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JASA ARTICLE

Hearing threshold quartiles from the 1999–2006 National Health and Nutrition Examination Surveys

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ABSTRACT:
This report extends the development of normative standards for estimating occupational hearing loss using data from the United States National Health and Nutrition Examination Survey (NHANES) conducted by the National Center for Health Statistics. A proposed revision of the International Organization for Standardization (ISO) 1999:2013 standard ("Acoustics—Estimation on noise-induced hearing loss") uses a linear interpolation of hearing threshold data to estimate the 25th and 75th percentiles for men and women at 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz. This paper revisits the NHANES data to provide these estimates, avoiding other types of interpolations that could misrepresent the population data. https://doi.org/10.1121/10.0035784

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I. INTRODUCTION

Percentiles of threshold distributions can be used to help discriminate between age- and exposure-related components of cross-sectional trends and longitudinal differences in hearing sensitivity at the group level, e.g., see ISO-1999:2013 (ISO, 2013) and ANSI/ASA S3.44-2016 (ANSI, 2016). In this approach, age-related hearing loss (ARHL) and noise-induced hearing loss (NIHL) components are identified separately and combined to estimate the expected distributions of thresholds within groups of similar age and noise exposure. Insufficient longitudinal data often forces investigators to estimate ARHL distributions from cross-sectional data (Dobie and Wojcik, 2015; Dobie, 2006). Population-based cross-sectional trends among people without significant noise exposure tend to overestimate longitudinal hearing threshold changes among occupationally-exposed workers (Flamme *et al.*, 2020). Nonetheless, methods like those used in ISO-1999 (ISO, 2013) and ANSI S3.44 (ANSI, 2016) are used frequently and require periodic updating.

Future revisions of ISO-1999 and ANSI/ASA S3.44 are expected to include the 5th, 10th, 25th, 50th, 75th, 90th, and 95th percentiles. These standards have historically expressed percentiles as exceedance proportions or fractions exceeding the nominal value, and therefore are complements of the nominal percentile (i.e., the 5th percentile is the 95% fractile). Some publications that have been or could be used as a basis for these standards do not include all of these percentiles (Hoffman *et al.*, 2010, 2012; Johansson and Arlinger, 2002; Von Gablenz and Holube, 2016). Hence, reasonable approaches must be used to specify the missing values. For example, the 25th and 75th percentiles were not included in the original manuscripts used in ISO-1999:2013 Table B.3 for the U.S. population.

When empirical results are unavailable, model-based approaches have been used. Common theoretical approaches begin with assumptions about the shape of the threshold distributions and use reported percentiles of those distributions to estimate other percentiles on those distributions. Parametric distributions (e.g., Gaussian/Normal, Weibull, Asymmetric Sigmoid) are often preferred for ease of facilitating interpolation and extrapolation (Flamme *et al.*, 2011). For example, the split-Gaussian distribution (i.e., a Gaussian distribution with different variances below and above the median) has been used (e.g., Johnson, 1978). Model-based estimates of percentiles can be expected to approximate empirical values only to the extent that the hypothesized distribution represents the empirical data. The split-Gaussian method has relied upon using the median and percentile values to estimate the standard deviations for the upper and lower half distributions. If each half is Gaussian, the estimated standard deviations can be used for interpolation or extrapolation of other percentiles. Interpolated values nearer the central are likely to represent empirical values better than extrapolated values in the tails of the distribution. The accuracy of percentile estimates derived from parametric-based approaches cannot be known without reference to the empirical data.

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In this study, the percentiles were estimated from the original data and compared with prior studies (Hoffman *et al.*, 2010, 2012). Missing 25th and 75th percentiles were estimated for the prior studies using the split-Gaussian method and compared with the newly determined empirical estimates of the 25th and 75th percentiles for men and women at each frequency and for each age group that are reported in this manuscript. Because Hoffman *et al.* (2010, 2012) reported the estimates of the 5th and 95th percentiles, descriptions of the results from extrapolation are not included in this manuscript.

II. METHOD

Source data for the current study include percentiles produced by Hoffman *et al.* (2010, 2012), which were drawn from the 1999 to 2006 United States National Health and Nutrition Examination Survey (NHANES) cycles. The 25th and 75th percentiles were calculated using SUDAAN® Statistical Software for analysis of studies with complex survey design features (based on random selection of primary sampling units, clustering, stratification, and weighting of observations), and Taylor series linearization was used for calculating standard errors. These methods are the same as were used in deriving the original tables. Publicly-available deidentified NHANES data were downloaded from the National Center for Health Statistics (NCHS) website, https://wwwn.cdc.gov/nchs/nhanes/. As in earlier reports using NHANES data (Hoffman *et al.*, 2010, 2012), we considered a measured threshold of "x" dB hearing level (HL) to be the midpoint of the interval from "$x - 2.5$" to "$x + 2.5$" dB HL. This "midpoint" convention has the

TABLE I. Statistical distribution of hearing threshold levels in decibels for men in the U.S., based on NHANES cycles 1999 to 2006 as reported by Hoffman *et al.* (2010, 2012). The 25th and 75th percentile interpolated estimates are highlighted with gray shading and bold fonts.

		Hearing threshold level for men (dB HL) by frequency						
Age	Percentile	500 Hz	1000 Hz	2000 Hz	3000 Hz	4000 Hz	6000 Hz	8000 Hz
25–34	5%	−2	−5	−7	−6	−5	−3	−5
	10%	−1	−2	−5	−5	−2	0	−2
	25%	**3**	**1**	**−1**	**−1**	**2**	**5**	**3**
	50%	7	4	4	4	7	11	8
	75%	**12**	**9**	**9**	**11**	**15**	**19**	**15**
	90%	16	14	14	17	23	27	21
	95%	20	17	19	23	34	34	30
35–44	5%	−2	−2	−6	−4	−1	2	−1
	10%	−1	−1	−3	−1	2	4	2
	25%	**3**	**2**	**1**	**4**	**7**	**10**	**8**
	50%	8	6	6	9	13	17	14
	75%	**14**	**12**	**13**	**20**	**27**	**30**	**28**
	90%	19	17	20	29	39	41	41
	95%	22	21	24	39	53	57	57
45–54	5%	−1	−1	−2	0	3	6	4
	10%	1	1	0	3	6	9	7
	25%	**5**	**5**	**5**	**9**	**14**	**17**	**15**
	50%	10	9	10	15	22	25	23
	75%	**15**	**14**	**17**	**31**	**40**	**46**	**43**
	90%	20	18	24	45	57	64	61
	95%	24	24	34	56	67	75	74
55–64	5%	−1	−2	−1	4	9	13	8
	10%	2	1	3	7	13	16	13
	25%	**6**	**6**	**8**	**16**	**23**	**27**	**27**
	50%	11	11	14	25	35	40	42
	75%	**17**	**17**	**27**	**42**	**51**	**58**	**61**
	90%	23	23	38	57	65	74	78
	95%	29	32	50	65	72	79	84
65–74	5%	1	3	4	10	15	20	23
	10%	4	4	6	13	20	26	30
	25%	**9**	**9**	**13**	**24**	**34**	**40**	**44**
	50%	15	14	21	37	49	56	60
	75%	**22**	**23**	**38**	**52**	**62**	**71**	**74**
	90%	28	31	54	66	73	84	86
	95%	35	39	61	72	80	93	93

desirable property that percentiles estimated by linear interpolation correspond closely and without bias to those estimated by simply counting cases, by using a spreadsheet such as MS Excel™, or by using the grouped-data method (Dobie, 2006). The minimum of right and left ear thresholds at each stimulus frequency was used to define the better threshold at that frequency. See Hoffman *et al*. (2010, 2012) for additional details.

Interpolated estimates of 25th and 75th percentiles were made using an approach similar to that of ISO-1999:2013 (Johnson, 1978),

$$P_{25} = \mu - \mathrm{norminv}(0.25)\sigma_{lower} = P_{50} - \frac{0.6745 \cdot (P_{50} - P_{10})}{1.28155}, \quad (1)$$

$$P_{75} = \mu + \mathrm{norminv}(0.75)\sigma_{upper} = P_{50} + \frac{0.6745 \cdot (P_{90} - P_{50})}{1.28155}, \quad (2)$$

where P_{xx} are the xx percentile estimates from the empirical data and the constants (0.6745, 1.28155) in the fractions are determined for the 25th/75th and 10th/90th percentile probabilities of the inverse standard normal probability function. The function, norminv(p), returns the inverse of the standard normal cumulative distribution function, evaluated at the probability values in p. This process is numerically more precise than the graphical procedure of drawing straight lines on normal probability paper that was used by Johnson (1978). Other percentiles (e.g., 95th and 5th) can be estimated with this approach, but the potential for error is even

TABLE II. Statistical distribution of hearing threshold levels in decibels for women in the U.S., based on NHANES cycles 1999 to 2006 as reported by Hoffman *et al*. (2010, 2012). The 25th and 75th percentile interpolated estimates are highlighted with gray shading and bold fonts.

		Hearing threshold level for women (dB HL) by frequency						
Age	Percentile	500 Hz	1000 Hz	2000 Hz	3000 Hz	4000 Hz	6000 Hz	8000 Hz
	5%	−2	−5	−7	−8	−8	−3	−5
	10%	0	−3	−4	−6	−5	0	−2
	25%	**3**	**0**	**−1**	**−2**	**−1**	**5**	**2**
25–34	50%	7	4	4	2	4	10	7
	75%	**12**	**8**	**7**	**7**	**9**	**15**	**12**
	90%	17	12	12	11	14	22	17
	95%	20	15	14	14	16	26	22
	5%	−2	−4	−5	−6	−5	0	−2
	10%	−1	−2	−2	−2	−2	3	1
	25%	**3**	**1**	**1**	**2**	**2**	**7**	**5**
35–44	50%	7	5	5	4	7	12	10
	75%	**12**	**10**	**10**	**10**	**12**	**20**	**17**
	90%	19	15	16	15	19	27	25
	95%	24	20	21	21	25	31	31
	5%	−1	−2	−4	−4	−2	1	1
	10%	1	−1	−1	−2	0	4	4
	25%	**5**	**3**	**3**	**2**	**5**	**9**	**9**
45–54	50%	9	7	7	7	10	17	16
	75%	**15**	**12**	**13**	**14**	**17**	**26**	**25**
	90%	21	19	21	21	26	34	39
	95%	26	23	27	27	32	40	48
	5%	3	−1	−1	−1	1	7	7
	10%	4	1	1	2	4	9	10
	25%	**8**	**5**	**6**	**6**	**9**	**14**	**17**
55–64	50%	13	10	11	12	16	24	26
	75%	**20**	**17**	**19**	**22**	**26**	**34**	**42**
	90%	27	26	28	33	40	49	58
	95%	35	34	37	43	51	58	66
	5%	2	1	2	5	7	14	11
	10%	5	3	4	8	10	17	16
	25%	**10**	**8**	**10**	**13**	**16**	**25**	**28**
65–74	50%	17	13	17	20	27	37	48
	75%	**24**	**23**	**24**	**32**	**40**	**51**	**62**
	90%	32	33	35	42	48	61	74
	95%	44	37	40	47	54	66	81

greater when this method is used to extrapolate hearing thresholds.

III. RESULTS

A. Original percentiles and interpolated estimates

Table I replicates the results reported by Hoffman *et al.* (2010, 2012) and adds the 25th and 75th percentile interpolated estimates per Eqs. (1) and (2) for men as a function of 10-year age bands. The 25th and 75th percentile interpolated estimates are highlighted with gray shading and bold fonts.

Table II replicates results reported earlier by Hoffman *et al.* (2010, 2012) and adds the 25th and 75th percentile interpolated estimates for women as a function of 10-year age bands. The 25th and 75th percentile interpolated estimates are highlighted with gray shading and bold fonts.

B. Empirical estimates

The updated distributions were estimated from the same NHANES datasets used by Hoffman *et al.* (2010, 2012). In this analysis, the results agreed precisely for men and women ages 25 to 64 at all frequencies. For the 65- to 74-year-old men and women, percentile differences between the Hoffman *et al.* (2012) and the newly derived empirical estimates were less than 1 dB, except for the 95th percentile for women at 500 Hz and 95th percentile for men at 8000 Hz. See Tables III and IV.

TABLE III. Updated statistical distribution of hearing threshold levels in decibels for men in the U.S., based on NHANES cycles 1999 to 2006. The 25th and 75th percentile empirical estimates are highlighted with gray shading and bold fonts. The empirical estimates that differ from the Hoffman *et al.* (2012) analysis are shown with italicized bold fonts and dark gray shading.

		Hearing threshold level for men (dB HL) by frequency						
Age	Percentile	500 Hz	1000 Hz	2000 Hz	3000 Hz	4000 Hz	6000 Hz	8000 Hz
25–34	5%	−2	−5	−7	−6	−5	−3	−5
	10%	−1	−2	−5	−5	−2	0	−2
	25%	**3**	**0**	**−1**	**−1**	**2**	**5**	**3**
	50%	7	4	4	4	7	11	8
	75%	**11**	**9**	**9**	**11**	**14**	**17**	**15**
	90%	16	14	14	17	23	27	21
	95%	20	17	19	23	34	34	30
35–44	5%	−2	−2	−6	−4	−1	2	−1
	10%	−1	−1	−3	−1	2	4	2
	25%	**3**	**2**	**1**	**3**	**7**	**10**	**7**
	50%	8	6	6	9	13	17	14
	75%	**13**	**12**	**12**	**17**	**22**	**27**	**25**
	90%	19	17	20	29	39	41	41
	95%	22	21	24	39	53	57	57
45–54	5%	−1	−1	−2	0	3	6	4
	10%	1	1	0	3	6	9	7
	25%	**5**	**4**	**4**	**8**	**12**	**16**	**14**
	50%	10	9	10	15	22	25	23
	75%	**14**	**13**	**16**	**25**	**37**	**41**	**40**
	90%	20	18	24	45	57	64	61
	95%	24	24	34	56	67	75	74
55–64	5%	−1	−2	−1	4	9	13	8
	10%	2	1	3	7	13	16	13
	25%	**6**	**5**	**8**	**15**	**22**	**24**	**22**
	50%	11	11	14	25	35	40	42
	75%	**17**	**18**	**23**	**44**	**55**	**60**	**61**
	90%	23	23	38	57	65	74	78
	95%	29	32	50	65	72	79	84
65–74	5%	***2***	3	4	10	15	20	***24***
	10%	4	4	6	13	20	26	30
	25%	**9**	**8**	**12**	**21**	**32**	**40**	**44**
	50%	15	14	21	37	49	**55**	60
	75%	**21**	**21**	**35**	**56**	**63**	**70**	**72**
	90%	***27***	***30***	54	***65***	***72***	84	***85***
	95%	35	***38***	***60***	***71***	80	***92***	***91***

TABLE IV. Updated statistical distribution of hearing threshold levels in decibels for women in the U.S., based on NHANES cycles 1999 to 2006. The 25th and 75th percentile empirical estimates are highlighted with gray shading and bold fonts. The empirical estimates that differ from the Hoffman *et al.* (2012) analysis are shown with italicized bold fonts and dark gray shading.

		Hearing threshold level for women (dB HL) by frequency						
Age	Percentile	500 Hz	1000 Hz	2000 Hz	3000 Hz	4000 Hz	6000 Hz	8000 Hz
25–34	5%	−2	−5	−7	−8	−8	−3	−5
	10%	0	−3	−4	−6	−5	0	−2
	25%	**3**	**0**	**−1**	**−2**	**−1**	**5**	**2**
	50%	7	4	4	2	4	10	7
	75%	**12**	**8**	**7**	**7**	**9**	**15**	**12**
	90%	17	12	12	11	14	22	17
	95%	20	15	14	14	16	26	22
35–44	5%	−2	−4	−5	−6	−5	0	−2
	10%	−1	−2	−2	−2	−2	3	1
	25%	**3**	**1**	**1**	**2**	**2**	**7**	**5**
	50%	7	5	5	4	7	12	10
	75%	**12**	**10**	**10**	**10**	**12**	**20**	**17**
	90%	19	15	16	15	19	27	25
	95%	24	20	21	21	25	31	31
45–54	5%	−1	−2	−4	−4	−2	1	1
	10%	1	−1	−1	−2	0	4	4
	25%	**5**	**3**	**3**	**2**	**5**	**9**	**9**
	50%	9	7	7	7	10	17	16
	75%	**15**	**12**	**13**	**14**	**17**	**26**	**25**
	90%	21	19	21	21	26	34	39
	95%	26	23	27	27	32	40	48
55–64	5%	3	−1	−1	−1	1	7	7
	10%	4	1	1	2	4	9	10
	25%	**8**	**5**	**6**	**6**	**9**	**14**	**17**
	50%	13	10	11	12	16	24	26
	75%	**20**	**17**	**19**	**22**	**26**	**34**	**42**
	90%	27	26	28	33	40	49	58
	95%	35	34	37	43	51	58	66
65–74	5%	2	***2***	2	5	7	14	***10***
	10%	5	***3***	4	8	10	17	16
	25%	**10**	**8**	**10**	**13**	**16**	**25**	**28**
	50%	17	13	17	20	27	37	***47***
	75%	**24**	**23**	**24**	**32**	**40**	**51**	**62**
	90%	32	33	35	***41***	48	61	***73***
	95%	***42***	37	***39***	***46***	***53***	66	***80***

C. Comparing interpolated and empirical estimates

Figure 1 illustrates a selection of the results from Hoffman *et al.* (2010, 2012), updated empirical estimates, and the percentile estimates from the split-Gaussian model for men in each age group at 6000 Hz. The empirical estimates are shown as unfilled blue diamonds and estimates from Hoffman *et al.* (2010, 2012) are shown as filled black squares; when these two estimates overlap, the superimposed unfilled blue diamonds are shown on top of the filled black squares. The split-Gaussian model estimates are shown as unfilled red circles. Although the 25th and 75th percentile estimates are the focus of this paper, the extrapolated 5th and 95th percentiles are included in Fig. 1 to demonstrate the shortcomings of using the parametric model to extrapolate into the tails of the distributions.

In Fig. 2, the differences at the 25th and 75th percentiles between the empirical and the split-Gaussian interpolated values were calculated for men (upper panel) and women (lower panel), frequencies (500 to 8000 Hz), and age bands (each one with differently shaped symbols). The ranges are shown by frequency and plotted for separate age bands. For women, the magnitude of the differences were 3 dB or less. For the three age bands encompassing 25 through 54 years, the differences were 1 or 2 dB for the 25th percentile for men and women. However, for the 75th percentile, the differences for men were as much as 4 to 6 dB.

IV. DISCUSSION

The present study reports hearing threshold percentiles as a function of age separately for men and women, based

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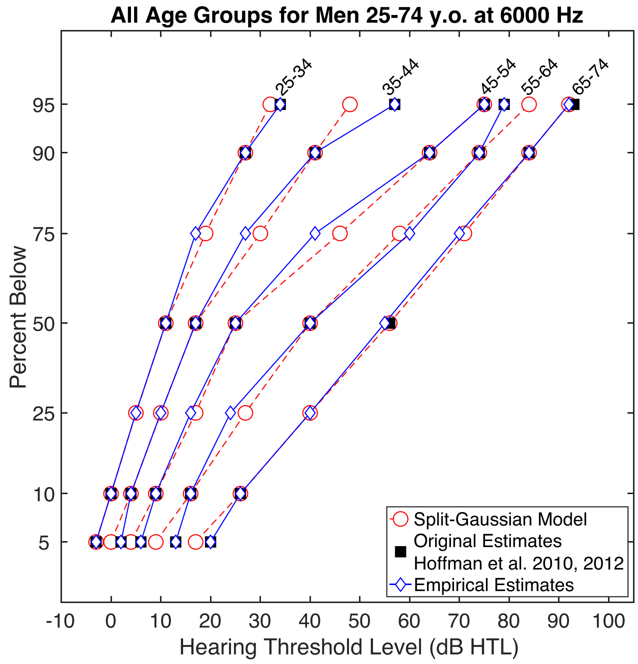

FIG. 1. Comparison of the original percentile estimates (filled black squares) from Hoffman *et al.* (2010, 2012) and the updated empirical estimates (unfilled blue diamonds); when these two estimates overlap, the superimposed unfilled blue diamonds are shown on top of the filled black squares. The split-Gaussian model estimates are shown as unfilled red circles. The interpolated estimates at the 25th and 75th percentiles exhibit more differences at the 75th percentile. The split-Gaussian extrapolated 5th and 95th percentiles exhibit differences with both the Hoffman and the empirical estimates.

on previous papers (Hoffman *et al.*, 2010, 2012) and recent analyses calculating proposed 25th and 75th percentiles. The empirical threshold percentile estimates were compared against a historical interpolation method (split-Gaussian) wherein these percentiles were calculated based on an assumed normal distribution having different variances above and below the median. The new percentiles are intended for investigators who want to compare threshold values from other studies to percentiles based on standard population normative data.

While empirical percentiles are preferred over interpolated values, the current results indicate that the 25th and 75th percentiles can be estimated by interpolation with a reasonable margin of error for women through about 54 years of age (Fig. 2). For men and for women over 54 years of age, split-Gaussian interpolation yielded substantial differences, particularly for the 75th percentile. This behavior is consistent with a distribution that becomes more asymmetric as age progresses. In addition, men trended toward worse hearing thresholds than women as a function of age. In future studies, we recommend researchers make empirical 5th, 10th, 25th, 50th, 75th, 90th, and 95th percentiles available whenever possible.

A. Biases and limitations

The interpolation results in this study were compared to the dataset used by Hoffman *et al.* (2010, 2012), and it must be conceded that these results might not generalize to populations with fundamentally different threshold distributions. While one could expect similarity in the shapes of underlying distributions of thresholds from nationally representative studies, differences across time periods and geography do occur. For example, subsequent analyses of the U.S. NHANES data (Hoffman *et al.*, 2017) indicate that the U.S. population for ages 25–69 in 2011–2012 had better hearing sensitivity compared to 1999–2004 NHANES cycles.

The thresholds presented in this paper represent the better threshold for individual stimulus frequencies in either ear. Averages based on tables of this type are not a representation of a "better ear." The better threshold at 500 Hz might be observed in a different ear than the better threshold at 2000 Hz, so any pure-tone average across stimulus frequencies is a composite of the best thresholds in either ear and not necessarily the ear with the best pure-tone average hearing sensitivity. Averages across stimulus frequencies taken from these tables will likely overestimate better ear hearing sensitivity at the population level.

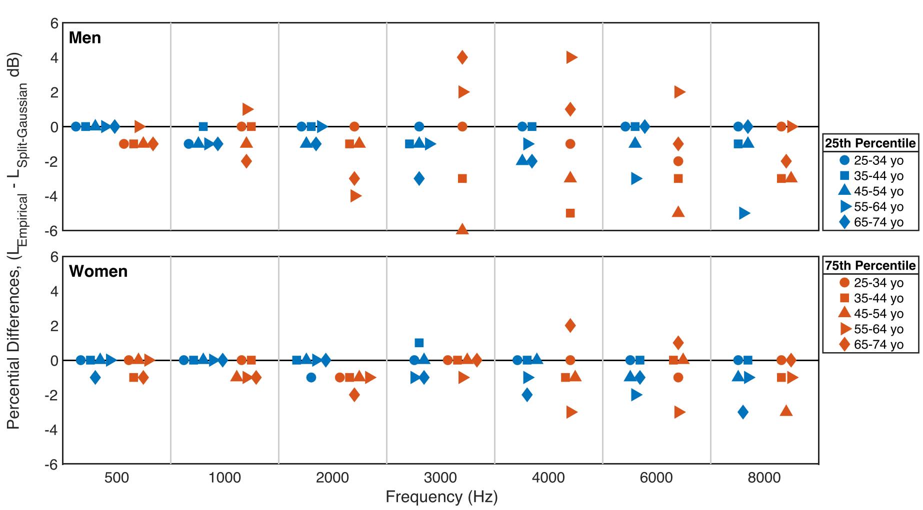

FIG. 2. The percentile differences for men and women as a function of the frequencies tested. At each frequency, the differences between observed and the interpolated 25th and 75th values are plotted. Age groups are represented by different symbols and are jittered to facilitate viewing the differences. The blue symbols are the 25th percentile differences and the orange symbols are the 75th percentile differences.

V. CONCLUSIONS

The present study produced empirical 25th and 75th percentile values that are compatible with and should be considered for inclusion in, upcoming revisions of ISO-1999 and ANSI S3.44. The split-Gaussian interpolation provides a less accurate fit to the empirical values for men and women over the age of 54.

AUTHOR DECLARATIONS

Conflict of Interest

The authors declare no conflicts of interest specific to this manuscript. H.J.H. works for NIH/NIDCD, which provided partial funding for the NHANES audiometric data collection. C.L.T. works for the CDC/NIOSH and W.J.M. retired from CDC/NIOSH in 2022. C.L.T. trained the technicians that collected audiometric data and she and W.J.M. provided quality control for the audiometric data. K.G.L. was a contractor for NIDCD/NIH to conduct statistical analysis. G.A.F. was a contractor for NIOSH to provide assistance with data collection protocols and analysis. G.A.F., W.J.M., and K.G.L. are employees of Stephenson and Stephenson Research and Consulting and are contractors with CDC/NIOSH to support ongoing NHANES audiometric data collection efforts, provide training to technicians, and support quality assurance. The findings and conclusions in this paper are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention, the National Institute on Deafness and Other Communication Disorders, National Institutes of Health.

Ethics Approval

This research was conducted using publicly available de-identified NHANES survey data that were collected by the Centers for Disease Control and Prevention, National Institute for Health Statistics. Informed consent was provided to all participants in the NHANES survey.

DATA AVAILABILITY

The datasets may be accessed at https://www.cdc.gov/nchs/nhanes/index.html.

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