

PAPER

Audibility of pure tones presented against domestic sounds: Comparison of ratings between young and older adults for auditory-signal design

Kenji Kurakata^{1,*}, Tazu Mizunami¹ and Kazuma Matsushita²

¹National Institute of Advanced Industrial Science and Technology (AIST),
AIST Tsukuba Central 6, 1-1-1 Higashi, Tsukuba, 305-8566 Japan

²National Institute of Technology and Evaluation (NITE),
2-49-10, Nishihara, Shibuya-ku, Tokyo, 151-0066 Japan

(Received 8 July 2009, Accepted for publication 27 November 2009)

Abstract: The audibility of pure tones presented against typical domestic sounds was investigated in a psychoacoustic experiment conducted with young and older listeners. The sound pressure levels of pure tones were varied at several signal-to-noise ratios to find a range of auditory signals that are audible and comfortably loud in noisy conditions. Ratings of the listeners were analyzed in terms of A-weighted sound pressure levels and 1/3 octave band levels of the target tones and background noises. The results revealed that both listener groups assigned similar ratings to various combinations of pure tones and domestic sounds. However, when the tone frequency was 2,000 Hz or higher, older listeners needed a higher tone level to attain a certain level of audibility. On the basis of the results, the authors propose sound-level ranges of auditory signals for consumer products intended for users of various ages and for users who might have age-related hearing loss.

Keywords: Auditory signal, Audibility, Domestic sound, Aging effect, Consumer product

PACS number: 43.66.Dc, 43.66.Sr [doi:10.1250/ast.31.239]

1. INTRODUCTION

Consumer products such as electric home appliances incorporate auditory signals in their user interfaces. Auditory signals are sounds that notify a user that the product has finished its task or that it has malfunctioned. Such signals are expected to improve the usability of products because the user can leave a product unsupervised while it is operating, yet remain informed of its progress. Moreover, they are indispensable for older users who are not accustomed to using such products and for visually impaired people who must manage appliances solely by responding to auditory signals.

However, auditory signals sometimes become difficult to hear or become completely inaudible in noisy environments. Loud domestic sounds in a user's surroundings can mask signals and affect their audibility. For instance, the sounds of cooking or washing dishes can mask auditory signals of kitchen appliances.

A possible countermeasure would be to raise the sound level of an auditory signal so that the signal becomes

distinct against background noise. However, overly loud signals can be unpleasant to users and other people. People would accept a loud signal for emergency purposes, such as fire alarms in public areas, but not for products intended for everyday use in the home. It is desirable that auditory signals for consumer products be adjusted to a level at which they do not sound overly loud, but which assures adequate audibility in noisy environments.

When determining a suitable level of signals, we must be mindful of the possibility that the user might have age-related hearing loss. Older people have more difficulty in hearing a target sound under noisy conditions than young people do. One reason is that the frequency selectivity of hearing, which is related to the ability to discern one sound component from others, declines with age [1], as reflected in the measurement of the auditory-filter bandwidth [2,3] or psychoacoustic tuning curves [4]. Domestic appliances are often used by family members of different ages. Auditory signals from such appliances must be audible to older users and yet not be too loud for young users.

Although auditory signals have often been used in various electric consumer products, no definite criterion for their sound levels has been established, except for a DIN

*e-mail: kurakata-k@aist.go.jp

Technical Report (TR) [5], which states: “[w]here the background noise of the surroundings is loud, acoustic signals should differ significantly from the noise of the surroundings both in terms of sound level and frequency spectrum. The signal-to-noise ratio should be at least 10dB(A).” In *Design for All*, as its title suggests, this sound level criterion was determined considering the hearing-ability decline of senior citizens.

ISO 7731 [6] specifies methods for adjusting the sound level of danger signals for public and work areas on the basis of signal-to-noise ratio (SNR) measurements. Danger signals in those areas are expected to have a high sound level to ensure detectability over noise for occupants including those with hearing impairments. Although auditory signals for consumer products might be determined using a similar measurement method, the criteria can be moderate. Otherwise, the signals would be annoyingly loud for users of those products.

Therefore, another set of criteria should be established to determine the sound level of auditory signals for consumer products. In its establishment, the following two factors must be examined: (1) the effect of masking by domestic sounds and (2) the age-related hearing-ability decline of older product users.

Furthermore, for the adjustment of the signal level with higher precision, signals and noises should be analyzed in terms of frequency-band levels, in addition to the A-weighted sound pressure levels as is done in the DIN TR [5]. The A-weighted sound pressure level can be measured easily using a conventional sound level meter. The SNR that is necessary for auditory-signal perception depends on both the signal and the noise frequency characteristics. The signal levels can be determined more precisely if a frequency-band analysis is introduced, as Laroche *et al.* [7] did in their model for predicting the detectability of warning signals in noisy workplaces. ISO 7731 also uses a frequency-band analysis.

In this paper, the authors propose sound-level ranges of auditory signals generally used for consumer products, which require different audibility criteria than danger signals for public and work areas. The ranges were determined taking the effects of masking by various domestic sounds and the age-related hearing loss of older users into consideration. The A-weighted sound pressure level measurement and the 1/3 octave band level measurement are employed for adjusting the level of auditory signals since both of them are widely used for sound-level measurements. To find a suitable signal-level range, we conducted a psychoacoustic experiment in which young and older adults evaluated the audibility of pure tones in the presence of various domestic sounds. The results of the experiment are reported to show how the level range of auditory signals was estimated.

2. EXPERIMENT

2.1. Method

Stimuli Seven domestic sounds were selected from a sound database and used as background noises [8,9]. They were typical sounds present in Japanese homes and were generated by the following electric appliances or by a person doing housework: (1) washing dishes in a kitchen sink, (2) a ventilation fan in the kitchen, (3) a clothes washing machine, (4) a hair dryer, (5) running water from a shower in a bathroom, (6) a television set, and (7) a vacuum cleaner in a living room.

Figure 1 presents long-term averages of 1/3 octave band levels of the above sounds. The levels were analyzed using a real-time analyzer (DS-9110, DS-0923; Ono Sokki Co., Ltd.) with 1/3 octave band filters that conformed with the relevant IEC standard [10]. Two portions, each with duration of 7 s, were extracted arbitrarily for each time-varying sound from the original recording (1 min) in the database to generate 14 noises in total. The onset and offset of the noises were tapered with a 10 ms ramp to avoid abrupt changes in the sound level.

Target tones were pure tones repeated three times with a 1 s silent interval. The duration of each tone was 1 s with a rise-fall time of 10 ms. The frequencies were 250, 500, 1,000, 2,000, and 4,000 Hz. The sound pressure levels were adjusted to five different values from -10 to 30 dB in 10 dB steps relative to the 1/3 octave band level of each domestic sound at the same center frequency as the target tone. Consequently, the total number of stimulus conditions was 350 (5 frequencies \times 5 levels \times 14 backgrounds).

The background noises and the target tones were reproduced from a personal computer using a 44.1 kHz sampling frequency and 16-bit resolution. They were subsequently amplified using a power amplifier (FA50ES; Sony Corp.) and were presented to the listener through a loudspeaker (DS-205; Mitsubishi Electric Corp.) in a soundproof room. The listener's chair was set 2.5 m from the loudspeaker. Frequency characteristics of the sound reproduction system were corrected to be flat (± 1.5 dB for 125–8,000 Hz) at the listener's position, using a digital equalizer (AMQ1; Yamaha Corp.). The A-weighted sound pressure level of each background noise was adjusted as designated in the database to reproduce its original recorded level. Those presentation levels, L_{Aeq} , in decibels (A-weighted) are presented in Fig. 1. Because the sound volume of the TV set varied, its A-weighted level was set at 50 dB on the basis of an experimental result for preferred listening levels of TV programs [11].

Procedure The stimulus sounds were presented to listeners one by one in random order. After each presentation, the listener rated the audibility of the target tone against the background noise and answered orally.

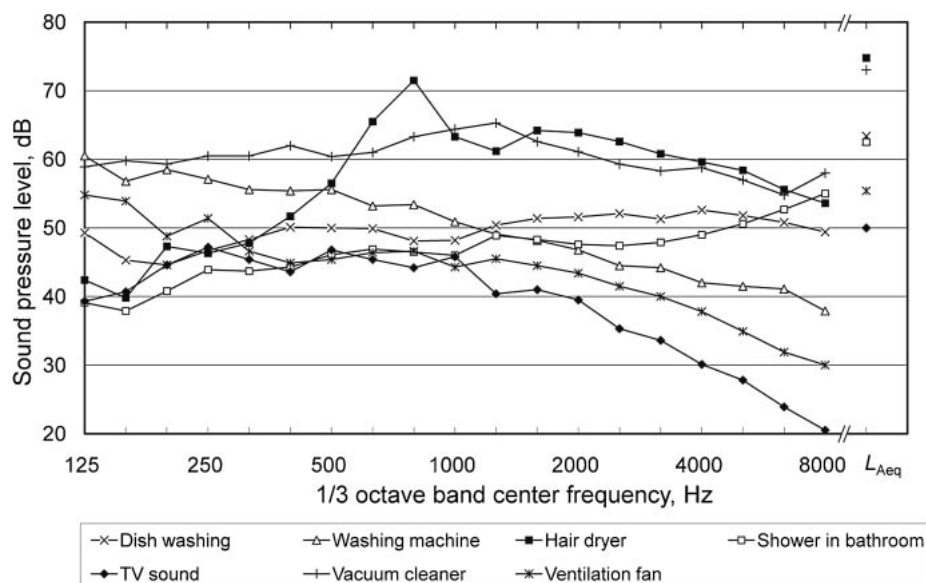


Fig. 1 1/3 octave band levels and A-weighted sound pressure levels of domestic sounds used in psychoacoustic experiment.

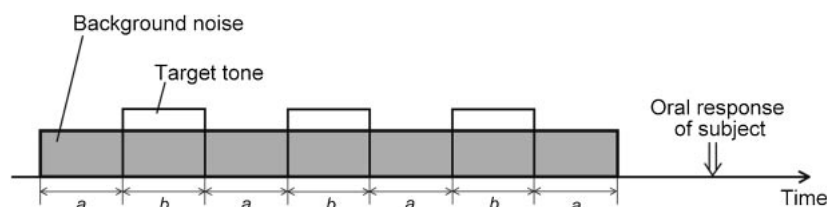


Fig. 2 Schematic illustration of stimulus presentation: $a = b = 1$ s.

The time sequence of the procedure is portrayed schematically in Fig. 2.

The rating was performed on a five-point scale: 5. “too loud”; 4. “loud”; 3. “audible”; 2. “barely audible”; and 1. “not audible.” Every listener made one judgment for each stimulus. When the listener was uncertain about a judgment, the stimulus sound was presented again on request.

Listeners Young listeners were university students, 16 men and 14 women, aged 18–24 years (median 20). Older listeners were 25 men and 29 women aged 55–79 years (median 67), who were introduced by a local employment agency.

Prior to participation in the experiment, all listeners performed pure-tone audiometry (AA-73; Rion Co., Ltd) and tympanometry (SI-50I; J. Morita MFG. Corp.). Consequently, one man and three women in the older listener group were excluded because of their hearing abnormalities (severe hearing loss at low and/or middle frequencies that was atypical for presbycusis and a middle-ear pressure out of the range of ± 50 daPa). Their ratings in the main experiment were excluded from the analysis below. Figure 3 displays the audiogram of young and older listeners after screening.

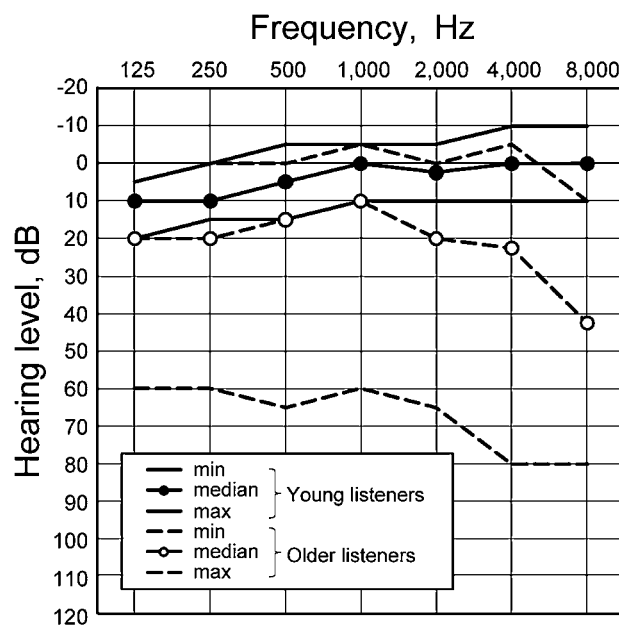


Fig. 3 Audiogram for young and older listener groups. Minimum, median, and maximum hearing threshold levels of better ears are presented for the two age groups separately.

2.2. Results and Discussion

2.2.1. General

The ratings of listeners were analyzed in terms of A-weighted sound pressure levels and 1/3 octave band levels of signals and background noises to determine a suitable level range of auditory signals. This section presents a description of general procedures for analyzing the listeners' ratings. Further analyses and discussion that are specific to those two measurements are presented respectively in Secs. 2.2.2 and 2.2.3.

A psychometric function that relates the five target-tone levels to the audibility ratings was estimated for the 14 background noises and the two age groups separately, as described below. First, the 90th percentile rating of the listeners was calculated for each of the five target-tone levels. Next, assuming that the ratings of listeners were on an interval scale, a sigmoidal curve was fitted to the psychometric function, R , expressed as

$$R = \frac{5}{1 + e^{-(L-\alpha)/\beta}} + 0.5, \quad (1)$$

where L is the sound pressure level of the target tone in decibels. α and β are parameters determining the form of the curve and were obtained using a curve-fitting tool (KaleidaGraph; Synergy Software). Then, L values that correspond to R from 1–5 were calculated using the inverse function of Eq. (1). Finally, the median and interquartile range of the L values were calculated to determine, respectively, their central tendency and variation among the 14 background noises.

Because scale point 1 was labeled “not audible” and scale point 2 was “barely audible,” the hearing threshold of the target tone under the experimental condition lies somewhere between the levels of $R = 1$ and $R = 2$. To produce an audible auditory signal, it must be at a level of $R = 2$ or higher. Scale point 4 was labeled “loud” and scale point 5 was “too loud.” The maximum sound level at which the target tone is not annoyingly loud lies between the levels of $R = 4$ and $R = 5$. To make an auditory signal comfortably loud, its level should not be higher than that of $R = 4$. Consequently, the tone level range of those of $R = 2$ (“barely audible”) and $R = 4$ (“loud”) inclusive are suitable for the auditory signal among the background noise. The signals in that range are audible and comfortably loud to 90% of the listeners in the age group.

In the following sections, the lower and upper ends of the range, which respectively correspond to the levels of $R = 2$ and $R = 4$, are determined on the basis of A-weighted sound pressure level measurements and 1/3 octave band analyses of signals and background noises.

2.2.2. Analysis based on A-weighted sound pressure level measurement

For noise evaluation, A-weighted sound pressure level

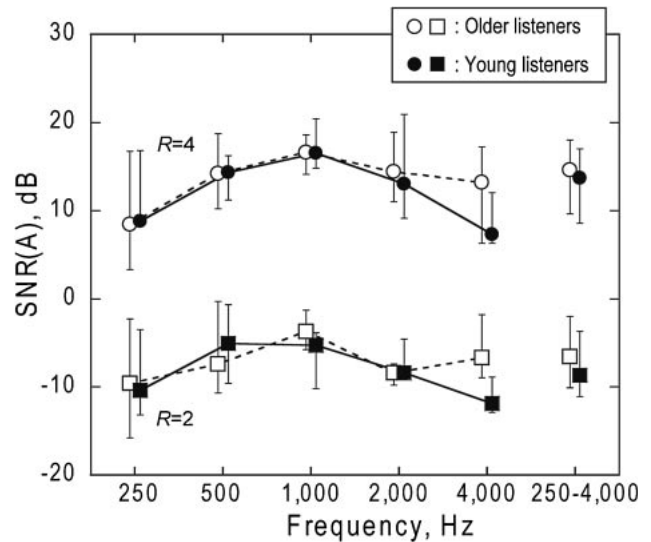


Fig. 4 Median audibility ratings of target tones derived from the psychometric function, R , analyzed in terms of the difference between A-weighted sound pressure level of tone and that of domestic sound, SNR(A). Error bars represent the interquartile range of ratings for 14 background noises. See Eq. (1) for the calculation of R .

measurements are preferred over 1/3 octave band analysis because the measurement can be performed using only a conventional sound level meter. Although the accuracy of the signal-level-range estimation may be worse than that of 1/3 octave band analysis, it would be beneficial for practitioners if the auditory-signal level can be determined using such a simple device.

In this section, we present a description of the range of the auditory-signal level determined in terms of A-weighted sound pressure levels of signals and noises.

(a) Lower end of signal level range ($R = 2$)

Figure 4 shows the level differences between A-weighted sound pressure levels of the target tone and background noise, SNR(A), for $R = 2$ and $R = 4$.

Although the median ratings for $R = 2$ varied among frequencies, the frequency dependence was small (about 5 dB) for both age groups. Older listeners needed a higher SNR(A) at 4,000 Hz than did the young listeners, possibly because of their age-related hearing loss at high frequencies. Furthermore, the interquartile range of ratings among background noises was small, except for the two lowest frequencies. Therefore, SNR(A) was sufficient to provide a rough estimate of the lower end of the signal level range. Averaging the results at frequencies of 250–4,000 Hz, the SNR(A) was about –10 dB for young listeners and about –5 dB for older listeners.

Figure 5 presents rating results expressed in terms of the A-weighted sound pressure level of the target tone. It is interesting that the curve for $R = 2$ is flat, particularly for

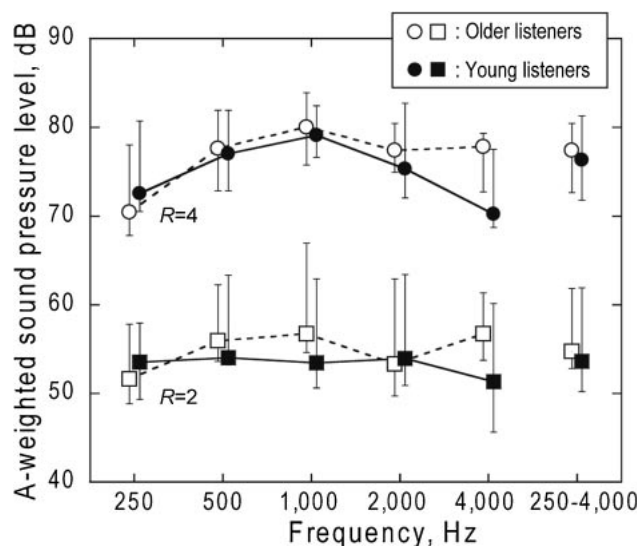


Fig. 5 Median audibility ratings of target tones derived from the psychometric function, R , analyzed in terms of A-weighted sound pressure levels of tone. Error bars represent interquartile ranges of ratings for 14 background noises. See Eq. (1) for the calculation of R .

young listeners, although the variation among background noises was large. Averaging the results of all frequencies, the lower end of the signal level range was about 55 dB for both age groups.

The DIN TR [5] recommends the following auditory-signal level: “[i]n quiet surroundings, the sound level at the ear of the user should be between 55 dB(A) and 65 dB(A) at the normal distance between the user and the product.” Figure 5 suggests that the A-weighted sound pressure level of 55 dB can be the lower-end level of auditory signals that are suitable not only in quiet surroundings, but also among domestic sounds at a moderate sound level, as used in this study. On the other hand, the upper end can be higher than the value in quiet surroundings, 65 dB, as discussed below.

(b) Upper end of signal level range ($R = 4$)

The upper end of the range can be determined in the same manner as the lower end. The $SNR(A)$ curves for $R = 4$ are displayed in Fig. 4; they were about 10–15 dB for both listener groups, although some variation is apparent among tone frequencies. After averaging the results at all frequencies, the upper end of the signal range is about 15 dB for both age groups.

When evaluated in terms of A-weighted sound pressure levels (Fig. 5), the ratings varied between 70–80 dB. Averaging the ratings at all frequencies, the upper end of the signal range was about 75 dB. This sound level is higher than the DIN TR value of 65 dB in quieter surroundings. A higher level of auditory signal is necessary so that the signal can be heard distinctly under noisy conditions.

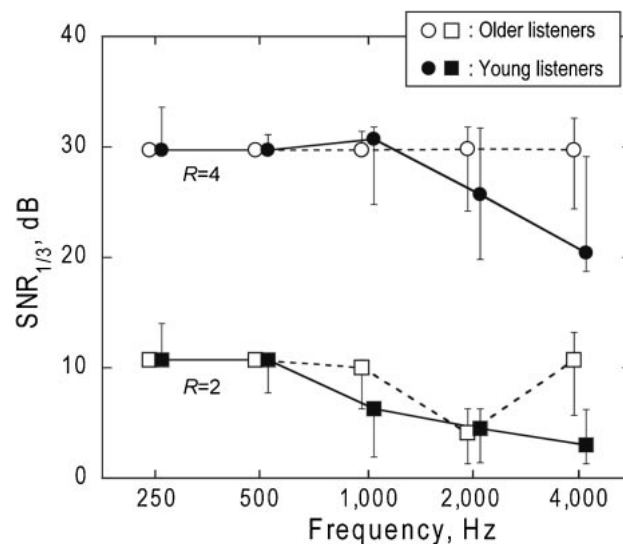


Fig. 6 Median audibility ratings of target tones derived from the psychometric function, R , analyzed in terms of the difference between 1/3 octave-band level of tone and that of domestic sound, $SNR_{1/3}$. Error bars represent interquartile ranges of ratings for 14 background noises. See Eq. (1) for the calculation of R .

2.2.3. Analysis based on 1/3 octave band level measurement

(a) Lower end of signal level range ($R = 2$)

The audibility of a signal against a background noise depends on the difference in the levels between the signal and the noise around the signal frequency. Figure 6 presents differences in 1/3 octave band levels between the target tone and background noise, $SNR_{1/3}$, for both age groups.

The interquartile ranges of the young listeners' ratings were small, about 5 dB or less at all frequencies, which suggests that the $SNR_{1/3}$ determines the audibility of target signals irrespective of the signal frequency and the variety of background noises. The older listener group showed similar results, except for 4,000 Hz. Therefore, the lower end of the signal level range at 2,000 Hz and below can be determined from the $SNR_{1/3}$ between the tone and noise.

At 4,000 Hz, the $SNR_{1/3}$ of the older listener group, at which $R = 2$, was higher than the $SNR_{1/3}$ of the young listener group. Furthermore, the variation of ratings among background noises was large at that frequency. The latter might be caused by the degraded hearing sensitivity of older listeners at that frequency; a higher signal level was necessary even when the level was well above that of noise, particularly for some background noises with very low levels at that frequency (see Fig. 1).

Therefore, the lower end of the signal level range at 4,000 Hz should be determined on the basis of not only the relative level of signal to noise (SNR), but also the absolute

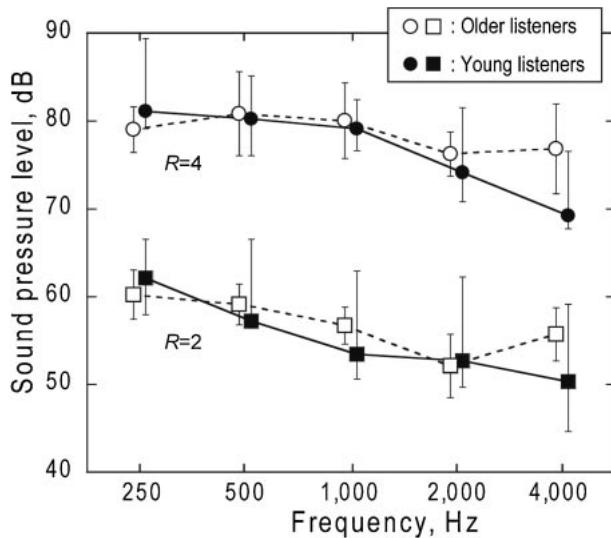


Fig. 7 Median audibility ratings of target tones derived from the psychometric function, R , analyzed in terms of $1/3$ octave-band level of tone. Error bars represent interquartile ranges of ratings for 14 background noises. See Eq. (1) for the calculation of R .

level of the signal. Figure 7 displays the same results as those presented in Fig. 6, but the ratings for target tones are expressed in terms of the sound pressure level. The median level of the tone at 4,000 Hz for $R = 2$ was about 55 dB; it should be the lower-end level.

(b) Upper end of signal level range ($R = 4$)

In Fig. 6, both age groups showed a similar $SNR_{1/3}$ of about 30 dB for $R = 4$. The variance among background-noise conditions was small for frequencies of 250–1,000 Hz. Therefore, the upper end of the signal level range for those frequencies can be determined in terms of the level difference between tone and noise.

On the other hand, the two groups displayed a large difference at higher frequencies. The young listeners judged the tone as “loud” at a lower $SNR_{1/3}$ as the tone frequency increased to above 1,000 Hz. Furthermore, the interquartile ranges of both groups were large for those frequencies. Some background noises showed a gradual decline in their average power at increasingly higher frequencies (Fig. 1). For those noises, the young listeners seemed to judge the target tone as sufficiently loud before its $SNR_{1/3}$ reached 30 dB. Such was also the case for older listeners, as the large interquartile ranges at the highest two frequencies suggest.

Therefore, the upper end of the signal level range, 2,000–4,000 Hz, should be determined on the basis of not only the relative level of signal to noise (SNR), but also the absolute level of the signal. According to Fig. 7, the sound pressure levels of those frequency tones were about 70–75 dB for both age groups.

3. GENERAL DISCUSSION

3.1. Level Range of Auditory Signals Suitable for Young and Older Adults

When evaluated in terms of SNR, the ratings of the older listener group did not markedly differ from those of the young listener group, except at the highest frequency of 4,000 Hz (Figs. 4 and 6). Although older adults are expected to have broader auditory filters and are therefore expected to be susceptible to masking by interfering noise, the effect on audibility judgments is apparently small. This finding is supported by a study [12] in which the detection threshold of pure tones among background noise was measured. Results of the study showed that 75% of older participants (aged 60–83 years) retained good signal-detection ability, even under the noisy condition. Their detection threshold was elevated by 4 dB or less from the young participants’ average. Consequently, the same level range of auditory signals for young and older adults can be established for frequencies of 250–2,000 Hz.

On the other hand, the rating for the 4,000 Hz tone showed a large difference between the two age groups. The older listener group needed a higher level to attain a certain level of audibility because of their poorer hearing ability at high frequencies. The level of 4,000 Hz signals is expected to cover the range for older adults, not young adults, considering the case in which both young and older users operate the same products with auditory signals. Otherwise, older users might fail to hear the signals.

Summarizing the findings of the experiment (Figs. 4–7), the level range of auditory signals that are suitable for young and older adults can be proposed as follows. Sound level values were rounded to the nearest multiple of 5 dB.

(a) Signal level range for A-weighted sound pressure level measurement

Lower end of range: The level difference is –5 dB between the A-weighted sound pressure level of the signal, $L_{S,A}$, and that of noise, $L_{N,A}$, irrespective of the signal frequency (i.e., $L_{S,A} - L_{N,A} = -5$). The lower-end level is expected to be 55 dB if thus-adjusted $L_{S,A}$ becomes lower than 55 dB (i.e., when $L_{S,A} - 5 < 55$).

Upper end of range: The level difference is 15 dB between $L_{S,A}$ and $L_{N,A}$, irrespective of the signal frequency (i.e., $L_{S,A} - L_{N,A} = 15$). The upper-end level is expected to be 75 dB if thus-adjusted $L_{S,A}$ becomes higher than 75 dB (i.e., when $L_{S,A} - 15 > 75$).

(b) Signal level range for $1/3$ octave band analysis

Lower end of range: The level difference is the value in Table 1(i), depending on the signal frequency, between the $1/3$ octave band level of the signal, $L_{S,1/3 \text{ oct}}$, and that of noise, $L_{N,1/3 \text{ oct}}$. The lower-end level is expected to be that in Table 1(ii) if thus-adjusted $L_{S,1/3 \text{ oct}}$ becomes lower than

Table 1 Lower end of signal-level range for 1/3 octave-band analysis. At least one frequency band should have a higher level than that in the table so that the auditory signal is audible against typical domestic sounds.

Frequency, Hz	250	500	1,000	2,000	4,000
(i) $L_{S,1/3 \text{ oct}} - L_{N,1/3 \text{ oct}}$, dB	10	10	10	5	10
(ii) $L_{S,1/3 \text{ oct}}$, dB	60	60	55	50	60

Table 2 Upper end of signal-level range for 1/3 octave-band analysis. All frequency bands should have a lower level than that in the table so that the auditory signal is not too loud against typical domestic sounds.

Frequency, Hz	250	500	1,000	2,000	4,000
(i) $L_{S,1/3 \text{ oct}} - L_{N,1/3 \text{ oct}}$, dB	30	30	30	30	30
(ii) $L_{S,1/3 \text{ oct}}$, dB	80	80	80	75	75

the value in Table 1(ii) (e.g., when $L_{S,1/3 \text{ oct}} + 10 < 55$ at 1,000 Hz).

Upper end of range: The level difference is the value in Table 2(i), depending on the signal frequency, between $L_{S,1/3 \text{ oct}}$ and $L_{N,1/3 \text{ oct}}$. The upper-end level is expected to be that in Table 2(ii) if the so-adjusted $L_{S,1/3 \text{ oct}}$ becomes higher than the value in Table 2(ii) (e.g., when $L_{S,1/3 \text{ oct}} + 30 > 80$ at 1,000 Hz).

For signals with an intermediate frequency between the two bands, the values in Tables 1 and 2 should be interpolated. For example, when a signal of 1,500 Hz is used, the $L_{S,1/3 \text{ oct}} - L_{N,1/3 \text{ oct}}$ value at 1,600 Hz band, which is the center frequency of the 1/3 octave band that contains the 1,500 Hz signal, is to be evaluated. The lower end is expected to be between 10 dB at 1,000 Hz and 5 dB at 2,000 Hz, which results in about 7 dB.

For both measurement methods (a) and (b), the upper and lower ends specify the *minimum* range of the signal level. In the case where the product user can control the sound volume of the auditory signal, the sound volume should at least cover the range of the upper and lower ends.

3.2. Frequency Components of Auditory Signals

In this study, we used pure tones to determine a suitable sound level for auditory signals of consumer products. Although pure-tone-like sounds are sometimes used in those products, the signals that are emitted from piezounders have multiple frequency components.

The sound level at which an auditory signal is barely audible among noise is determined by the level difference between the signal and the noise, or the SNR. When the signal has multiple components and their frequencies are widely separate from each other, the component that has the largest SNR determines the signal's audibility. The

whole signal is audible even when other components fall far below the noise level if only one component of the signal exceeds the noise level by a certain amount. Under this condition, the audibility of complex tones can be estimated in the same way as that of pure tones. The lower end of the signal level range in the previous sections would be applicable to such multiple-tone signals.

On the other hand, the sound level at which the signal sounds comfortably loud might vary depending on the structure of the frequency contents. When two or more components of the signal are at an above-threshold level, they can affect the perception of the whole signal. However, the effect might not be large when the additional components are few and their levels are low compared with that of the main component, particularly when the frequencies of the components are high for older ears. The effect should be investigated in future studies to confirm the experimental results obtained in this study.

3.3. Comparison with Level-Adjustment Criteria for Auditory Danger Signals

As described in the *Introduction*, some methods for adjusting the sound level of auditory danger signals used in public and work areas have been proposed and established as ISO 7731 [6]. Such signals are classified into another category, in which a higher sound level is required to ensure listeners' detection and recognition. However, it would be interesting to compare criteria for the level adjustment of those signals to clarify their differences.

Table 3 presents sound levels of danger signals specified in the ISO standard [6] and those of auditory signals of consumer products proposed in this study. It is readily apparent that the sound levels required for the former are higher than those for the latter.

That ISO standard introduced the "effective masked threshold," which incorporates the effects of masking that spreads toward higher frequency bands, in place of the 1/3 octave band level. However, the effect is negligibly small when the frequency characteristics of noise are as flat as many of the noises used in this study. Therefore, we can say that auditory signals for consumer products do not require as high a sound level as auditory danger signals, irrespective of whether the masked threshold or 1/3 octave band level is used for noise measurements.

Laroche *et al.* [7] developed a model that enabled the prediction of the capability of workers to detect auditory warning signals in noise, considering the effects of aging. The criterion that they adopted was a 1/3 octave band level of 10 dB above the masked threshold. The level difference is similar to or larger than that proposed in the present study for auditory signals of consumer products. They did not propose a criterion for a comfortable level because of the high noise level.

Table 3 Requirements for sound pressure level of auditory danger signals for public and work areas and auditory signals for consumer products.

	Auditory danger signals for public and work areas, ISO 7731 [6]	Auditory signals for consumer products, present study
Lowest A-weighted sound pressure level in quiet environment	65 dB	55 dB
Maximum A-weighted sound pressure level	118 dB	75 dB
Difference between A-weighted sound pressure level of signal and that of noise	>15 dB	> -5 dB
Difference between 1/3 octave-band level of signal and that of noise (see Notes 1 and 2)	>13 dB	>5 or 10 dB, dependent on frequency band

Note 1 ISO 7731 uses masked threshold instead of the sound pressure level, taking masking effects of noise into consideration.

Note 2 At least one frequency band is required to meet the criterion.

It is interesting that the model presented by Laroche *et al.* predicted the effects of aging as small as was found in the present study. The difference of signal levels required for 18-year-old subjects and 60-year-old subjects was only 1–2 dB. They attributed the small effects to the minor increase in the critical bandwidth that occurs with aging, as described in a study by Patterson *et al.* [2] on which the model of Laroche *et al.* was based.

3.4. Other Factors that Might Affect Audibility of Signal in Noise

In the experiment of this study, only one domestic noise was presented at a time and the noise and signal came from the same forward location. However, the conditions in which consumer products are used in the home can be different from the experimental setup in some cases: (1) several sound sources may emit noise at the same time and (2) the noise source may be located at a different position from that of the signal source. These factors might affect the audibility of the signal in noise.

Multiple noises from the same direction can be treated as a single mixed noise if the effect of the *meaning* of each individual noise is negligible. In fact, the variation of audibility ratings among various domestic noises was small (< 5 dB) and the ratings were explainable in terms of SNR in most cases (see Figs. 4 and 6). Other cases where an extraordinarily large variation was observed (at high frequencies in Fig. 6) were caused by the lowering of noise levels and the large variation among them.

On the other hand, the directions from which the noise and signal originate can be critical. As studies of the binaural masking level differences demonstrate, the detectability of a tone among noise is improved when those sounds are located at different positions in space [13]. The improvement of detectability can be larger than 10 dB under some experimental conditions using stereo headphones. In real situations without headphones, however,

the effect might be smaller than that because the noise and the signal are not so clearly separated from each other. Furthermore, it is known that the amount of improvement is reduced for signal frequencies above about 1,500 Hz when the signal is presented in a broadband masker [13].

To summarize, the sound-level ranges of auditory signals presented in the present study are expected to be applicable under other conditions where multiple noise sources exist or the noise and signal originate from different directions. However, it will be interesting to study further the audibility of signals under the latter condition to examine the effect of sound source location.

4. CONCLUSIONS

The audibility of pure tones presented with typical domestic noises was investigated in a psychoacoustic experiment to determine a sound level range that is suitable for auditory signals of consumer products used by young and older people. The results of the experiment showed that the effects of aging on audibility were not large, except at high frequencies of 2,000 Hz and 4,000 Hz.

On the basis of the results, we proposed a sound level range of auditory signals that covers the lowest level at which auditory signals are audible and the highest level at which they are not too loud when both young and older adults hear the signals against domestic sounds. The proposed signal levels were similar to or higher than those recommended for auditory signals under quiet conditions and were lower overall than those for auditory danger signals used in public or work areas.

Many auditory signals used for consumer products include multiple-frequency components. The detectability of such signals among noise is expected to be similar to that for pure tones. However, the loudness of signals might be affected by the frequency-component structure. For that reason, the effects of multiple components should be investigated in future studies to review the level range that

is suitable for auditory signals. In addition to that, it will be interesting to examine the effect of the location of the signal and noise to confirm the applicability of the results of this study to real environments in the home.

ACKNOWLEDGMENTS

The authors are grateful to the two anonymous reviewers for helpful comments on an earlier version of the manuscript.

REFERENCES

- [1] J. F. Willott, *Aging and the Auditory System: Anatomy, Physiology, and Psychophysics* (Singular Publishing Group, Inc., San Diego, 1991), pp. 181–184.
- [2] R. D. Patterson, I. Nimmo-Smith, D. L. Weber and R. Milroy, “The deterioration of hearing with age: Frequency selectivity, the critical ratio, the audiogram, and speech thresholds,” *J. Acoust. Soc. Am.*, **72**, 1788–1803 (1982).
- [3] B. R. Glasberg, B. J. Moore, R. D. Patterson and I. Nimmo-Smith, “Dynamic range and asymmetry of the auditory filter,” *J. Acoust. Soc. Am.*, **76**, 419–427 (1984).
- [4] R. G. Matschke, “Frequency selectivity and psychoacoustic tuning curves in old age,” *Acta Oto-laryngol. Suppl.*, **476**, 114–119 (1991).
- [5] DIN Technical Report 124, *Products in Design for All*, EU-Version (DIN Deutsches Institut für Normung e. V., Berlin, 2002).
- [6] ISO 7731, *Ergonomics — Danger Signals for Public and Work Areas — Auditory Danger Signals* (International Organization for Standardization, Geneva, 2003).
- [7] C. Laroche, H. Tran Quoc, R. Héту and S. McDuff, “‘Detectsound’: A computerized model for predicting the detectability of warning signals in noisy work places,” *Appl. Acoust.*, **32**, 193–214 (1991).
- [8] JIS/TR S 0001, *A Guideline for Determining the Acoustic Properties of Auditory Signals used in Consumer Products — A Database of Domestic Sounds* (Japanese Standards Association, Tokyo, 2002).
- [9] K. Kurakata, K. Matsushita and Y. Kuchinomachi, “A database of domestic sounds for evaluation of auditory-signal audibility: JIS/TR S 0001,” *Acoust. Sci. & Tech.*, **24**, 23–26 (2003).
- [10] IEC 60225, *Octave, Half-Octave and Third-Octave Band Filters Intended for the Analysis of Sounds and Vibrations* (International Electrotechnical Commission, Geneva, 1966).
- [11] K. Kurakata, Y. Kuba, T. Kizuka and Y. Kuchinomachi, “Relationship between hearing levels of the elderly and preferred volume levels of television,” *Jpn. J. Ergonomics*, **35**, 169–176 (1999) (in Japanese).
- [12] K. Kurakata, K. Matsushita, A. Shibasaki-Kawamoto and Y. Kuchinomachi, “Detection thresholds for pure tones presented against a broadband noise — A comparison of young and elderly listeners —,” *Proc. 17th Int. Congr. Acoust.*, Vol. IV, 3A.15.02 (2001).
- [13] B. C. J. Moore, *An Introduction to the Psychology of Hearing*, 5th Ed. (Academic Press, London, 2003), pp. 257–261.