 dB. An example of the power spectrum of a 28 kHz pure tone is presented in Figure 2. In the left figure shows, the sound-pressure level of the sound stimuli is102 dB; in the right figure shows, it is 90 dB. When the sound-pressure level is 102 dB, some distortion occurs at frequencies of 12 kHz (arrow in the figure). Such distortion cannot be observed when the sound-pressure level is 90 dB.

Figure 3 shows the power spectra of a 24 kHz pure tone and a 26 kHz pure tone at a sound-pressure level of 90 dB. There was no distortion that obviously exceeded the background noise level. Analysis of the sound stimuli from 16 kHz to 32 kHz indicated no sub-harmonic distortion detectable at a sound pressure level of 90 dB.

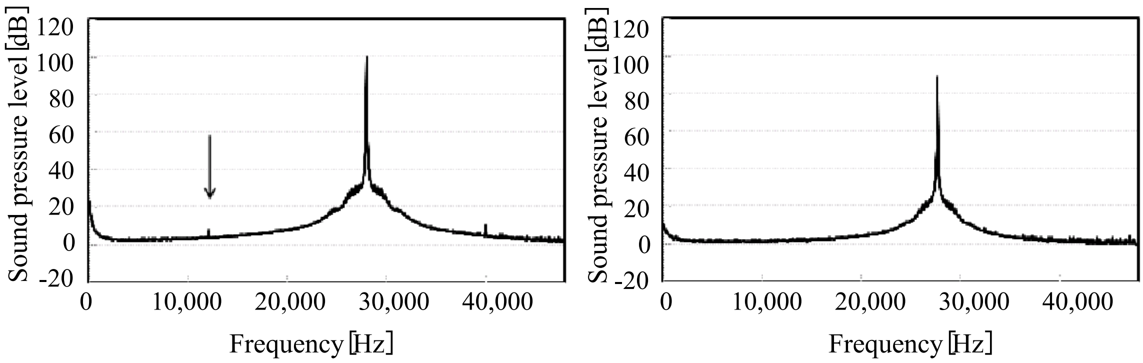


Figure 2 – Power-spectra of 28 kHz tone:

Power -spectra of a tonal stimulus at 28 kHz are shown. The sound pressure level of the tone was 102 dB(left) and 90 dB(right).

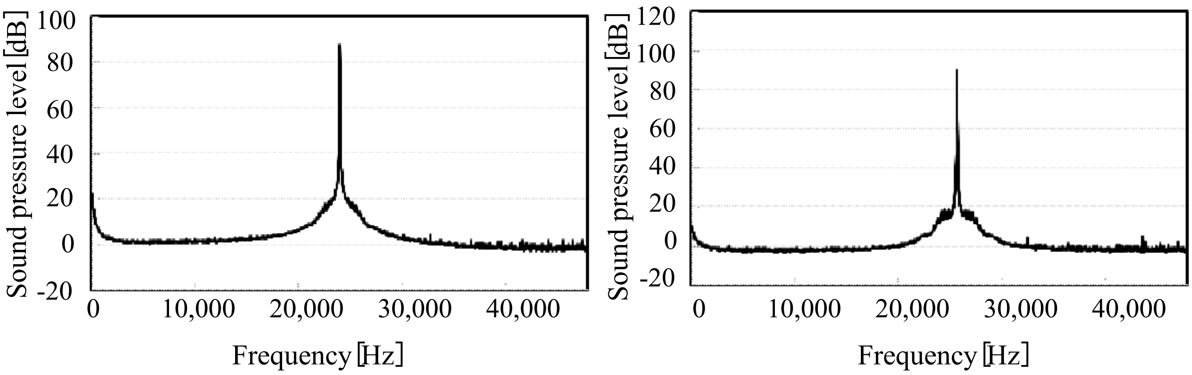


Figure3 – Power-spectra of tonal stimuli:

Power-spectra of tonal stimuli at 24 kHz(left) and 26 kHz(right) are shown. The sound pressure level of the tone was 90 dB. These power-spectra were obtained by a 4096-point FFT.

3.2 Pure-tone hearing threshold

To measure the threshold, two or more trials were conducted at each frequency, and the average of measured values was determined as the threshold. Furthermore, any measured value that exceeded a sound-pressure level of 90 dB even once was scaled out. As described above, measured values using the method of limits are strongly influenced by cognitive bias. Therefore, to determine whether or not a participant's response was reliable, catch trials were used. A catch trial is the same as an ordinary trial, except no sound stimuli are presented. Therefore, when participants respond based on their predictions and beliefs, their responses also appear during catch trials. In this study, some participants made such responses during catch trials. Data of these participants were discarded, due to their low reliability.

Figure 4 presents the thresholds of 21 participants (including seven female participants); four were judged to be unreliable and were excluded. These participants were grouped as follows: ages 6 to 8 (five participants), ages 9 to 11 (nine participants), and ages 12 to 15 (seven participants). Here, × indicates the thresholds of the male participants, and ○ indicates those of the female participants. The solid line in the figure represents the threshold of a healthy person who hears a pure tone in a free-sound field, as specified in ISO 389-77.

During the test in this study, thresholds of all participants could be measured at frequencies of 18 kHz or less. At 20 kHz, the thresholds of eight participants were scaled out. Although the thresholds at 2 kHz and 4 kHz are higher than the values indicated in ISO, the thresholds of many participants were less than the values of ISO at frequencies above 12 kHz (Figure 4).

Thresholds at 2 kHz and 4 kHz may have been higher than the values in ISO because the measurement environment for this test is a soundproof room, where the background noise level is higher than in a free sound field (anechoic room). In other words, the lower limit of the measured value may be governed by the background noise level of the room. Furthermore, the background noise level seemed to be higher when the participant entered the room accompanied by his or her parent. Indeed, one participant expressed dislike regarding the presence of a parent, saying “Myself alone is better; another person is noisy.”

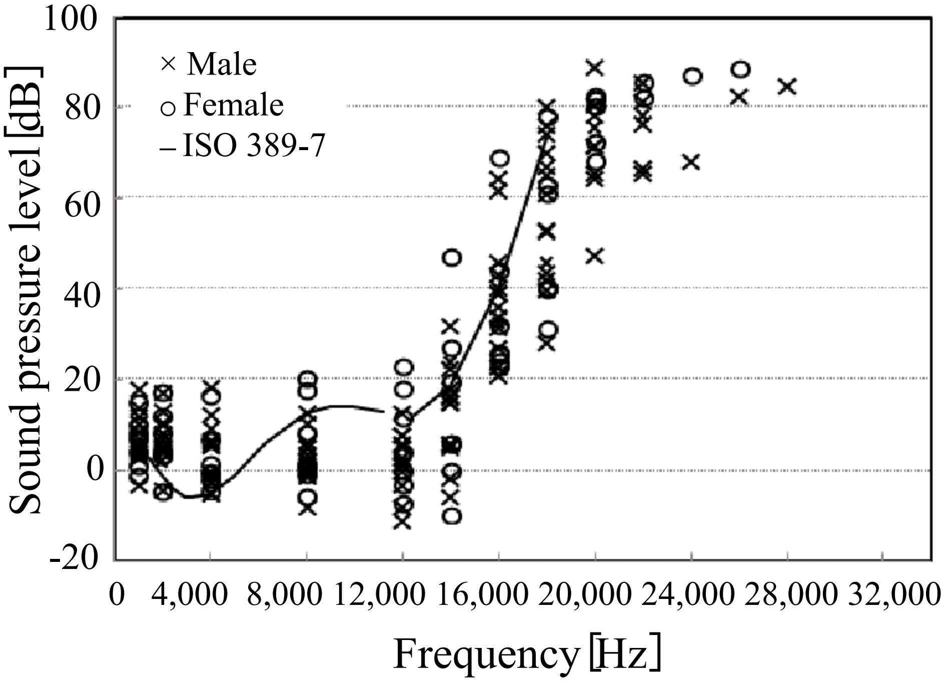
A speaker as the sound source was placed in front of the participant at a distance of 1m or more for measuring the threshold indicated in ISO. However, the sound source in this test was installed to the left of the participant 500 mm from the ear to secure a sufficient sound pressure level of 90 dB or above at the hearing position. When the sound source is placed in front of the participant, sound is heard by both ears; however, during this test, it can be assumed that the threshold measured was that of the left ear in most cases. The threshold decreases by several decibels when sound stimuli are heard by both ears, compared to that when stimuli are heard by a single ear8.

Participants were instructed not to move the head if possible during measurement of thresholds; however, no headrest or other support was used. Therefore, the position and direction of the heads of some participants fluctuated greatly during the measurement.

These factors are assumed to have made the measured value higher than the actual threshold. Thresholds lower than the values of ISO were observed in many cases in the high-frequency band over 12 kHz, in spite of these negative factors; this result indicates the hearing thresholds of children are lower than those of adults in the high-frequency band. While the threshold at 18 kHz indicated in ISO is a sound pressure level of 73.2 dB, only four of the twenty-one cases in this study exceeded this value, even when the highest threshold recorded was 80.2dB. However, the lowest threshold recorded was 28.2 dB, which was 45 dB lower than the ISO value. The average of the participants was 55.0 dB, which was 18 dB lower than the ISO value. Even at 20 kHz, which is commonly assumed to be the upper limit of audible frequency, the threshold was less than the sound pressure level of 80 dB in half of the total cases, with seven participants scaled out.

If the super tweeter generates any sub-harmonic distortion detectable from the hearing position, it is difficult to judge whether the participant is responding to the sound stimuli or the distortion. Therefore, to investigate how much distortion was generated when sound stimuli were presented, sound stimuli were presented from the super tweeter in the absence of the participant, recorded using a recorder installed 500 mm in front of the super tweeter, and subjected to frequency analysis.

After the test, participants commented that higher-frequency sounds felt noisier and were unpleasant. When sound stimuli over 16 kHz were presented, one participant complained of ear pain even though the sound pressure level was low.



Figur 4 – Children's hearing threshold:

Hearing threshold values of each listener are shown as a function of frequency. A solid line represents the adults' threshold specified in ISO 389-7.

4. DISCUSSION AND CONCLUSIONS

During the test conducted on children aged 6 to 15 years, values commonly lower than the thresholds indicated in ISO were observed, especially at frequencies of 14 kHz, 16 kHz, and 18 kHz. The ISO value is based on the values measured on healthy 20 year olds. Therefore, the results obtained from this study suggest that the ability of children to hear in the high-frequency band begins to deteriorate in less than 10 years until they grow up. We will continue to obtain such psychological and physiological knowledge in the future. Furthermore, although high-frequency sounds, including ultrasonic waves, are utilized in various products, especially in public spaces, it is important to consider not only the hearing ability data of adults but also that of children when designing, installing, and operating those products. Therefore, it is also necessary to consider sounds with frequencies that have been assumed to be in the ultrasonic band as being audible.

In the future, we will investigate the psychological and physiological influences of the sound generated on children and youths and then examine the feasibility of a more effective countermeasure.

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