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Yôiti Suzuki*, Hisashi Takeshima, Kenji Kurakata

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INVITED REVIEW

Revision of ISO 226 "Normal Equal-Loudness-Level Contours" from 2003 to 2023 edition: the background and results

Yôiti Suzuki[1*], Hisashi Takeshima[2], Kenji Kurakata[3]

[1] *Faculty of Engineering, Tohoku Bunka Gakuen University, Kunimi 6-45-11, Aoba-ku, Sendai, 981-8551 Japan*[1]

[2] *National Institute of Technology, Sendai College, Ayashi Chûô 4-16-1, Aoba-ku, Sendai, 989-3128 Japan*[2]

[3] *Faculty of Human Sciences, Waseda University, Mikajima 2-579-15, Tokorozawa, 359-1192, Japan*[3]

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Abstract: As significant errors were reported in 1985 for the international standard related to equal-loudness-level contours (ELLCs) for pure tones, the earlier international standard was fully revised in 2003 as ISO 226:2003, after 18 years of revision work. Twenty years later, the standard has been revised again as ISO 226:2023. One motivation for the revision was to reflect the lowering of the threshold of hearing at 20 Hz by 0.4 dB in ISO 389-7:2019. In addition, the following two points of substance were revised: (1) implementation of the power exponent relating loudness perception to physical intensity formulated in an academic paper published in 2004, which describes the derivation of ELLCs relating to ISO 226:2003, and (2) adoption of mathematical expressions that preserve the appropriate number of significant digits. In this review, the process of the revision and the technical details of the changes are described. The differences from the 2003 edition are only 0.6 dB at most, and the 2023 standard can be regarded as the same as the 2003 edition in terms of practical use.

Keywords: Equal-loudness-level contour, Equal-loudness level, ISO 226, Loudness, Sensitivity of hearing, Threshold of hearing

1. INTRODUCTION

The subjective magnitude of sound, loudness, can greatly change when the frequency spectrum is changed, even if the sound pressure level or the intensity of the sound is held constant. In the case of pure tones and narrowband sounds, the loudness changes with (center) frequency even if the sound pressure level or the intensity of sound is held constant. For such sounds, the sound pressure levels that are heard as equally loud, plotted as a function of frequency, are called equal-loudness-level contours (ELLCs).

The degree of loudness for a given ELLC is represented by its loudness level, which has the unit phon. The loudness level of a sound is defined as the sound pressure level of a 1-kHz pure tone that sounds equally loud. For example, a 40-phon ELLC represents the sound pressure level of a pure tone as a function of frequency that has the same loudness as that of a 1-kHz pure tone at a sound pressure level of 40 dB.

ELLCs represent a basic characteristic of hearing and they are important for acoustic measurements. Their importance has been acknowledged for nearly one hundred years, and especially, early efforts to measure ELLCs for pure tones with various phon values presented in a free sound field were carried out in the 1930s, by Fletcher and Munson at AT&T Bell Laboratories. They measured ELLCs over almost the entire audible range of frequencies and a wide range of sound pressure levels. The measurements were obtained using earphones. The data were then converted to the sound pressure levels equivalent to those measured in a free sound field to derive a set of ELLCs [1] for pure tones coming from the front in a free sound field. The ELLCs were widely used as a *de facto* standard throughout the world. As *de jure* standard of ELLCs, an international standard, ISO/R 226, was standardized in 1961 (it became international standard ISO 226:1987 in 1987). These ELLCs were not based on the contours derived by

* suzuki.yoiti@tohoku.ac.jp

Fletcher and Munson, but on the results obtained using loudspeakers by Robinson and Dadson [2] in the United Kingdom in the 1950's.

In 1985, new experimental results from Germany were presented to ISO. The data showed large differences to the contours of the current international standard in the frequency region below 1 kHz. In response to this, the 43rd Technical Committee (ISO/TC 43), which is in charge of acoustics in ISO, decided to revise the standard. The revision work in ISO was started by Working Group 1 of ISO/TC 43, hereinafter referred to as WG 1.

In response to this decision, measurements of ELLCs were started in Germany, Denmark, and Japan. In Japan, the Research Institute of Electronic Communication, Tohoku University started a cooperative study with the National Institute of Advanced Industrial Science and Technology (formerly called Agency of Industrial Science and Technology, Electrotechnical Laboratory, abbreviated as ETL). By around 1990, it was clear that the data in the current ISO standard differed by more than 10 dB in the range below 1 kHz from the data of all three nations. While measurements of ELLCs were almost stopped in countries other than Japan by the middle 1990s, Japanese teams continued such measurements using ordinary research expenses and grants-in-aid for scientific research (*Kakenhi*) as well as with the support of private foundations.

Since it was not reasonable to ignore the large error, ISO convened a project team and Suzuki was appointed to be its project leader (PL) in 1999. An international research grant of NEDO (New Energy and Industrial Technology Development Organization, Japan) was given in 2000 [3,4], which allowed considerable advancement of the standardization work [5]. As a result, the full revision work of the international standard on ELLCs was completed and led to ISO 226:2003. This standard was in use until the revision in 2023.

In what follows, the background of this revision and the differences between the ELLCs in the 2003 and 2023 editions are described, to demonstrate that the 2023 edition may be practically treated as equivalent to the 2003 edition. Moreover, a brief history of the revision work is given.

2. What has changed in ISO 226:2023?

2.1. The academic paper concerned with ISO 226:2003 was published in 2004

In the year after the publication of ISO 226:2003, an academic paper with a detailed description of the derivation of the ELLCs in ISO 226:2003 was published in the Journal of the Acoustical Society of America [6] (hereinafter referred to as "the JASA 2004 paper"). In this paper, its authors showed their gratitude to WG 1 in the acknowledgements, but did not mention the revision work of ISO 226 at all. Although the revision work was mentioned in the initial manuscript submitted, the reviewer commented that "the description should be limited to academic contents and not touch on the work of standardization", and the authors accepted this recommendation.

The ELLCs given in ISO 226:2003 and in the JASA 2004 paper look very similar. However, there are differences, albeit minor. The differences were caused by a difference in the procedure of ELLC derivation from experimental data, which was modified in the JASA 2004 paper to reflect reviewer's comments given in the peer review process, after the final draft of ISO 226:2003 had been sent to the ISO central office.

The experimental values of the equal-loudness levels used in the development of ISO 226:2003 are a collection of discrete data for loudness levels ranging from 20 to 100 phons at specific frequencies ranging from 20 to 12,500 Hz, each measured in a certain country [6]. However, the amount of experimental data and the distribution of frequencies varied greatly with the phon values [6]. If the ELLCs had been drawn individually for each loudness level by simply using a smoothing function across frequency for that loudness level, the contours would have changed shape in an irregular manner from one loudness level to the next. To achieve smoothly varying ELLCs, the smoothing process must be performed in a two-dimensional plane that takes into account both the frequency and sound pressure level. To realize this along sound pressure level axis, in ISO 226:2003 a model representing the change of loudness with sound pressure level (loudness function, loudness growth curve) was used. The model parameters were estimated using all equal-loudness level data and ELLCs were drawn as a set based on the estimates [6].

The loudness function selected [7,8] is:

$$S = k(P^{2\alpha} - P_t^{2\alpha}),$$

where P is the sound pressure (Pa) of a certain sound and S is its loudness (sone). P_t is the sound pressure corresponding to the threshold of hearing (Pa), α is the exponent relating loudness to the intensity of sound (W/m^2), and k is a proportionality coefficient. This loudness function has two adjustable parameters, α and k.

These parameters were estimated over the frequency range from 20 to 12,500 Hz. It was necessary to determine the value of k at 1 kHz which is taken as a reference frequency. This value (k_r in ISO 226:2003) was chosen to fulfill $S = 1.0$ sone at 2 mPa (sound pressure level of 40 dB).

The value of α at 1 kHz (α_r in ISO 226:2003) was set to 0.25 in ISO 226:2003, based on the following considerations. The model proposed by Attneave [9] was used, as shown in Figure 1.

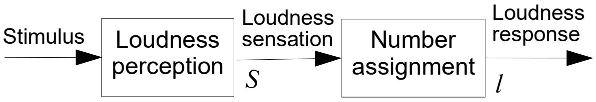

Fig. 1 Block-diagram of a psychological model of loudness perception

He argued that there are two different processes involved in absolute magnitude estimation (AME), which is a method for assessing the functional relation between assigned numbers and the corresponding perceived magnitudes, which is, in this case, the loudness of a tone presented at a certain sound pressure level. The first process is denoted a "loudness perception process," where the loudness sensation S is evoked by the input stimulus. In the next "number assignment process," the loudness S is converted to the reported value l. The relationship between S and l is estimated to be a power function with an exponent of 1.08 [10].

According to this model, the exponent observed in psychophysical experiments must be the product of the exponents of the two underlying processes. This two-stage model is known to show good performance in accounting loudness growth [10,11] as introduced in the JASA 2004 paper.

Based on the AME method, the power exponent of the loudness function as a function of the intensity of a sound is 0.27 (corresponding to 0.54 for sound pressure). While the values reported by subjects using the AME method are influenced by the "number assignment process," loudness itself is determined by the output of the "loudness perception process." To compensate for this, in ISO 226:2003, the exponent 0.25 was used, which was obtained by dividing the power exponent reported in papers using the AME method (0.27) by the power exponent 1.08 for the second stage.

In the peer review process of the JASA 2004 paper, the following criticism was given:

1. Not only the exponent values obtained using the AME method but also values obtained using other methods based on the additivity of loudness, such as experiment involving a doubling or halving of loudness, must be taken into consideration and the average of all available data should be used.
2. To calculate the average, since judgments of equal loudness between two sounds must be based on comparison of the outputs of the "loudness perception process," the exponent value based on loudness additivity, such as experiments involving doubling or halving of loudness, should be used without modification. On the other hand, values based on the methods of magnitude estimation and production should be corrected to eliminate the effect of the number assignment process by dividing by the exponent of the "number assignment process."

We found these comments to be quite reasonable and fully accepted them.

As described in detail in the JASA 2004 paper, the reported power exponent values for loudness perception are as follows. Many investigators have reported that for a 1-kHz tone the exponent in Stevens's power law has a value of about 0.3 for sound intensity. In 1995, Fletcher examined results from several studies based on the doubling and halving of loudness, tenfold magnification and reduction, and the multi-tone method and proposed an exponent of 0.33. In 1955, Stevens examined available data measured with various methods at that time and suggested 0.3 as the median of the data. Robinson measured exponents based on doubling and halving of loudness and tenfold increase and reduction and derived an exponent of 0.29 in 1953, but later, in 1957, he adjusted the results to allow for the central tendency and order effects to obtain a slightly corrected value of 0.30. In 1990, Zwicker and Fastl suggested an exponent for a 1-kHz tone of 0.3, based on an experiment on the doubling and halving loudness reported in 1963. On the other hand, as mentioned above, a typical exponent value obtained using the AME method is 0.27. In 1963, Hellman and Zwislocki confirmed this value using a combination of magnitude estimation and magnitude production.

We suggested that the value of 0.27 based on the methods of magnitude estimation and production is equivalent to 0.25 (0.27/1.08) for values from experiments based on the additivity of loudness. The average of the exponent values across all methods and data was 0.296. A rounded value of 0.30 was used for the JASA 2004 paper as the value of the exponent of the loudness function at 1 kHz, α_r.

It is noteworthy that a preliminary examination showed that the assumed value of the exponent hardly affects the resultant shape of the ELLCs at least for exponents in the range 0.20 to 0.33 [6,7]. In fact, as shown later, the differences in ELLCs between ISO 226:2003 and the JASA 2004 paper are 0.6 dB or less.

Since the value of α_r forms an important part of the standard, the authors tried to revise ISO 226:2003. As described in section 4, however, the opinion arose that it was not a large difference. Realization of the revision was once in danger.

2.2. ISO 389-7 was revised in 2019

ISO 389-7 defines the threshold of hearing for pure tones in a free sound field. In both the 2003 edition and the 2023 edition of ISO 226, the hearing threshold contour was included in the figure showing the ELLCs. This was done because the frequency characteristic of the threshold of hearing is similar to the ELLCs for low loudness levels. Indeed, it has been suggested that the threshold of hearing corresponds to a fixed low loudness level [12]. It should be noted, however, that the frequency characteristic of the threshold of hearing is not always regarded as an ELLC as introduced in the JASA 2004 paper [1,13,14]. It is thus controversial whether the hearing threshold contour can be regarded as an equal-loudness-level contour.

In the development of ISO 226:2003, the threshold of hearing used was based on some new data in addition to the data used in the first edition of ISO 389-7:1996. The threshold of hearing in ISO 226:2003 was standardized in 2005 as ISO 389-7:2005.

Later, at a meeting of the ISO in 2009, a review of ISO 389-7:2005 was proposed, and the start of the revision work was approved. As the result, a new standard ISO 389-7:2019 was established in 2019. In this edition, new data measured in Japan were added, and accordingly, the threshold of hearing at 20 Hz was lowered by 0.4 dB compared with that of the 2005 edition.

In response to this revision, the revision work of ISO 226 was resumed in 2019. Details are given in section 4, including the process described in section 2.1.

2.3. Change in the notation format of mathematical expression

The same procedure as in the 2003 edition was used to derive the ELLCs in the 2023 edition, but the power exponent value and the threshold of hearing at 20 Hz were changed. At first glance, however, the notation used in the equations seems to have changed considerably. These modifications were introduced to reduce the impact of rounding, following suggestions of Dr. Roland Sottek (Germany), the PL for the 2023 revision.

One example is shown. The following two equations are both equation (1) of the 2003 and 2023 editions of ISO 226, which give the sound pressure level L_p (L_f in the 2023 edition) at which the loudness level of a pure tone of frequency f is L_N. Note that ISO uses a comma to represent the decimal point and lg for the common logarithm. The variables and constants in the equation are as follows.

α_r Power exponent for the loudness perception of sound intensity of a 1-kHz pure tone (reference sound)

α_f Power exponent for loudness perception of pure tones (comparison sounds) of frequency f

L_U, L_U The absolute value of the transfer function of the sound propagation path to the inner ear in a free sound field normalized by the value at 1 kHz (dB)

p_0 Reference sound pressure of 20 μPa

T_r Threshold of hearing in free field of reference sound (1-kHz pure tone) (dB)

T_f Threshold of hearing in free field of pure tones of frequency f (dB)

Notation of 2003 edition:

$$L_p = \left(\frac{10}{\alpha_f}\lg A_f\right)\ \mathrm{dB}\ - L_U + 94\ \mathrm{dB},$$

where

$$A_f = 4{,}47 \times 10^{-3} \times (10^{0{,}025 L_\mathrm{N}} - 1{,}15) + [0{,}4 \times 10^{(\frac{T_f + L_U}{10} - 9)}]^{\alpha_f}$$

Notation of 2023 edition:

$$\begin{aligned} L_f &= \frac{10}{\alpha_f}\lg\left\{\left[\left(\frac{p_0}{\mathrm{Pa}}\right)^2\right]^{\alpha_r-\alpha_f}\cdot\left[10^{\left(\alpha_r\frac{L_N}{10\ \mathrm{phon}}\right)} - 10^{\left(\alpha_r\frac{T_r}{10\ \mathrm{dB}}\right)}\right]\right.\\ &\qquad \left. + 10^{\left(\alpha_r\frac{T_f+L_\mathrm{U}}{10\ \mathrm{dB}}\right)}\right\}\mathrm{dB}\ - L_\mathrm{U}\\ &= \frac{10}{\alpha_f}\lg\left\{(4\cdot 10^{-10})^{(0{,}3-\alpha_f)}\cdot\left[10^{\left(0{,}03\,\frac{L_N}{\mathrm{phon}}\right)} - 10^{0{,}072}\right]\right.\\ &\qquad \left. + 10^{\left(\alpha_r\frac{T_f+L_\mathrm{U}}{10\ \mathrm{dB}}\right)}\right\}\mathrm{dB}\ - L_\mathrm{U} \end{aligned}$$

In the 2003 edition, since the appropriate number of significant digits of the equal loudness level is considered to be three at most, the equation was shown in an easily understandable form. In the 2023 version, the meaning of the numbers in the formula is easy to understand, and the accuracy of the result increases if data with good accuracy are used. It should be noted, however, that the experimental equal-loudness level values used to derive ELLCs typically have a standard deviation of about 5–6 dB. Also, the exponent α_r at 1 kHz used in the 2023 edition is rounded to 0.30 from the average value of 0.296, as mentioned above. Therefore, the authors think it unnecessary to show values of the ELLC with more than three significant digits.

Note that the denominator indicating the unit of the variable is shown here, but this is not the standard style of ISO. This seems to be the style of Dr. Sottek, the PL.

3. Evaluation of ISO 226:2023

Figure 2 shows the frequency characteristics of the exponent α_f relating loudness to intensity used in ISO 226:2003 and ISO 226:2023. The figure shows that the value in ISO 226:2023 has systematically increased over the entire frequency band, reflecting the change of the value at 1 kHz from 0.25 to 0.30. The values of α_f in ISO 226:2023 are the same as those of the JASA 2004 paper at all frequencies; there was no effect of lowering the threshold of hearing by 0.4 dB at 20 Hz according to ISO 389-7:2019.

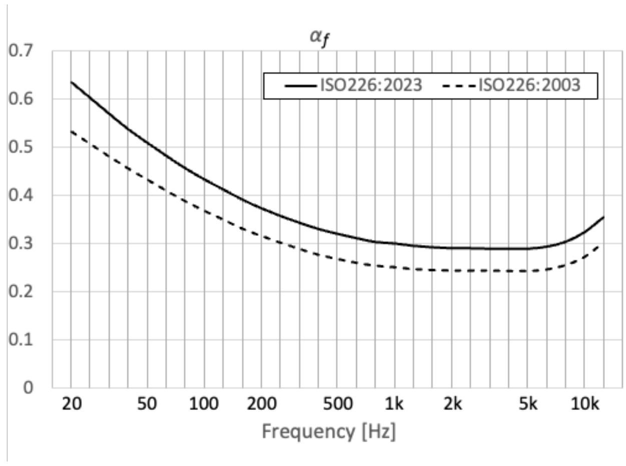

Fig. 2 Power exponent α_f for ISO 226:2003 and 2023

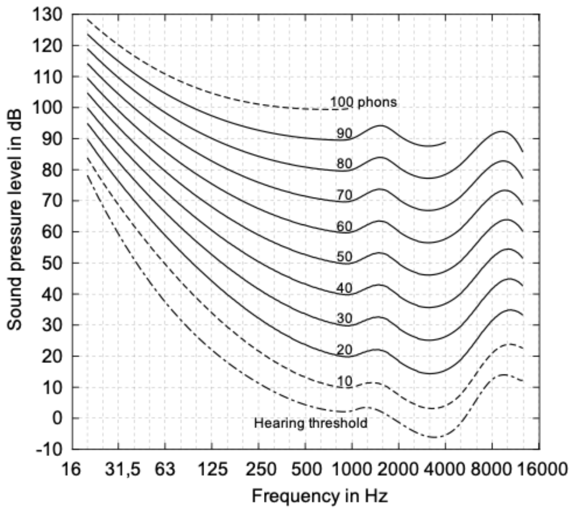

Fig. 3 ELLCs provided by Japan for ISO 226:2023

Figure 3 shows the ELLCs derived using the power exponents shown by the solid line in Figure 2 and the threshold of hearing defined in ISO 389-7:2019. All the experimental data of the equal loudness levels to draw these ELLCs are the same as those used in the 2003 edition and the JASA 2004 paper.

Although this figure and the one in ISO 226:2003 appear to be identical, let's take a closer look at the differences. Figure 4 shows the difference in dB between the equal-loudness levels of the 2003 and 2023 editions of ISO 226 for each 10-phon step in loudness level and every 1/3-octave-band center frequency. The area of each circle is proportional to the dB difference. The filled circle indicates that the value in the 2023 edition is larger, while the open circle indicates that the value in 2023 edition is smaller. The figure shows that at 10 phon, 20 phon, and above 80 phon the equal-loudness levels in the 2023 edition are larger than those of 2003 edition at many frequencies. Moreover, over the range 40 to 70 phon, the values in the 2023 edition are generally smaller than those in the 2003 edition (open circles) at frequencies below 1 kHz. Nevertheless, the differences fall within the range −0.6 to +0.3 dB. Differences over 0.4 dB occur only at 10 phon, and differences are within ±0.3 dB for loudness levels over 10 phon. Based on these observations, in practice, ISO 226:2023 may be regarded as having the same characteristics as the ISO 226:2003.

4. Summary of the development history of ISO 226:2023

The journey up to the issue of ISO 226:2023 was quite uneven. The history of the revision is summarized below in preparation for future revisions.

4.1. The academic paper concerned was published the following year

Since there were small discrepancies between the academic paper (the JASA 2004 paper) published in 2004 and ISO 226:2003, the authors proposed a revision to ISO.

May 2008 in Borås: The situation was explained orally at the WG1 meeting. As a result, a document describing the necessity of a revision was requested. Further, in the first systematic review of ISO 226 conducted from April to September of the same year, Japan proposed that this standard should be revised.

November 2009 in Seoul: At the WG 1 meeting, Suzuki presented a document showing a detailed comparison of ISO 226:2003 and the JASA 2004 paper. As a result, the revision work was registered as a preliminary work item (PWI) with Suzuki as the PL at the TC 43 plenary meeting held subsequently. In the WG 1 meeting in Seoul, Kurakata proposed a review of the 20 Hz (and 18 kHz) thresholds of hearing in ISO 389-7:2005, which was also registered as PWI at the subsequent TC 43 plenary meeting. As described later, as a result, this revision of ISO 389-7 boosted the revision of ISO 226.

April 2011 in London: A working draft (WD) prepared by Suzuki was submitted to the WG 1 meeting, although Suzuki himself did not participate due to the Great East Japan Earthquake in March 2011. In October of the same year, a vote was held in ISO/TC 43 on whether or not to start the revision based on this. However, following voting at the end of January 2012, the number of actively participating countries was only four, which did not reach the prescribed five countries, and the revision was thus rejected. Two countries objected because the correction was small, less than 1 dB.

In this vote, the following points were made by Germany: (1) How can a plane traveling wave in the range down to 20 Hz be realized? (2) The distance between sound source and listener should be specified. (3) The influence of harmonic distortion should be estimated (especially for measurements at low frequencies).

In practice, none of these were taken into account in the 2023 edition because the revision was relatively minor. Although it is impossible to make these points clear by going back to the past, they are important study items for the future. Note that, regarding (3), in Japan, an attempt to actively cancel harmonic distortion was carried out in the revision work preparing the 2003 edition.

November 2012 in Florianopolis: At the WG 1 meeting, re-measurement was proposed by Germany. It was argued that the difference in measurement values between research groups was large at low levels such as 30 phon, and that the measurement method needed to be reviewed. Therefore, an ad-hoc group was organized for the study.

May 2014 in Berlin: No progress report was submitted to the WG 1 meeting. The discussion of ISO 226 was temporarily suspended, and ISO 226:2003 was maintained for the time being.

4.2 Boost from the review of ISO 389-7

While the revision of ISO 226:2003 was suspended, a revision of ISO 389-7, which defines the threshold of hearing under free-field conditions, gave a major impetus. In July 2016, the Amendment 1 edition (Amd 1:2016) of ISO 389-7:2005 was published, and it was noted that the threshold of hearing at 20 Hz was different from that of ISO 226:2003.

May 2017 in Copenhagen: Since the Florianopolis meeting in 2012, a proposal had been made to transfer the revision work of ISO 226 to WG 9, which is in charge of the loudness calculation method (ISO 532 series). By the meeting, however, WG 9 had formally responded that they were not willing to accept the plan. Thus, at the Copenhagen meeting, it was decided that WG 1 continued to be responsible for the revision work of ISO 226.

October 2019: ISO 389-7:2019 incorporating the content of Amendment 1 of 2016 was published and resulted in a discrepancy with the threshold of hearing at 20 Hz used in ISO 226:2003. The threshold of hearing at 20 Hz in ISO 389-7:2019 was 0.4 dB lower than that of ISO 226:2003. In a systematic review conducted from July to December in the same year, three nations (Australia, Germany, Norway) proposed a revision of ISO 226. The following comments were added: from Australia, the progress of research after the issue of the 2003 edition should be reflected; from Germany, re-measurement is necessary because measurement in a low-frequency range is difficult and uncertainty is large; and from Norway, the discrepancy with ISO 389-7 should be corrected.

June 2020: At the WG 1 Paris Conference (held online), Dr. Sottek proposed a minor revision of ISO 226 concerning the following items before a major revision of ISO 226: (1) clarification of the scope, (2) revision of Introduction and Bibliography, and (3) consistency with ISO 389-7. As a result, it was agreed to start revision work with Dr. Sottek as PL in the TC 43 Plenary meeting held subsequently.

February 2021: Dr. Sottek circulated the first working draft (1WD) in WG 1 and invited comments with a deadline of the end of March. Suzuki presented some comments. At the same time, it was found that "minor revision" could not proceed since revision concerning technical content, i.e., change of threshold of hearing, was involved even if the prospected change was minor. Therefore, a policy decision to upgrade to a "full revision" work was made in WG 1 in March, and the change was accepted in TC 43 in July.

October 2021: WG 1 meeting was held online. As a result of a discussion on the 1WD, WG 1 approved preparation of the draft international standard (DIS) by reflecting the comments in 1WD, including those by Suzuki. A few days later, Dr. Sottek sent a revised draft to Suzuki.

May-July 2022: DIS voting was conducted, and it was approved to proceed based on 15 out of 16 countries voting to approve (one abstained). Although there were no technical comments, a lot of editorial comments were presented. Canada made a lot of comments mainly on wording and Japan made several editorial comments including the following two: Improvement of ELLCs caused by wrong drawing by polygonal lines, and clarification of the positioning of the JASA 2004 paper. After the meeting, the WG 1 secretariat requested Suzuki to provide a figure of the ELLCs based on the comments from Japan, and with the cooperation of Takeshima, Fig. 2 was provided.

August 2022: A WG 1 meeting was held online. Proposed responses to comments on the DIS were presented, including the new figure. After the meeting, as all the comments were editorial, the WG 1 secretariat proposed sending the final draft to the ISO Central Office without further discussion in WG 1 and, in October, the final draft was circulated in WG 1 and sent to the ISO Central Office.

March 2023: ISO 226:2023 was published with the above-mentioned revision processes and with the contents explained in sections 2 and 3.

The authors feel that the exchange of opinions within the ad hoc group during the drafting process was not frequent enough; most of the work was carried out between the PL and the secretariat. This is quite different from how the 2003 version was created. There could have been a better approach.

5. Concluding remarks

It is gratifying to note that ISO 226 has been and will continue to be used as an International Standard to which Japan has made significant contributions.

Nevertheless, the 2023 edition is not perfect. For example, this edition states that the hearing threshold contour corresponds to the ELLC of 0 phon, which is obviously incorrect. The threshold of hearing at 1 kHz is 2.4 dB, not 0 dB. In addition, the loudness at the hearing threshold may vary with frequency as mentioned earlier. Such a mistake could have been prevented if we had spent more time deliberating the draft. The authors would like to propose a correction at the next systematic review.

In ISO/TC 43/WG 1, we made considerable contributions not only to ISO 226 and the ISO 389 series but also to ISO 7029, which presents the distribution of the hearing thresholds by age. Also, Kurakata served as the convenor of WG 1 from 2013 to 2018. The authors hope that readers of this article may become interested in international standardization activities in the field of acoustics and join the WG.

Acknowledgement

The authors would like to express their deep appreciation to Toshio Sone, who decided to start research in Japan devoted to a full revision of ISO 226 immediately after the decision of ISO in 1985, and to all others over the world who worked hard to develop the 2003 edition, as well as to all those who participated in the revision work for the 2023 edition. The authors also thank Brian C.J. Moore (University of Cambridge) for his careful reviewing of an earlier version of this paper.

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Appendix

Figure A shows the differences in dB between the equal-loudness levels of the edition based on the JASA 2004 paper [6] and those of the 2023 edition of ISO 226 for every 10-phon step in loudness level and every 1/3-octave band center frequency. The area of each circle is proportional to the dB difference, and the filled and open circles, respectively, indicate that the value of the 2023 edition is larger and smaller than in the JASA 2004 paper. This figure shows that the difference is within 0.1 dB over the whole range except for 20 Hz, where the threshold of hearing changed by 0.4 dB. This result means that the ELLCs presented in the JASA 2004 paper are essentially the same as in the 2023 edition.

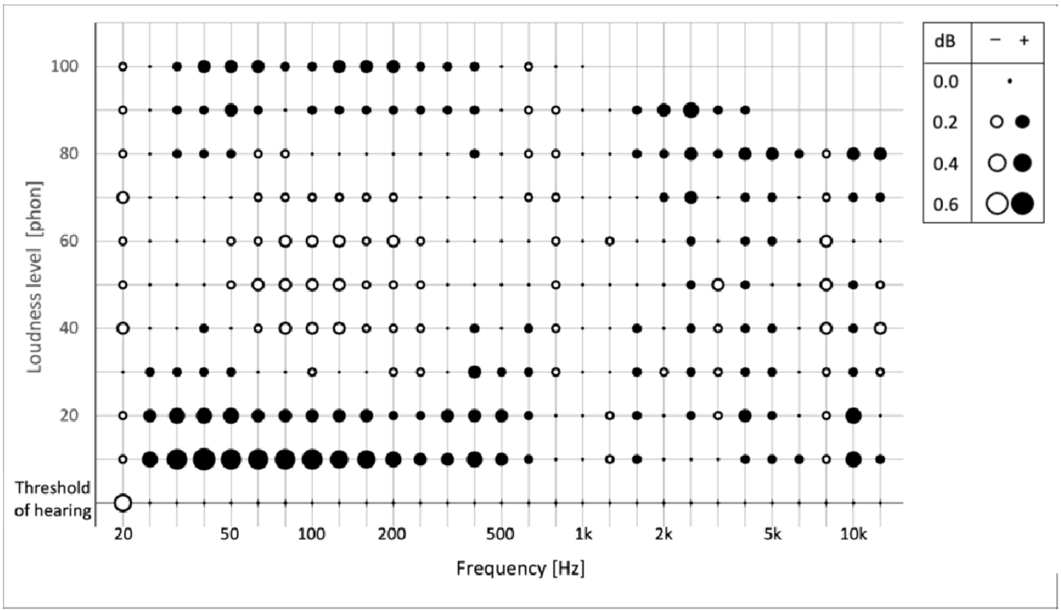

Fig. 4 Differences in dB between the equal-loudness levels based on the 2003 and 2023 editions of ISO 226. The areas of the circles are proportional to the dB difference, and the filled and open circles, respectively, indicate that the value in the 2023 edition is larger or smaller than in the 2003 edition.

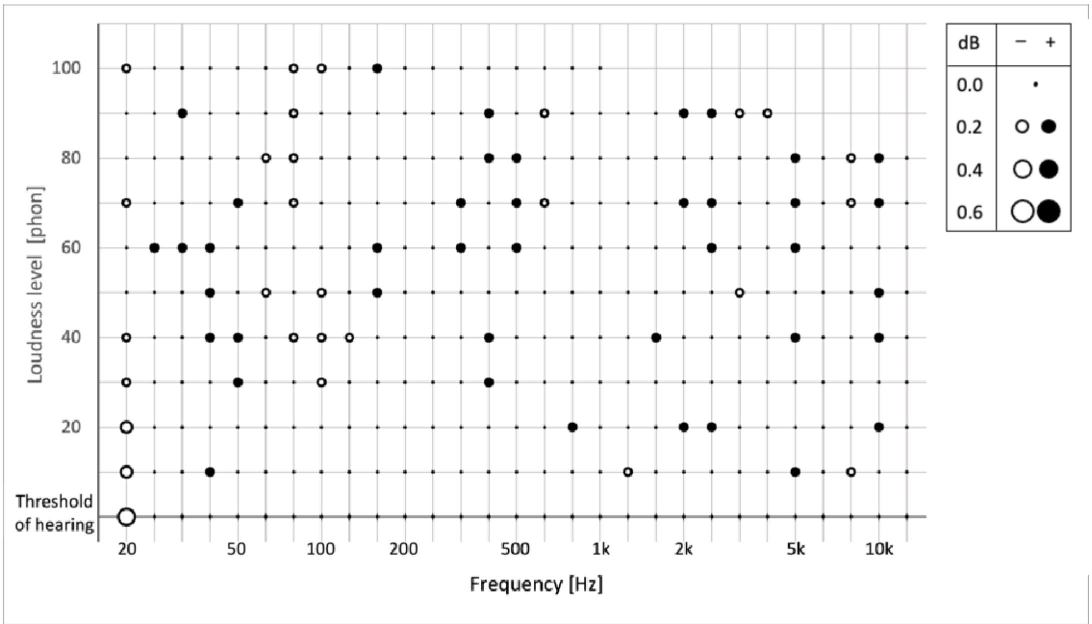

Fig. A Differences in dB between the equal-loudness levels based on the JASA 2004 paper [6] and the 2023 edition of ISO 226. The notation is the same as for Fig. 4.