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Article

Longitudinal Effect of Music Exposure on Hearing Among Vocal Performance Students

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Abstract: The effects of music exposure on vocal performers remain relatively unknown. This study aimed to assess the immediate and long-term effects of music and singing practice on the peripheral auditory system of vocal performers using otoscopy, pure-tone audiometry, and noise dosimetry. The hearing status, sound pressure levels (SPLs), and sound doses of 12 vocal performers with normal hearing at the study's onset were evaluated. Pre- and post-study questionnaires regarding the participants' otologic health and music-making activities, as well as repeated hearing evaluations, were implemented. Additionally, noise dosimetry was conducted on each participant's most vocally active day of the week. Audiometric assessments generally revealed normal hearing thresholds, with some exceptions. Half of the participants exhibited elevated low-frequency thresholds and over half of the participants displayed emerging audiometric "notches" at 6000 Hz. Noise dosimetry measurements indicated that most of the participants were consistently exposed to SPLs during music-making activities that exceeded recommended limits. Questionnaire responses highlighted that the participants often engaged in extra-curricular music-making activities, frequently with piano accompaniment, and with little to no use of hearing protection devices. A few of the participants reported histories of otologic issues and potential hearing problems.

Keywords: noise exposure; noise-induced hearing loss; music exposure; vocal performers

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1. Introduction

1.1. Noise Exposure and Noise-Induced Hearing Loss (NIHL)

Recreational sound exposure, including music, is often overlooked as a potential hazard contributing to noise-induced hearing loss (NIHL). However, noise exposure is the most common occupational and recreational hazard, and the second leading cause of acquired sensorineural hearing loss (SNHL) after age-related hearing loss [1]. Noise refers to unwanted and/or harmful sound pressure levels (SPLs), while sound is defined as vibrations traveling through a medium, typically air, that can be heard [2]. SNHL specifically affects the inner ear (sensory) and auditory nerve (neural) [3]. NIHL can develop gradually through persistent exposure to high SPLs over time, or suddenly due to acoustic trauma from instantaneous, impulsive, very high SPLs [4,5]. The progression of NIHL typically begins with a temporary threshold shift (TTS), where initial, reversible damage occurs to the hair cells within the cochlea (inner ear); threshold being the lowest detectable sound pressure level [6]. With continued exposure, this can lead to a permanent threshold shift (PTS), resulting in lasting damage [4]. Audiometrically, NIHL is characterized by a "notch" in pure-tone air-conduction thresholds between 3000 and 6000 Hz [3]. This frequency range is particularly vulnerable to the effects of noise exposure due to the ear canal resonance, which can amplify SPLs by 20 dB or more [3]. Lees et al. [7] defined a noise notch as a 10 dB depression of hearing thresholds below the audiometric frequencies on both sides. Understanding these mechanisms and characteristics of NIHL is crucial for recognizing and preventing hearing damage from various sound sources, including music.

Research on noise exposure's effects on hearing has a long history, with studies on occupational noise exposure dating back centuries [8]. However, investigations into music's impact on auditory health only began in the 1960s [8]. Consequently, most research on the effects of sound exposure on one's auditory health focuses on occupational (work-related) rather than recreational sound exposure. Audiometrically, occupational noise exposure manifests as a "boilermaker's notch", characterized by a "notch" at 4000 Hz [3]. This extensive research has led to the establishment of occupational noise exposure standards by the Occupational Safety and Health Administration (OSHA) and the National Institute for Occupational Safety and Health (NIOSH). These standards incorporate key concepts such as exchange rate, criterion sound level, and time-weighted average (TWA). Exchange rate is a value in dBA that when added to the overall noise level requires the exposure time to be cut in half [9]. Criterion sound level is the level of sound that, when averaged over an 8 h workday, produces a noise dose of 100% [9]. Noise dose refers to the amount of noise an individual is exposed to over a duration of time [10]. TWA describes the method of calculating an individual's noise dose for a given period of time [11]. OSHA and NIOSH standards differ slightly in their specifications. OSHA sets a maximum sound level of 115 dBA, an exchange rate of 5 dBA, a criterion sound level of 90 dBA, and recommends implementing a hearing conservation program when noise dose is at or above 85 dBA averaged over 8 h (8 h TWA) [12]. In contrast, NIOSH recommends an exchange rate of 3 dBA, a criterion sound level of 85 dBA, and a recommended exposure limit (REL) of 85 dBA averaged over 8 h (8 h TWA) [13]. These standards use A-weighted decibels (dBA), which most closely approximates the response of the human ear to relatively weak sounds [11]. Decibel (dB) is a ratio unit of measurement used to express SPLs on a logarithmic scale [10].

1.2. Music Exposure and Music-Induced Hearing Disorders (MIHDs)

Musicians may be at a higher risk of developing hearing loss or other hearing-related disorders than industrial workers due to the unique nature of music-making activities [14]. The exposure patterns and sound characteristics in musical settings differ significantly from those in industrial environments. Unlike the typical 8 h, 5 day work week of industrial workers, musicians often experience irregular exposure patterns, and may be subjected to higher SPLs over shorter durations [15]. Royster et al. [16] found that the average sound dose in classical musicians is comparable to that of industrial workers at 85.5 dBA, which slightly exceeds NIOSH's REL and OSHA's standard for implementing a hearing conservation program. However, maximum SPLs for musicians can be considerably higher, ranging from 83 to 112 dBA [17]. Similarly, Phillips and Mace [18] reported that college music students and faculty are typically exposed to SPLs between 80 and 104.5 dBA.

Given these differences, applying industrial noise exposure standards (OSHA or NIOSH) to musicians may not be appropriate [19]. However, specific music exposure standards have not been established nationally or internationally. To address this gap, the American Academy of Audiology (AAA) created a task force to develop clinical guidelines for audiological services for musicians and music industry personnel. The task force recommended the use of current OSHA and NIOSH guidelines for calculating music exposure and assessing the risk of music-induced hearing disorders (MIHDs) [15].

MIHDs encompass various conditions, including music-induced hearing loss (MIHL), tinnitus, hyperacusis, diplacusis, and dysacusis [17]. MIHL, like NIHL, is characterized by temporary and permanent threshold shifts resulting from overexposure to high SPLs [20]. Audiometrically, MIHL typically presents as a "notch" in the range of 3000–6000 Hz, with the majority seen at 6000 Hz [17,21]. However, MIHL differs from NIHL in that music is the damaging stimulus, it can lead to a higher incidence of asymmetric hearing loss, and its clinical presentation is less predictable due to greater variability in exposure [15].

Hyperacusis, diplacusis, and dysacusis are distinct auditory disorders that affect sound perception in different ways. Hyperacusis is characterized by an abnormally heightened sensitivity to sound, causing ordinary sounds to be perceived as excessively loud or even painful [22]. Diplacusis, on the other hand, involves a distortion in pitch perception, where the same sound may be heard at different frequencies in each ear [22]. Lastly, dysacusis manifests as a decrease in auditory clarity or a distortion in frequency perception, affecting the overall quality of sound experienced by an individual [15].

For musicians, hearing is crucial for providing feedback during practice and performance. Hearing disorders can significantly impact a musician's ability to perceive and produce accurate pitch, loudness, timbre, tempo, and style. Beyond communication difficulties and reduced quality of life, hearing disorders pose a substantial threat to musicians' careers, lifestyles, and artistic expression [15]. Research has shown a prevalence of MIHL ranging from 37 to 58% in classical musicians [17], while Comeau et al. [21] found that 85% of student musicians exhibited a "notch" at 6000 Hz. The prevalence of tinnitus among professional musicians (both classical and pop/rock) is 26.3%, with a relatively equal distribution across musical genres [22]. Ziegler and Taylor [23] reported that 58.9% of music students in a small music department at a private college experienced tinnitus to some degree. Although less prevalent, hyperacusis, diplacusis, and dysacusis also contribute to hearing difficulties in both professional and student musicians [22,24].

1.3. Music Exposure and MIHDs Among Vocal Performers

Research on music exposure and MIHDs among vocal performers is relatively scarce compared to studies on instrumentalists. The limited existing research primarily focuses on choral singing, with fewer studies examining voice teaching and non-choral singing. Despite the common perception that the human voice may not produce SPLs comparable to musical instruments, choirs can generate SPLs exceeding 110 dBA, similar to an orchestral ensemble [25]. However, it is crucial to remember that acquired sound doses vary depending on venue and context [10].

Within choirs, sopranos typically experience higher sound doses (with a mean of 94 dBA) compared to other voice parts (with a mean of 92 dBA), likely due to the higher frequency sound waves they produce. Interestingly, this increased exposure does not necessarily translate to greater hearing damage among sopranos. Steurer et al. [26] found no significant difference in hearing acuity among the different voice parts among choir singers, although they did find that low-frequency thresholds were most affected among the singers. These findings contrast with typical MIHL patterns, possibly due to the predominance of sound stimuli below 1000–500 Hz in choral singing [10,27].

Research on voice teachers and vocal performance students aligns more closely with general MIHL findings, showing bilateral high-frequency SNHL as the most common type [25,28]. Hu et al. [25] observed slightly worse thresholds in the left ear, attributed to its proximity to other sound sources in the environment. Voice teachers show a higher prevalence of MIHL (51.7%) compared to vocal performers (17.5%), with age, years of music exposure, gender, and voice type being associated with greater hearing loss [25,29].

Regarding sound exposure, Redman et al. [28] found that six out of eight voice teachers experience sound doses exceeding NIOSH recommendations. For vocal performance students not in choral settings, Phillips and Mace [18] reported noise doses of 88.4 dBA. These findings underscore the need for further research and preventative measures to protect the hearing health of vocal performers and teachers.

1.4. Longitudinal Studies on Music Exposure and MIHDs Among Musicians and/or Vocal Performers

While research on music exposure and MIHDs in musicians and vocal performers continues to expand, a critical gap remains in our understanding of the long-term effects. A comprehensive review of the current literature reveals a notable absence of longitudinal studies examining the prolonged impact of music exposure and the associated risk of

MIHDs in these populations. To this date, no known studies have investigated the long-term consequences of music exposure on hearing health for musicians or vocal performers.

This gap in knowledge underscores the urgent need for research to determine whether professional and academic vocal activities pose a significant threat for MIHDs due to prolonged music exposure. Longitudinal studies in this area would provide valuable insights into the cumulative effects of music exposure over time, potentially informing more effective preventative measures and hearing conservation strategies for musicians and vocal performers.

1.5. Research Questions

This study aimed to address the following key research questions:

1. Do students at the University of Illinois Urbana-Champaign (UIUC) in vocal performance experience SPLs that exceed the recommended limits?
2. Does exposure to SPLs change throughout the vocal performance curriculum at UIUC?
3. What is the prevalence of MIHDs among vocal performance students at UIUC?
4. Are certain voice types at a higher risk of developing MIHDs due to exposure to elevated SPLs?
5. Is there a need for the development and implementation of a hearing conservation program specifically tailored for UIUC vocal performance students?

2. Materials and Methods

2.1. Participants

This study involved 12 vocal performance students from UIUC, all of whom had normal hearing at the onset of the study. Participant demographics are summarized in Table 1. Recruitment was conducted through departmental email, which outlined the study's objectives, measurement procedures, equipment used, testing duration, and assured participant confidentiality. All study procedures were approved by the Institutional Review Board at the University of Illinois Urbana-Champaign (IRB #22413).

Table 1. Demographic Information: age (at the beginning of the study), gender, voice type, and years of vocal experience (solo and/or ensemble).

Participant (Number)	Age Range (Years)	Gender	Voice Type	Vocal Experience (Years)
1	19	Female	Mezzo-Soprano	7
2	29	Male	Tenor	11
3	23	Female	Soprano	6
4	24	Male	Baritone	8
5	20	Female	Soprano	8
6	40	Male	Baritone	10
7	26	Male	Baritone	8
8	22	Female	Mezzo-Soprano	5
9	24	Male	Tenor	16
10	23	Female	Soprano	7
11	22	Male	Baritone	4
12	25	Male	Countertenor	8

2.2. Equipment

The equipment used in this study included twelve TASCAM DR-10L (TEAC, Los Angeles, CA, USA) noise dosimeters equipped with lavalier microphones for sound measurement. Prior to their use, the dosimeters were calibrated in a sound booth against a class 1 Sound Level Meter (XL2 Audio and Acoustic Analyzer, NTI Audio, Tigards, OR, USA).

The initial hearing assessments for semesters 1 and 2 (Fall 2021 and Spring 2022) were conducted at the University of Illinois Speech-Language and Hearing clinic using a GSI 61 audiometer (Grason-Stadler, Eden Prairie, MN, USA) along with corresponding transducers.

However, due to scheduling conflicts and location constraints, the hearing assessments for semesters 3 and 4 (Fall 2022 and Spring 2021) were performed at the University of Illinois Speech and Hearing Sciences Building. It is important to note that the audiometers used in semesters 3 and 4 differed; the audiometer for semester 3 was an Otometrics Madsen Astera 2 (Natus Medical, Middleton, WI, USA), while the one for semester 4 was a GSI Audiostar Pro (Grason-Stadler, Eden Prairie, MN, USA). Despite the change in audiometers, all the devices used were calibrated and the location and transducers (bone oscillator and TDH39 supra-aural headphones) remained consistent throughout all semesters.

2.3. Data Collection Procedure

Data collection for this study comprised three main components: questionnaires, hearing assessments, and noise measurements. Two written questionnaires were administered before the participant's first hearing evaluation at the University of Illinois Speech-Language and Hearing Clinic. The first was a case history questionnaire, which gathered demographic information, participation in music-making activities, noise exposure history, medical history, and otologic history. The second was the American Academy of Audiology's (AAA's) Hearing Health Quick Test, designed to assess the need for a hearing check. This 15-question survey covers hearing difficulties, otologic history, noise exposure, family history, and psychological effects of perceived hearing loss. Scoring is based on a point system: "yes" (2 points), "sometimes" (1 point), and "no" (0 points). A cumulative score of 3 or more suggests a potential hearing problem, while 6 or more warrants a hearing check.

After the completion of the participant's last hearing evaluation, participants met for an individual online meeting debrief, during which the relevant sections of the Health and Wellbeing Questionnaire were filled out. This questionnaire addressed hearing protection use, perceived hearing changes, and awareness, knowledge, competency, and attitudes toward hearing health and well-being as a future professional musician.

Semesterly hearing assessments consisted of otoscopy followed by pure-tone air- and bone-conduction audiometry. This procedure involves viewing the ear canal and tympanic membrane to determine the presence of cerumen (or ear wax), foreign bodies, and anatomical abnormalities.

Hearing assessment results are presented as audiograms, depicting hearing thresholds (the softest sounds we can hear). In these figures, the blue 'X' symbols represent left ear air-conduction thresholds, and the red 'O' symbols represent right ear air-conduction thresholds. Pure-tone bone-conduction thresholds are indicated by '>'. Air-conduction thresholds were obtained at 250, 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz, while bone-conduction thresholds were measured at 500, 1000, 2000, and 4000 Hz. The dotted line at 20 dB HL on the audiograms depicts the boundary of normal hearing. Thresholds above this line ($\leq$20 dB HL) indicate normal hearing, while those below (>20 dB HL) suggest some degree of hearing loss. An increase (or elevation) in hearing threshold denotes a worsening of hearing acuity, while a decrease in hearing threshold indicates improvement. Due to location and tester variability, thresholds obtained from the semesterly hearing evaluations were averaged and presented annually. Each participant was asked to wear the noise dosimeter for 4 h. The time and day of the week varied for each of them, as the only instruction was that participants were asked to wear it during their most vocally active day. Noise dosimetry measurements were conducted each semester on the participants' most vocally active day using 12 TASCAM DR-10L sound recorders (TEAC, Los Angeles, CA, USA) with corresponding lavalier microphones. The participants met with a tester prior to the beginning of their most vocally active day to have their sound recorder applied and turned on. The microphones were clipped to the participants' shoulder, approximately 15 cm from the ear, to measure ear-level SPLs from both the participants and noise from their surrounding environment. Participants were given instructions on how to use the sound recorders. Participants wore the sound recorder throughout the entirety of their most vocally active day whereupon they met with the tester to return the sound recorder. Data from the sound recorders was extracted and analyzed semesterly after each completed session.

2.4. Data Analysis

Sound measurements were extracted from the sound recorders and analyzed using MATLAB (version R2022b) to calculate a time history of A-weighted SPLs with approximately 2 ms time stamps. The analysis focused on two key parameters: instantaneous SPLs in dBA, which are derived from a single 2 s window of a waveform [11], and Equivalent levels (*Leq*) in dBA, which represent the A-weighted equivalent continuous SPL [10]. The equivalent level is calculated as

$$L_{eq} = 10\log\left[\frac{1}{T}\int\left(\frac{p_A}{p_0}\right)^2 dt\right] \quad (1)$$

where T is the monitored time, p_A is the instantaneous pressure (Pa), and p_0 is the reference sound pressure (20 Pa). The sound recorders were set to a sampling rate of 44.1 kHz, and maximum input sound pressure was set to 115 dB SPL. They were calibrated in a soundproof test booth by comparison with a Class 1 Sound Level Meter (XL2 Audio and Acoustic Analyzer, NTI Audio, Tigards, OR, USA). The obtained calibration constant obtained from this procedure was then applied to the MALTAB script to derive absolute SPL values.

To classify the SPLs associated with the different participant activities during each monitoring session, a Gaussian Mixture Model was employed on the distribution of instantaneous dBA levels. This probabilistic model assumes that all data points are generated from a finite number of Gaussian distributions with unknown parameters, extending K-means clustering to include information about the covariance structure of the data, as well as the centers of the latent Gaussians. Based on the number of Gaussian distributions and their means, hypotheses regarding various activities, such as singing exposure, music exposure, and background noise exposure, were formulated.

Histograms of the SPL distributions were created from the time history of instantaneous SPLs showing the relative occurrences of the SPLs recorded. From these histograms and the Gaussian mixture models, three main sound sources/activities were hypothesized: (1) background noise levels, (2) speech levels or choral (group) singing levels, and (3) solo singing levels. Bar graphs were then constructed to better depict the mean SPL for each hypothesized sound source/activity.

For each participant, the equivalent level (*Leq*) during each monitored day was calculated. Following NIOSH's recommended criterion exposure limit of 85 dBA for 8 h, with an exchange rate of 3 dB, the maximum duration of the exposure (T_i) can be calculated as follows:

$$T_i = \frac{8}{2^{\left(\frac{Leq-85}{3}\right)}} \quad (2)$$

This comprehensive analysis approach allowed for a detailed examination of the participants' sound exposure levels and duration throughout the study.

3. Results

3.1. Questionnaires

Two initial written questionnaires were administered to gather background information on the singers prior to testing: the Case History and the AAA's Hearing Health Quick Test. After completion of the study, participants met over an online session and completed the Health and Wellbeing Questionnaire, which aimed to assess what they had learned, how they utilized the study's information, and any perceptual changes in their hearing.

The results from the first two (written) questionnaires indicated that seven out of twelve participants were employed as voice instructors. Among these instructors, five typically used piano accompaniment during instruction. One participant out of the twelve is a choral instructor, and utilizes piano accompaniment during instruction. Additionally, six out of twelve of the participants engaged in additional music-related extracurricular activities, such as church choirs and a cappella groups. Of these six participants, four reported that their environments were noisy, and two noted the presence of an echo.

When asked about otologic history, one participant expressed concerns regarding their hearing and communication abilities, while three participants felt that one ear was better than the other. One participant reported experiencing tinnitus, six had a history of earaches, five had a history of ear infections, four had a history of aural fullness (pressure), one had a history of vertigo or dizziness, and two had a family history of hearing loss.

Regarding the Hearing Health Quick Test, the cumulative scores suggested that five might have a hearing problem, and five others should have their hearing checked. The remaining two participants scored below three, indicating that they likely do not have a hearing problem or need a hearing check. Table 2 provides the scores of each participant.

Table 2. Participant cumulative scores on the American Academy of Audiology's Hearing Health Quick Test.

Participant (Number)	Cumulative Score	Score Suggestion
1	4	possible hearing problem
2	0	healthy hearing
3	2	healthy hearing
4	8	hearing check warranted
5	4	possible hearing problem
6	9	hearing check warranted
7	7	hearing check warranted
8	13	hearing check warranted
9	8	hearing check warranted
10	5	possible hearing problem
11	5	possible hearing problem
12	3	possible hearing problem

The Health and Wellbeing Questionnaire, administered online at the conclusion of the study, provided insights into participants' perceptions of their hearing health and protective behaviors. Of the eleven participants who completed the questionnaire, three reported noticeable changes in their hearing health over the course of the study. One participant described developing increased sensitivity to sound (possibly hyperacusis), while two others noted significant cerumen accumulation despite proper removal and consistent maintenance. Regarding hearing protection practices, the questionnaire revealed that only a minority of participants (four out of eleven) use hearing protection devices when exposed to high SPLs. Among these four, usage patterns varied: two reported seldom wearing hearing protection, primarily during others' performances, while the other two sometimes used hearing protection during both others' performances and during rehearsals with other musicians. Regarding awareness, knowledge, competency, and attitudes toward hearing health and wellbeing as a future professional musician, these findings highlight the limited adoption of hearing protection practices among the study participants, despite their regular exposure to potentially harmful noise levels in their musical activities.

3.2. Hearing Assessments

3.2.1. Otoscopic Examination Findings per Participant

Semesterly otoscopic examinations, conducted prior to each participant's hearing assessment, revealed that in semester 1 (Fall 2021), seven out of twelve participants had partially occluding cerumen in at least one ear. After discussion with the participants about how to properly manage the accumulation of cerumen (e.g., seeing a primary care physician or ENT and/or Debrox), there were fewer participants with partially occluding cerumen in semesters 2 (Spring 2022) through 4 (Spring 2023). However, there were four participants who had ongoing problems with cerumen management, presenting with partially occluding cerumen every semester, despite proper management. Table 3 displays the otoscopic examination results per participant for each semester.

Table 3. Otoscopic observations per participant from otoscopic examinations per semester.

Participant (Number)	Semester 1 (Fall 2021)	Semester 2 (Spring 2022)	Semester 3 (Fall 2022)	Semester 4 (Spring 2023)
1	X	X	X	X
2	Partially occluding (L)	X	X	X
3	Partially occluding (B)	Partially occluding (B)	Partially occluding (B)	Partially occluding (B)
4	Partially occluding (B)	Partially occluding (B)	Partially occluding (B)	Partially occluding (B)
5	Partially occluding (B)	X	X	X
6	X	X	X	X
7	Partially occluding (B)	Partially occluding (B)	Partially occluding (B)	Partially occluding (B)
8	Partially occluding (R)	X	X	X
9	X	X	X	X
10	Partially occluding (B)	Partially occluding (B)	Partially occluding (B)	Partially occluding (B)
11	X	Partially occluding (B)	X	X
12	X	X	X	X

3.2.2. Additional Noise Exposure Outside of Typical Musical Activities per Participant

Semesterly reports of additional noise exposure outside typical musical activities were recorded prior to each participant's hearing assessment. As shown in Table 4, six out of twelve participants experienced at least one instance of such exposure throughout the study, with one participant reporting two or more instances. These additional exposures stemmed from various activities, including attending sporting events and concerts, participating in performances, working on production scenery, and counseling at a summer camp. In Table 4, 'Yes' indicates one or more instances of additional noise exposure, while 'No' signifies no such exposure beyond typical music-making activities. These data highlights the diverse sources of potential noise exposure that musicians may encounter beyond their primary musical pursuits, underscoring the importance of comprehensive hearing conservation strategies.

Table 4. Additional noise exposures per participant.

Participant (Number)	Additional Noise Exposures (Yes/No)
1	No
2	No
3	No
4	Yes
5	Yes
6	No
7	Yes
8	No
9	Yes
10	Yes
11	Yes
12	No

3.2.3. Audiometric Findings per Participant

Audiometric analysis was completed for both the overall findings among participants and for each participant. When looking at all of the participants, the audiograms for Participants One through Twelve reveal that the majority, specifically ten out of twelve, exhibited air- and bone-conduction thresholds within the normal hearing range for both years. However, two participants had thresholds that either exceeded the normal hearing range, or were at the cusp of normal hearing (>20 dB HL).

Notably, audiometric "notches" began to form at 6000 Hz in seven participants for at least one year. Among the five participants who did not show "notches" at this frequency, two experienced increases in their hearing thresholds at both 6000 and 8000 Hz, bilaterally from year one to year two. Additionally, six participants demonstrated increased low-frequency hearing thresholds in at least one ear for at least one year, while the remaining four exhibited bilateral increases in both years.

When examining specific voice parts, increased low-frequency thresholds were observed in one mezzo-soprano, one tenor, two sopranos, and two baritones. Audiometric "notches" at 6000 Hz were detected in two mezzo-sopranos, one tenor, two sopranos, and two baritones. Furthermore, thresholds at 20 dB HL were reported in at least one ear for one soprano, two mezzo-sopranos, two baritones, and one tenor. Lastly, thresholds at or above 20 dB HL in at least one ear for at least one year were noted in one soprano and one mezzo-soprano.

The yearly audiograms for each participant can be found in Appendix A.

Following the group analysis, individual audiometric analyses were conducted for each participant. Participant One began the study with seven years of vocal experience. Throughout the duration of the study, this participant had no difficulties with cerumen accumulation or reported instances of additional noise exposures.

While Participant One (a mezzo-soprano with seven years of vocal experience) maintained air- and bone-conduction thresholds within the normal range in both years, a notable finding was the presence of a bilateral audiometric notch forming at 6000 Hz in both years.

During the initial hearing assessment in Fall 2021 (semester 1), Participant Two (a soprano with six years of vocal experience) had a partially occluding cerumen in the left ear. However, no cerumen-related issues were observed for the remainder of the study. Participant Two reported no additional instances of noise exposure throughout the study period.

While Participant Two maintained air- and bone-conduction thresholds within the normal range for both years, two notable findings emerged. First, increased low-frequency thresholds were observed bilaterally in both years, and second, the development of a bilateral audiometric notch at 6000 Hz was observed in year 2.

Throughout the study, Participant Three experienced difficulties with cerumen accumulation, with partially occluding cerumen noted bilaterally at each semesterly hearing assessment. Participant Three had no additional instances of noise exposure throughout the study.

Participant Three's air- and bone-conduction thresholds remained within the normal range for both years. However, increased thresholds were observed bilaterally in the low frequencies in both years. Additionally, an audiometric notch began forming at 6000 Hz in the left ear during year 2.

Throughout the study, Participant Four (a baritone with eight years of vocal experience) consistently experienced cerumen accumulation issues, with partially occluding cerumen observed bilaterally during each semesterly hearing assessment. In addition to music-making activities, Participant Four reported attending concerts throughout the course of the study without the use of hearing protection devices and working in the UIUC scene shop for two semesters (3 and 4; Fall 2022 and Spring 2023) with the use of hearing protection devices.

While Participant Four maintained air- and bone-conduction thresholds within the normal range for both years, two notable observations were made. First, increased low-frequency thresholds were noted in both years, and a significant increase in high-frequency hearing thresholds was seen in year 2.

During the initial hearing assessment in Fall 2021, Participant Five (a soprano with eight years of vocal experience) had partially occluding cerumen, bilaterally. Participant Five did have one additional instance of noise exposure during the study by going to a concert during semester 3 (Fall 2022) without the use of hearing protection devices.

In year 1, Participant Five's air and bone-conduction thresholds were within the normal range from 250 to 6000 Hz in the left ear and from 250 to 8000 Hz in the right ear. In year 2, thresholds remained within the normal range from 250 to 8000 Hz bilaterally. However, the threshold at 8000 Hz in the left ear in year 2 was obtained at 25 dB HL, placing it on the cusp of normal hearing.

Throughout the study, Participant Six (a baritone with ten years of vocal experience) had no issues with cerumen accumulation and no reported instances of additional noise exposures.

While Participant Six maintained air- and bone-conduction thresholds within the normal range for both years, a notable finding emerged. An audiometric notch was observed forming in the left ear during both years.

Throughout the study, Participant Seven (a baritone with eight years of vocal experience) consistently experienced cerumen accumulation issues, with partially occluding cerumen observed bilaterally during each semesterly hearing assessment. In addition to music-making activities, Participant Seven reported attending four sporting events during semesters 3 and 4 (Fall 2022 and Spring 2023) without the use of hearing protection.

While Participant Seven maintained all air- and bone-conduction thresholds within the normal range for both years, a significant observation was made. The formation of a bilateral audiometric notch at 6000 Hz was noted in both years.

During the initial hearing assessment, in Fall 2021 (semester 1), Participant Eight had partially occluding cerumen in the right ear. However, no cerumen-related issues were observed for the remainder of the study. Participant Eight reported no instances of additional noise exposure during the study.

Participant Eight (a mezzo-soprano had five years of vocal experience) maintained air- and bone-conduction thresholds within the normal range for both years, several notable observations were made. First, a bilateral conductive component in the low-frequencies was observed in both years, prompting a referral for appropriate management and testing. Second, in year 1, increased high-frequency thresholds were observed, and third, in year two, a bilateral audiometric notch at 6000 Hz was observed.

Throughout the study, Participant Nine (a tenor with 16 years of vocal experience) had no issues with cerumen accumulation. They did, however, attend a live music event during semester 4 (Spring 2023) without the use of hearing protection devices. While participant nine maintained air- and bone-conduction thresholds, in both years, increased low-frequency thresholds were observed bilaterally.

Participant Ten (a soprano with 1 year of vocal experience) experienced ongoing issues with cerumen accumulation, with bilateral partially occluding cerumen noted at each semesterly hearing assessment. Additionally, the participant did have one instance of additional noise exposure from attending a live music event during semester 3 (Fall 2022). The participant initially did not utilize hearing protection devices, but opted to use them halfway through the performance due to intolerable sound levels.

Participant Ten maintained air- and bone-conduction thresholds within the normal range for both years. However, two significant observations were made. First, increased low-frequency thresholds were observed bilaterally in both years, and second, a bilateral audiometric notch at 6000 Hz began forming in year 2.

For Participant Eleven (a baritone, had a total of four years of vocal experience), cerumen-related issues were observed only during the semester 2 (Spring 2022) hearing evaluation, with partially occluding cerumen noted bilaterally. No cerumen accumulation difficulties were observed before or after this instance. Participant Eleven did have one instance of additional noise exposure from working as a camp counselor in the summer between semesters 2 and 3 (Spring 2022 and Fall 2022).

While Participant Eleven maintained air- and bone-conduction thresholds within the normal range for both years, increased thresholds were obtained at 250, and 3000 through 8000 Hz in year 1.

Participant Twelve (a countertenor with eight years of vocal experience) had no issues with cerumen accumulation, and reported no additional instances of noise exposure. While

Participant Twelve maintained all air- and bone-conduction thresholds within the normal range for both years, in year two thresholds were increased at 8000 Hz in the right ear and at 6000 and 8000 Hz in the left ear.

3.3. Music Exposure

3.3.1. SPLs per Participant

The histograms of the time history of instantaneous SPLs for each participant throughout the study provided valuable insights into the various activities participants engaged in, as well as their associated sound levels during noise dosimetry measurements. These activities included background noise, speech, choir participation, and solo singing. Figure 1 depicts the histograms of the time history of SPLs per participant for semester 1 through semester 4 (Fall 2021 through Spring 2023), using color-coded representations to distinguish between hypothesized noise sources and activities. Solid orange represents background noise levels, solid navy blue indicates speech levels, dashed navy signifies singing levels in a choral setting, and solid dark orange denotes solo singing levels. The mean SPL in dBA for each of these categories is highlighted in bold. Unfortunately, due to equipment malfunction, sound measurements could not be retrieved from three participants (Participants One, Two, and Three) for semester 4 (Spring 2023). Notably, based on the recorded SPLs, it was estimated that at least one participant engaged in choral activities during noise dosimetry measurements in all semesters except semester 4 (Spring 2023). This comprehensive visualization and analysis of SPL data allowed for a nuanced understanding of the acoustic environments experienced by the participants throughout the course of the study.

The histograms of the time history of instantaneous SPLs per participant throughout the study gave good indications of the SPLs associated with different activities the participants were engaging in (e.g., background noise, speech/choir, and solo singing) during noise dosimetry measurements per semester. For all of the semesters except for semester 4 (Spring 2023), it was estimated that at least one of the participants engaged in choir during noise dosimetry measurements based on the SPLs recorded.

3.3.2. Hypotheses Regarding Sound Sources/Activities

From the hypotheses made regarding sound sources/activities by the models of mixture of Gaussians, bar graphs were created to better depict the mean SPL for each sound source/activity.

Figure 2 shows the mean background noise, speech/choir, and singing per participant for semester 1 (Fall 2021). Mean background noise is depicted in blue, speech in solid orange, choir in orange/white, and singing in gray. The dark orange dashed line across the graph represents 85 dBA, which is the criterion exposure limit recommended by NIOSH for a period of 8 h, and is labeled as such. The dark blue dashed line across the graph represents 90 dBA, which is the criterion exposure limit recommended by OSHA. Mean background noise ranged from 36 dBA to 64 dBA. Mean speech ranged from 60 dBA to 74 dBA and mean choir ranged from 81 dBA to 89 dBA. Mean singing ranged from 73 dBA to 105 dBA. Mean singing was looked at further by voice type. Mean singing for sopranos ranged from 73 dBA to 105 dBA. Mean singing for mezzo-sopranos ranged from 84 dBA to 96 dBA. Mean singing for tenors ranged from 85 dBA to 90 dBA. Mean singing for baritones ranged from 82 dBA to 87 dBA. Mean singing for the countertenor was 88 dBA.

Figure 3 shows the mean background noise, speech/choir, and singing per participant for semester 2 (Spring 2022). The color coding, dashed lines, and labeling established in Figure 2 is continued in Figures 3–5. For semester 2 (Spring 2022), mean background noise ranged from 39 dBA to 69 dBA. Mean speech ranged from 43 dBA to 75 dBA and mean choir ranged from 82 dBA to 83 dBA. Mean singing ranged from 75 dBA to 102 dBA. Mean singing was looked at further by voice type. Mean singing for sopranos ranged from 75 dBA to 102 dBA. Mean singing for mezzo-sopranos ranged from 82 dBA to 95 dBA. Mean singing for tenors ranged from 75 dBA to 83 dBA. Mean singing for baritones ranged from 80 dBA to 90 dBA. Mean singing for the countertenor was 96 dBA.

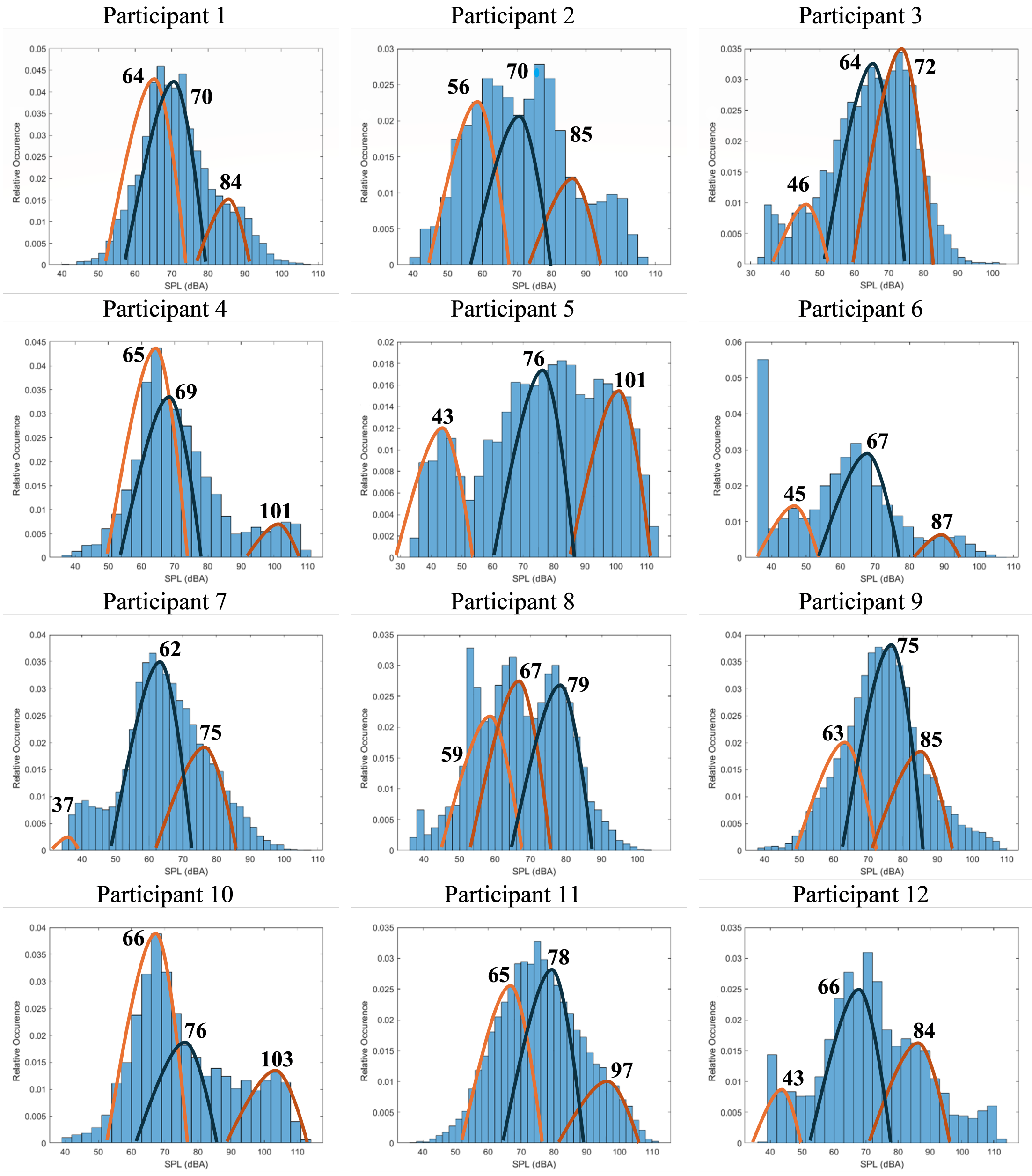

Figure 1. Histograms of the time history of instantaneous SPLs per participant for Spring 2023. The three curves represent the three main sound sources/activities identified by the Gaussian mixture model.

Figure 4 shows the mean background noise, speech/choir, and singing per participant for semester 3 (Fall 2022). Mean background noise ranged from 50 to 67 dBA. Mean speech ranged from 60 to 78 dBA. Mean choir ranged from 81 to 82 dBA. Mean singing ranged from 77 dBA to 105 dBA. Mean singing was looked at further by voice type. Mean singing for sopranos ranged from 93 dBA to 105 dBA. Mean singing for mezzo-sopranos ranged from 78 dBA to 83 dBA. Mean singing for tenors ranged from 90 dBA to 101 dBA. Mean singing for baritones ranged from 77 dBA to 95 dBA. Mean singing for the countertenor was 88 dBA.

As noted earlier, due to equipment malfunction, we were unable to retrieve sound measurements from three (Participants One, Two, and Three) of the twelve participants. Figure 5 shows the mean background noise, speech/choir, and singing per participant for Participants Four through Twelve for semester 4 (Spring 2023). Mean background noise ranged from 37 dBA to 66 dBA. Mean speech ranged from 62 dBA to 78 dBA. For semester 4 (Spring 2023), none of the participants had noise sources or activities that were hypothesized as choir. Thus, the orange/white bar coloring is not utilized. Mean singing ranged from 75 dBA to 103 dBA. Mean singing was looked at further by voice type. Mean singing for sopranos ranged from 101 dBA to 103 dBA. Mean singing for the mezzo-soprano was 79 dBA. Mean singing for the tenor was 85 dBA. Mean singing for baritones ranged from 75 dBA to 101 dBA. Mean singing for the countertenor was 84 dBA.

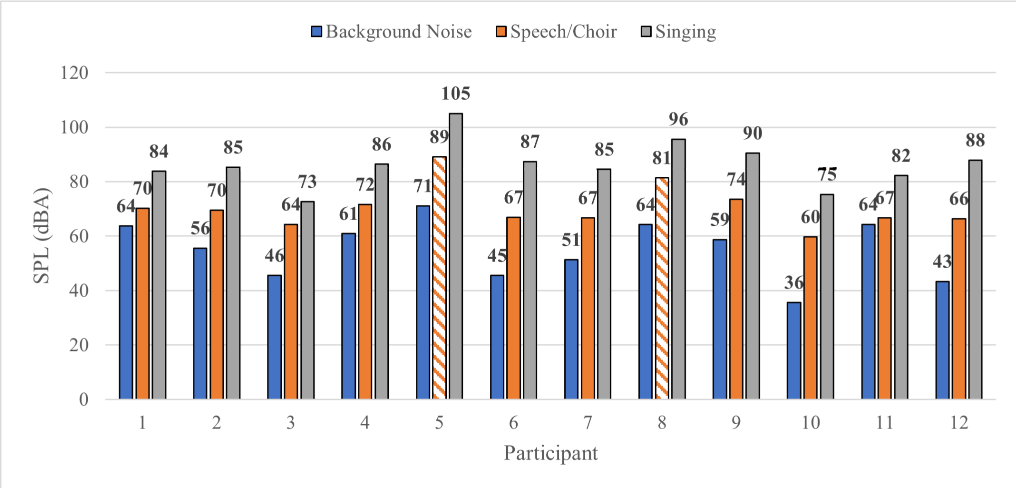

Figure 2. Mean background noise, speech/choir, and singing per participant for Fall 2021. The orange-white striped bins represent choir activity, while the solid orange bins represent speech levels.

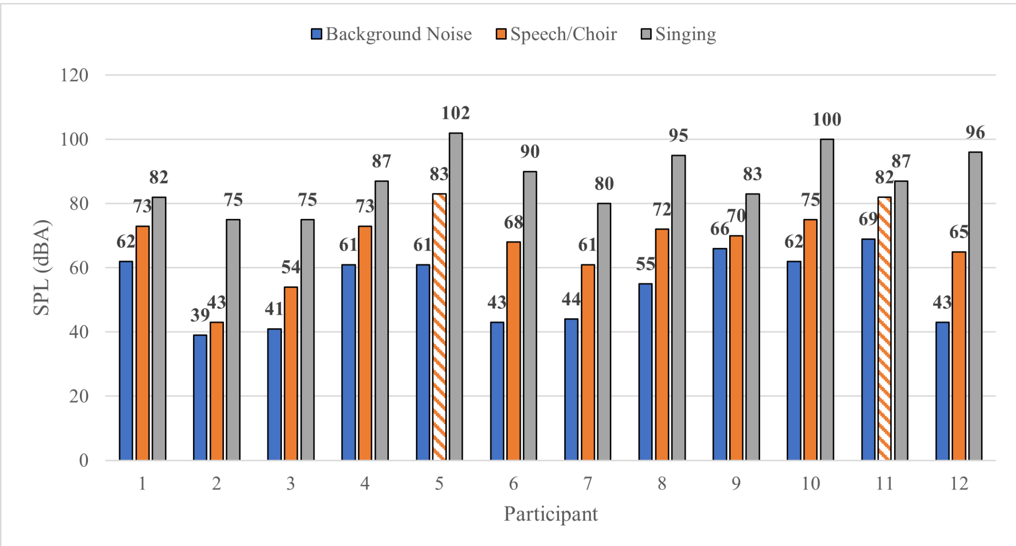

Figure 3. Mean background noise, speech/choir, and singing per participant for Spring 2022. The orange-white striped bins represent choir activity, while the solid orange bins represent speech levels.

Further analysis of the hypotheses made the models of mixture of Gaussians regarding noise sources/activities revealed that mean background noise throughout the study ranged from 36 to 69 dBA; mean speech ranged from 43 to 78 dBA; mean choir ranged from 81 to 89 dBA; mean singing for all participants ranged from 73 to 105 dBA; mean singing for sopranos ranged from 73 to 105 dBA; mean singing for mezzo-sopranos ranged from 78 to 96 dBA; Mean singing for Tenors ranged from 75 to 101 dBA; mean singing for baritones ranged from 75 dBA to 101 dBA; and mean singing for the countertenor ranged from 84 to

96 dBA. Throughout the course of the study, sopranos had the loudest SPLs out of all of the voice parts when singing alone, and mezzo-sopranos had the quietest SPLs out of all of the voice parts when singing alone.

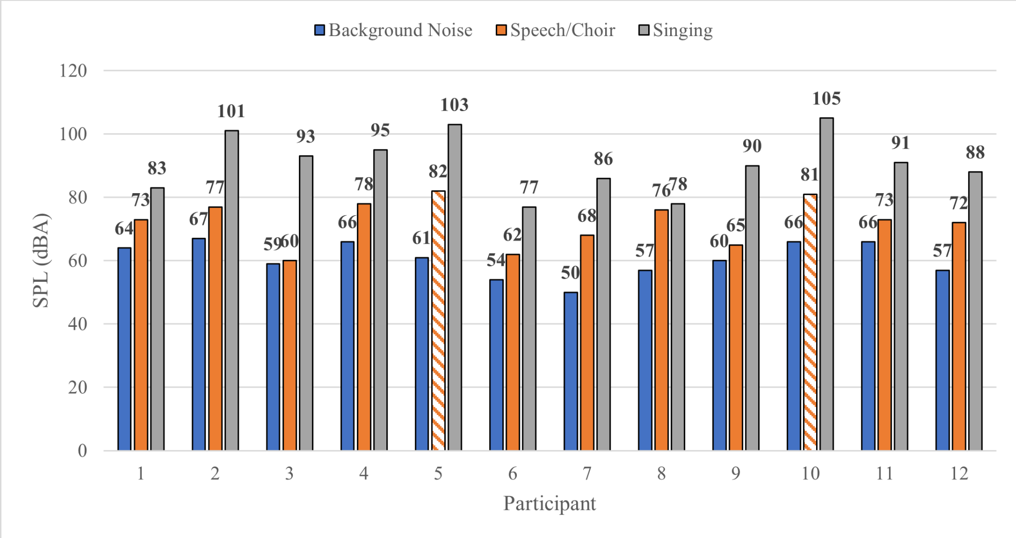

Figure 4. Mean background noise, speech/choir, and singing per participant for Fall 2022. The orange-white striped bins represent choir activity, while the solid orange bins represent speech levels.

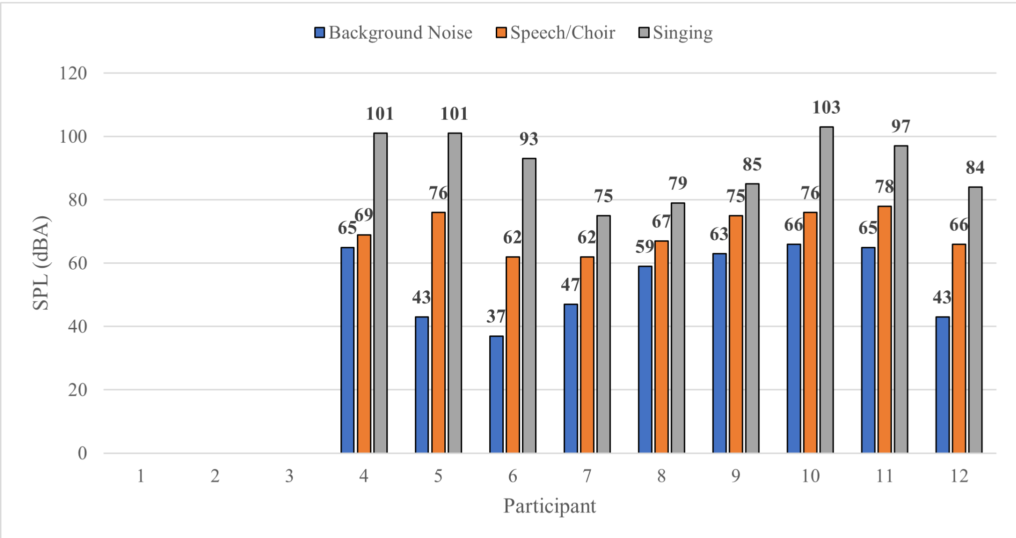

Figure 5. Mean background noise, speech/choir, and singing per participant for Spring 2023.

3.3.3. Equivalent Noise Levels and Maximum Durations of Exposure

For each participant, the equivalent level (*Leq*) during each monitored day was calculated. NIOSH (1998) has recommended a criterion exposure limit of 85 dBA for 8 h; exposure at or about this level is considered hazardous. Using this recommendation with an exchange rate of 3 dB, the occupational noise exposure measured during monitoring should be controlled in such way so that the maximum duration, Ti, of the exposure can be calculated as follows:

$$T_i = \frac{8}{2^{\left(\frac{Leq-85}{3}\right)}} \quad (3)$$

The equivalent levels (*Leq*) and the maximum duration of the exposure for semester 1 (Fall 2021) are reported in Figure 6. On the *Leq* graph, with the blue bars, the dark orange dashed line represents NIOSH's criterion exposure limit of 85 dBA and the dark blue dashed line represents OSHA's criterion sound level of 90 dBA. On the maximum duration of exposure graph, with the orange bars, the dark orange dotted line represents the common time weighted average of 8 h utilized by both OSHA and NIOSH. For semester 1 (Fall 2021), out of the twelve participants, eight were exposed to SPLs higher than the NIOSH criterion exposure limit of 85 dBA.

The equivalent levels (*Leq*) and the maximum duration of the exposure for semester 2 (Spring 2022) are reported in Figure 7. The dashed lines depicted in Figure 6 will also be shown in Figures 7–9. For semester 2 (Spring 2022), out of the 12 participants, eight were exposed to SPLs higher than the NIOSH criterion exposure limit of 85 dBA.

The equivalent levels (*Leq*) and the maximum duration of the exposure for semester 3 (Fall 2022) are reported in Figure 8. Out of the twelve participants, ten were exposed to SPLs higher than the NIOSH criterion exposure limit of 85 dBA.

The equivalent levels (*Leq*) and the maximum duration of the exposure for Participants Four through Twelve for semester 4 (Spring 2023) are reported in Figure 9. Out of the nine participants from whom noise measurements were retrieved for semester 4 (Spring 2023), six were exposed to SPLs higher than the NIOSH criterion exposure limit of 85 dBA.

The bar graphs of the equivalent levels (*Leq*) and maximum duration of exposure per participant revealed that throughout the study, more than half of the participants per semester had noise doses above NIOSH's recommended criterion exposure limit of 85 dBA for 8 h.

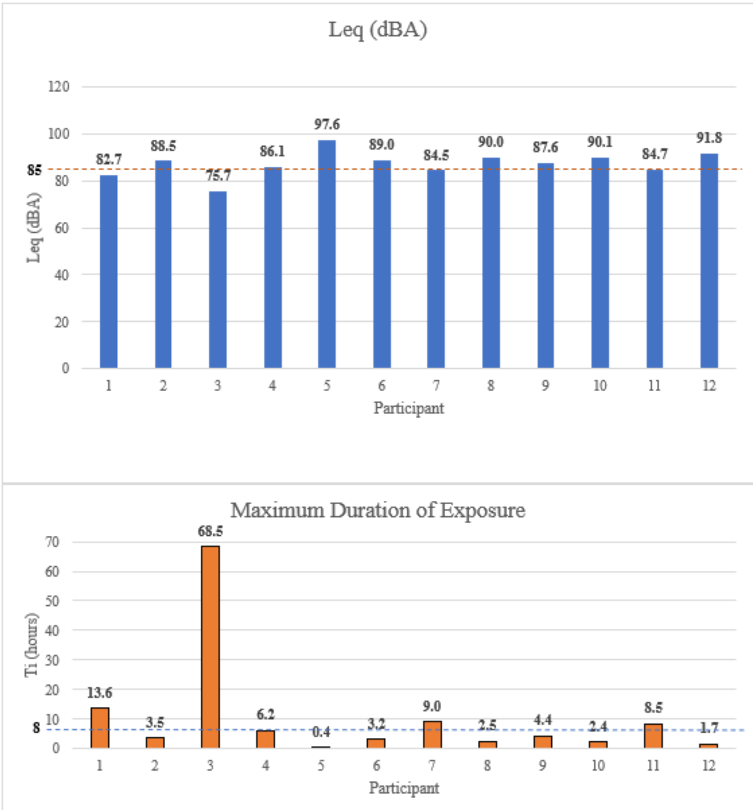

Figure 6. Equivalent levels (*Leq*) and maximum duration of exposure per participant for Fall 2021.

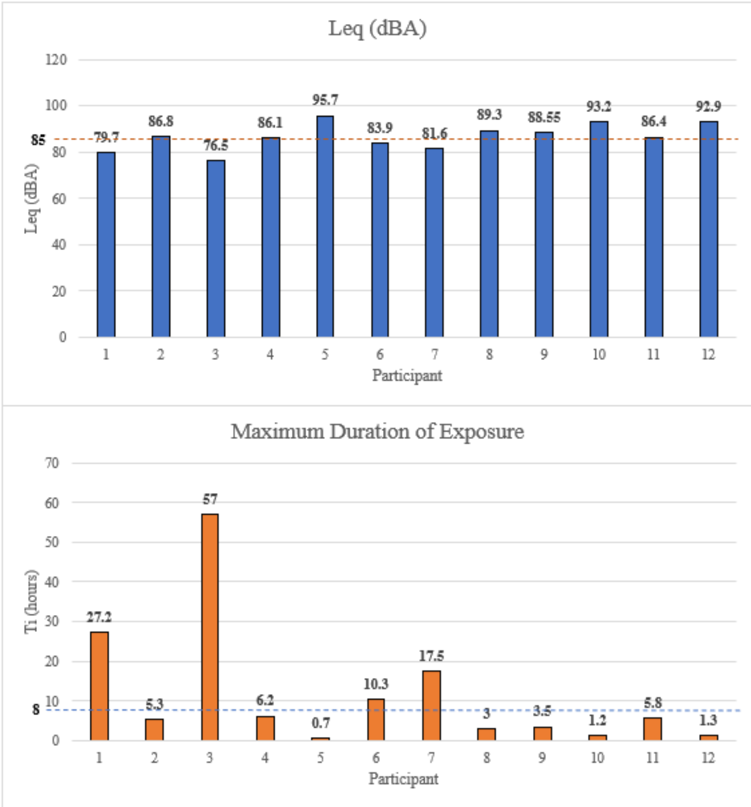

Figure 7. Equivalent levels (*Leq*) and maximum duration of exposure per participant for Spring 2022. The dashed lines indicate the NIOSH recommended exposure limit of 85 dBA and 8 working hours.

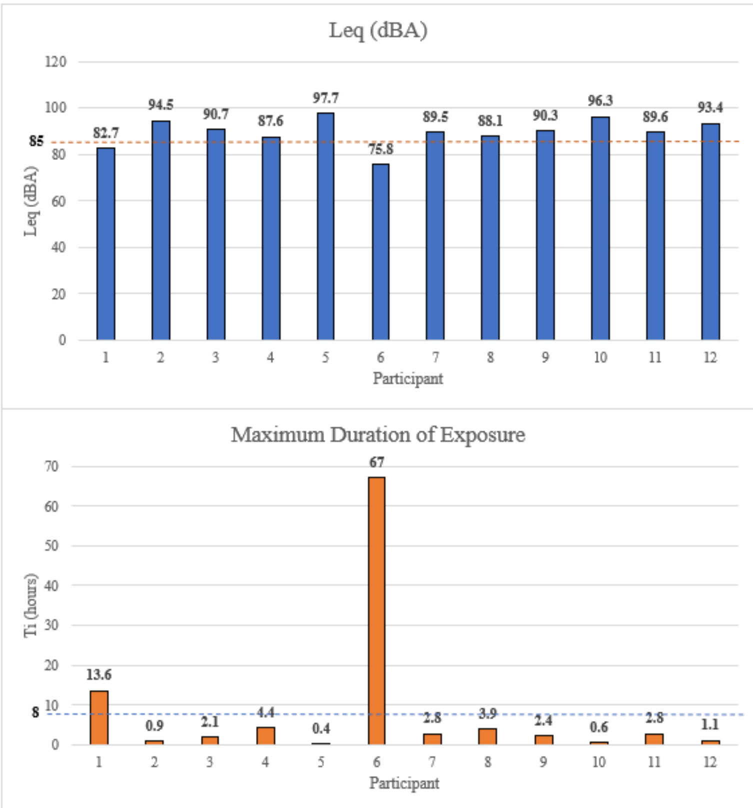

Figure 8. Equivalent levels (*Leq*) and maximum duration of exposure per participant for Fall 2022. The dashed lines indicate the NIOSH recommended exposure limit of 85 dBA and 8 working hours.

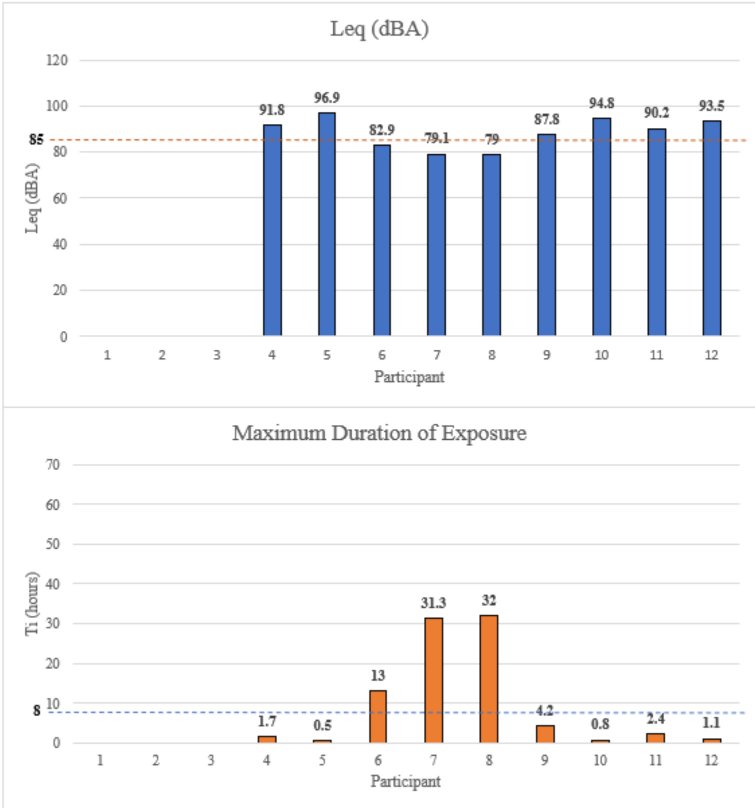

Figure 9. Equivalent levels (*Leq*) and maximum duration of exposure per participant for Spring 2023. The dashed lines indicate the NIOSH recommended exposure limit of 85 dBA and 8 working hours.

4. Discussion

While numerous studies have examined the impact of music exposure on musicians' hearing health, vocal performers remain comparatively understudied in this regard. The current literature exploring music exposure and MIHDs among vocal performers predominately centers on choral (or group) singing, with fewer studies delving into the effects of voice teaching or solo singing, respectively. Despite the discrepancy in volume of research, the current literature has revealed that vocal performers, like their instrumentalist counterparts, and regardless of the context, have an increased risk for MIHDs due to consistent music exposure [10,18,25–28,30]. However, a gap remains in our understanding of how music exposure affects vocal performers' auditory system over an extended period. Throughout this study, the main areas of interest are: (1) Are university vocal performance students exposed to SPLs higher than the limits suggested by national standards? (2) Are the SPLs changing throughout the vocal performance curriculum? (3) What is the prevalence of MIHDs among vocal performance students? (4) Is one voice type/part at a higher risk of MIHDs due to higher SPLs? And (5) is there a need to create and implement a hearing conservation program for university vocal performance students? Through a comprehensive examination of these factors, this study seeks to provide valuable insights into safeguarding the hearing health of vocal performers and informing future research in this domain. The intention of this research is to bring forth awareness and acknowledgment of MIHDs among vocal performers, subsequently serving as a foundation for further research and providing information that directly reinforces the importance of hearing protection among vocal performers.

4.1. Music Exposure

In the United States, national standards regarding acceptable occupational noise exposure have been created and implemented by both OSHA and NIOSH. However, concerns have been raised about the applicability of these standards to the continuous music exposure experienced by musicians [19]. This concern stems from disparities in both the sound stimuli, as well as the pattern of exposure experienced by musicians compared to industrial workers [15]. Despite these concerns, specific standards pertaining to music exposure have yet to be developed. Consequently, current practices rely on the utilization of OSHA and NIOSH to determine musicians' exposure to music.

Furthermore, the bulk of the published research evaluating music exposure pertains to instrumentalists, with limited attention dedicated to vocalists. As stated previously, within the sparse amount of literature concerning music exposure among vocal performers, a majority of the studies center on choral singing. Notably, choirs without accompaniment can produce SPLs comparable to those produced by full orchestras, and surpass national standards [25]. Among the vocal parts present within a choir, sopranos tend to generate the highest SPLs [30]. Moreover, while research on music exposure among voice teachers and solo singers is limited compared to choral singers, it is revealing. Studies in these areas have noted that both voice teachers and solo singers are frequently exposed to SPLs exceeding national standards from partaking in music-making activities [18,28].

In this study, histograms were created to provide insight into the SPLs associated with the different activities participants engaged in during noise measurements, including background noise, speech/choir, and (solo) singing. Apart from one semester, at least one participant was involved in choir activities during measurements. Analysis using Gaussian mixture models for sound sources/activities showed varying mean SPLs: background noise (36–69 dBA), speech (43–78 dBA), choir (81–89 dBA), and singing (73–105 dBA). When looking at the voice parts specifically, sopranos consistently had the highest SPLs when singing alone, while mezzo-sopranos had the lowest. Graphs of equivalent levels (*Leq*) and maximum exposure durations revealed that every semester, over half of the participants, exceeded NIOSH's recommended limit of 85 dBA for 8 h. These findings suggest that vocal performance students are continuously exposed to high SPLs from music-making activities within (and outside of) their curriculum, and a majority cannot currently safely partake in these activities without the risk of developing MIHDs including, but not limited to, MIHL.

4.2. Hearing Assessments

Research on MIHL in choral singers has discovered that choral singing affects hearing acuity uniformly across voice parts, primarily impacting low-frequency hearing thresholds [26]. Unlike other MIHL studies, this phenomenon may be the result of the sound stimuli generated by choirs predominately falling below the range of 500–1000 Hz, but not lower than 100 Hz [10,27]. Research on voice teachers and vocal performance students confirms bilateral high-frequency SNHL as the most common type of hearing loss among this population [25,28]. Notably, one study found slightly worse hearing thresholds among this population in the left ear, due to its proximity to sound stimuli within the environment [25]. Additionally, voice teachers were found to exhibit a higher prevalence of MIHL compared to vocal performers, attributed to factors like age, duration of music exposure, gender, and voice type, with baritones having the highest prevalence among the voice parts [25,29].

In this study, the questionnaire given at the beginning showed that most participants engaged in additional music-making activities outside of their curriculum, such as voice instruction, a cappella groups, or choir participation. Otologic histories varied among the participants, with concerns including hearing and communication, unequal ear function, tinnitus, earaches, ear infections, aural fullness, dizziness/vertigo, and a family history of hearing loss. Some participants showed potential hearing issues at the study's onset, as identified by the AAA's Hearing Health Quick Test. Throughout the course of the study, few participants perceived changes in their hearing, but half had exposure to loud SPLs from activities outside of music-making activities. These activities included sporting events, concerts, performances, working on scenery for productions, and duties as a summer camp counselor. Despite the prevalence of these exposures, only a minority of the participants utilized HPDs. Semesterly otoscopic examinations indicated cerumen issues in some participants, with ongoing problems for a few. Audiograms averaged per year showed mostly normal hearing thresholds among participants, with some exhibiting thresholds beyond the normal range or developing notches at 6000 Hz. Increases in low-frequency thresholds were also observed, consistent with the impact of choral singing on hearing acuity, as seen in the literature. Notably, when looking at the voice parts individually, increased low-frequency thresholds were most prevalent in baritones and sopranos, while notches forming at 6000 Hz were most prominent in baritones and mezzo-sopranos. Additionally, two out of the 12 participants exhibited thresholds at or above 25 dB HL in at least one ear for greater than or equal to one year, one of whom was a soprano and the other a mezzo-soprano.

Current national standards for acceptable occupational noise exposure recommend implementing a hearing conservation program when the daily noise dose exceeds or is equal to 85 dBA averaged over 8 h (8 h TWA) [12,13]. Despite the variability in participants' weekly schedules and uncertainty regarding whether this exposure occurs for a full 8 h per day, more than half of the participants surpassed NIOSH's recommended limit of 85 dBA during their daily activities. Given the high levels of noise exposure, it is highly advisable to establish a hearing conservation program for university vocal performance students. Furthermore, the observed prevalence of initial noise notches at 6000 Hz and increased low-frequency thresholds underscores the urgency for implementing a program tailored specifically to the auditory needs of university vocal performance students.

4.3. Limitations

This study has several limitations that should be considered when interpreting the results. First, the study faced challenges with variations in testing conditions, equipment, and tester experience, as first-year audiology students, who were inexperienced, assisted in data collection. Issues with participant retention and occasional equipment malfunctions also impacted data reliability. Additionally, this project began in the first author's initial year of her doctoral program, which meant that certain tests, such as tympanometry and distortion-product otoacoustic emissions (DPOAEs), were not utilized. These additional assessments would have provided valuable information about middle ear and inner ear status and helped better detect hearing changes from exposure to high sound pressure levels (SPLs). As a result, audiograms were averaged and reported annually, rather than per semester, and all retrievable noise measurements were presented, excluding any that could not be retrieved. Moreover, the limited sample size of 12 participants restricts the generalizability of the findings. We acknowledge that this sample may not fully represent the diversity of vocal performers, and thus a larger sample would enhance the robustness of our findings. We have incorporated this limitation in our manuscript, and are planning follow-up studies with a more extensive and varied participant pool. Such future studies will allow for a more comprehensive analysis and increase the generalizability of insights related to the impact of music exposure on vocal health. Although this study was longitudinal, it was limited by the relatively short observation period, as participants were Master's students with only a two-year program tenure. This limited timeframe restricts the ability to observe extended effects of music exposure on hearing health. In response, we have added a note on this constraint in the manuscript. Future studies with longer-term cohorts or alumni would enable a more in-depth understanding of prolonged music exposure's effects over a more extended period. Finally, sound exposure measurements were taken on participants' "most vocally active day" during each semester. Consequently, SPL and noise dose values reflect the maximum exposure levels for this group. While noise doses at times exceeded industrial standards of 85–90 dBA over 8 h, these values should be viewed with caution, as the average exposure over time would likely be lower than indicated. Therefore, the high readings reported here, while informative, may not necessarily signal immediate alarm but rather highlight the need for ongoing monitoring.

5. Conclusions

In conclusion, this study sheds light on how music exposure affects vocal performers' hearing acuity over time, a topic area that has lacked attention. While research has extensively examined the impact of music exposure on instrumentalists, vocalists remain understudied, with a primary focus on choral singing. The existing literature indicated that vocal performers, like instrumentalists, are at an increased risk for developing MIHDs, like MIHL, due to consistent exposure to high SPLs during music-making activities. This study further corroborated these findings, revealing that vocal performance students are frequently exposed to SPLs exceeding NIOSH recommended standards. Additionally, otoscopic examinations and audiograms conducted throughout the study uncovered variations in hearing acuity among participants, with some exhibiting increased low-frequency thresholds, developing notches at 6000 Hz, or thresholds exceeding the normal range. Overall, vocalists were largely oblivious to the risks posed by their music activities and additional unrelated noise in their environments. Likewise, participants displayed a minimal understanding of basic auditory care and prevention of injury. This study highlights the need for greater hearing health awareness and education regarding workplace noise and its impact on auditory health at this institution and proposes establishing a hearing conservation program for students and instructors.

Author Contributions: Conceptualization, P.B.; methodology, P.B.; validation, P.B., R.L.L., C.J.N. and Y.G.R.; formal analysis, P.B., R.L.L., C.J.N. and Y.G.R.; investigation, R.L.L.; writing—original draft preparation, R.L.L.; writing—review and editing, P.B., R.L.L., C.J.N. and Y.G.R.; visualization, R.L.L. and C.J.N.; supervision, P.B. and Y.G.R.; project administration, P.B. and Y.G.R. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Institutional Review Board of the University of Illinois Urbana-Champaign (IRB #22413 and date of approval 18 November 2021).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy.

Acknowledgments: The authors would like to thank all the participants for their kind cooperation and interest in the study.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

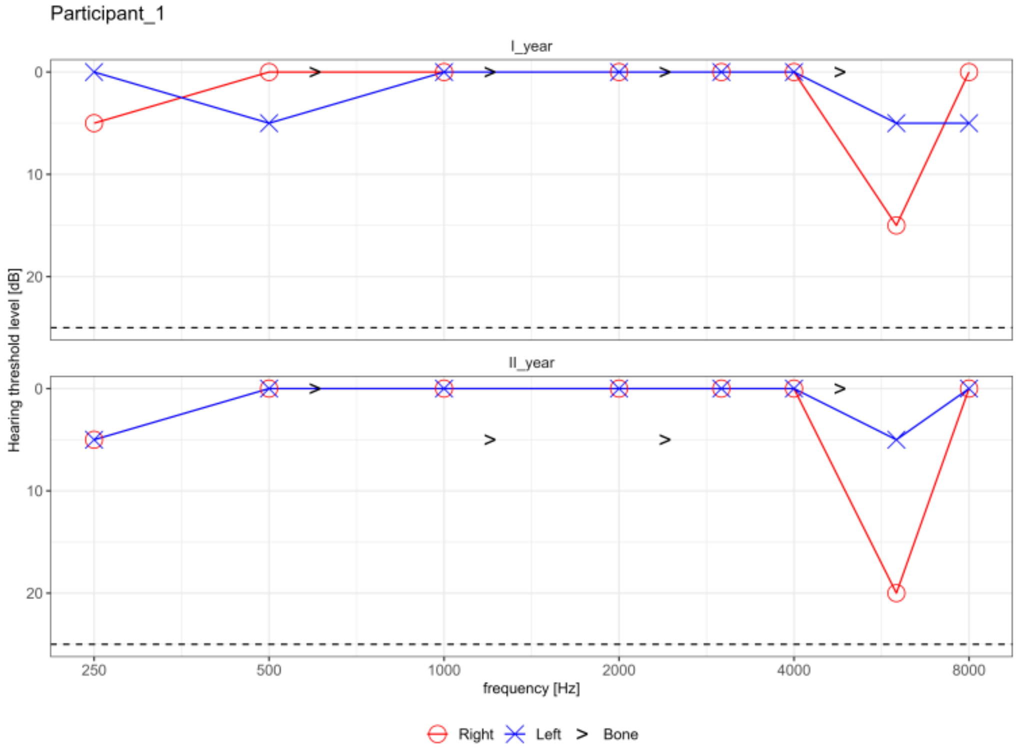

Figure A1. Yearly audiograms for Participant 1.

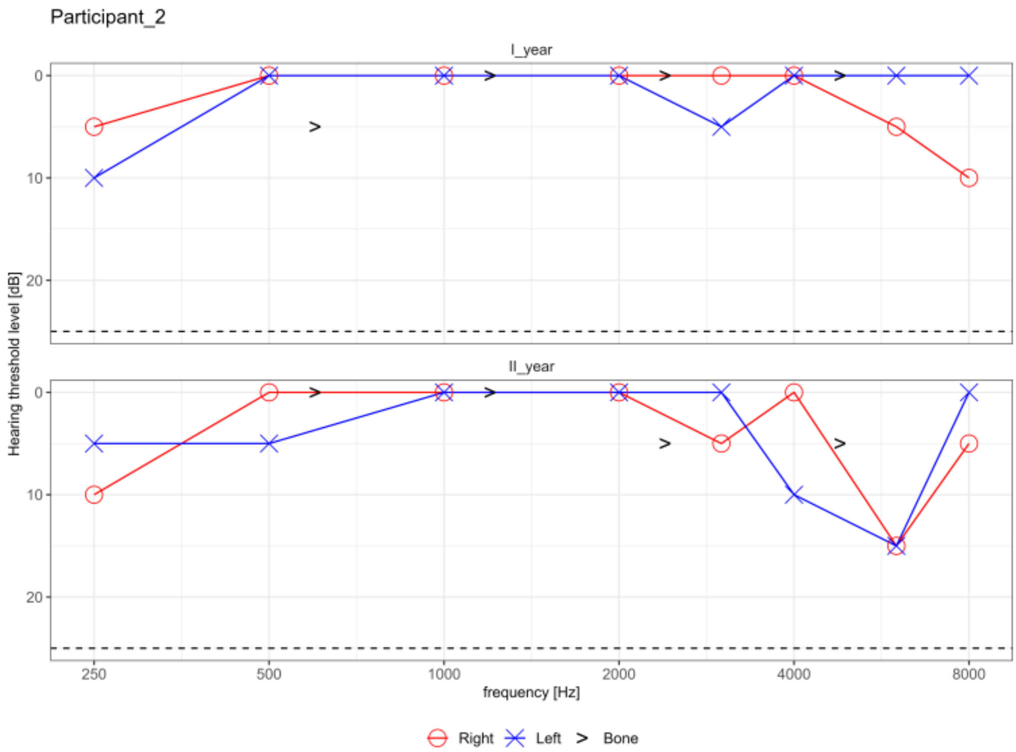

Figure A2. Yearly audiograms for Participant 2.

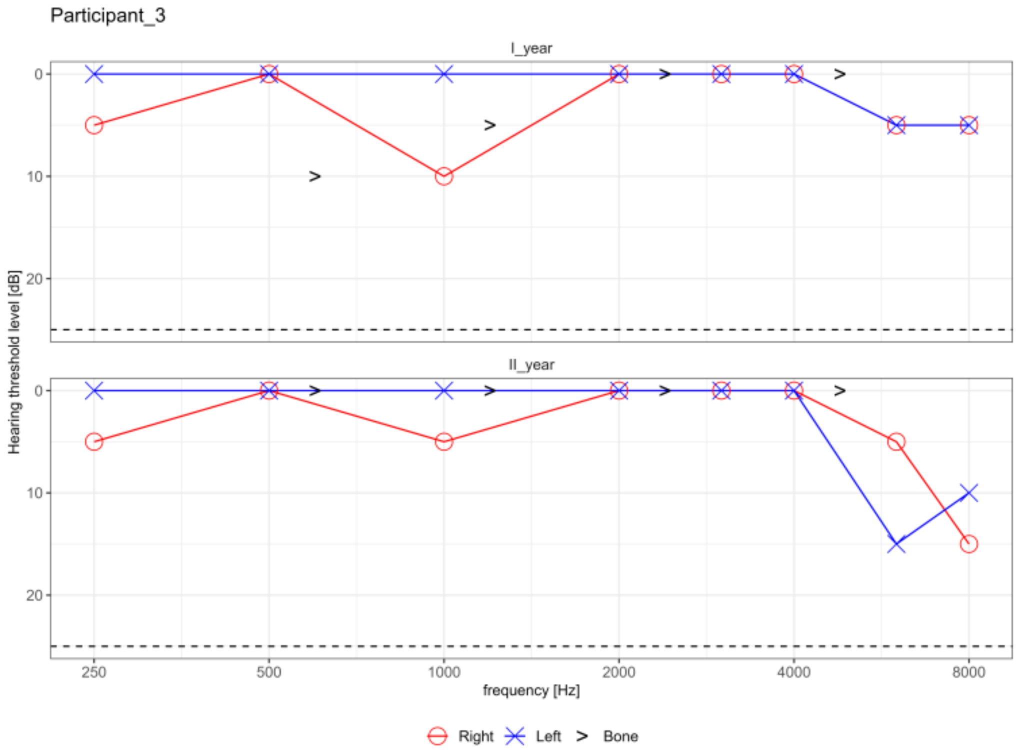

Figure A3. Yearly audiograms for Participant 3.

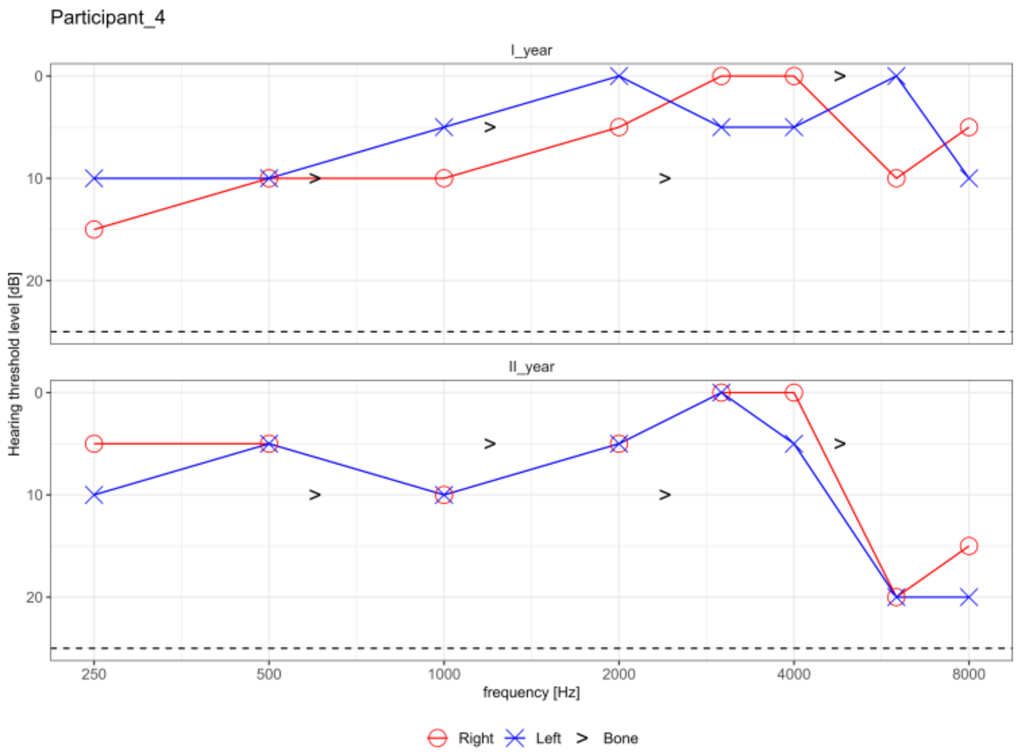

Figure A4. Yearly audiograms for Participant 4.

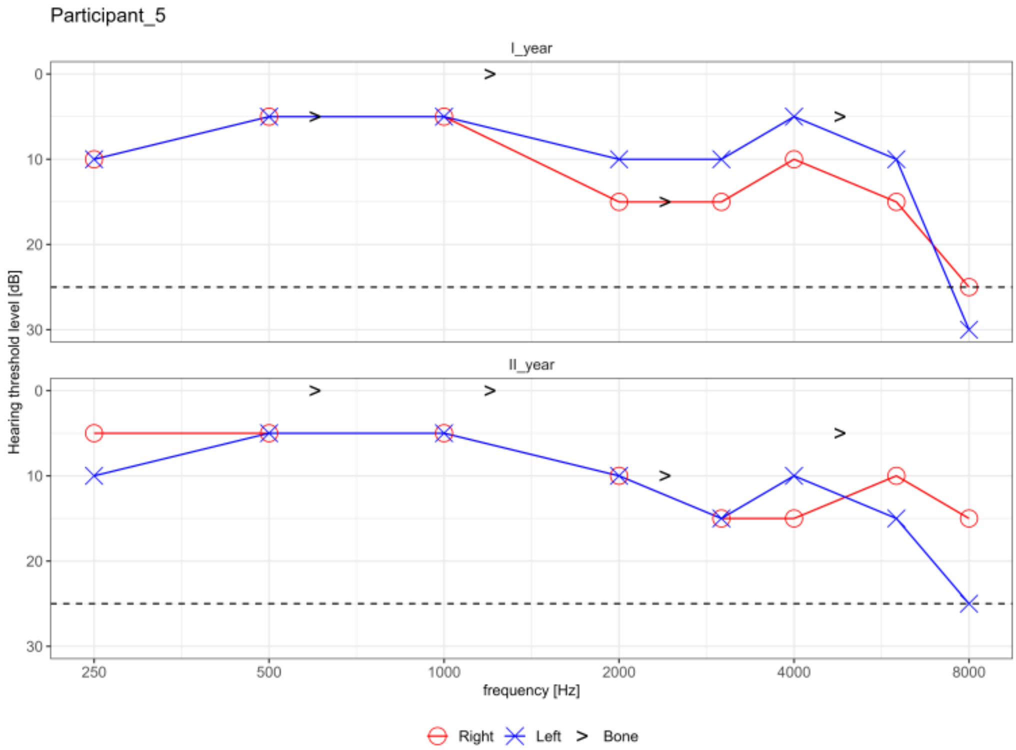

Figure A5. Yearly audiograms for Participant 5.

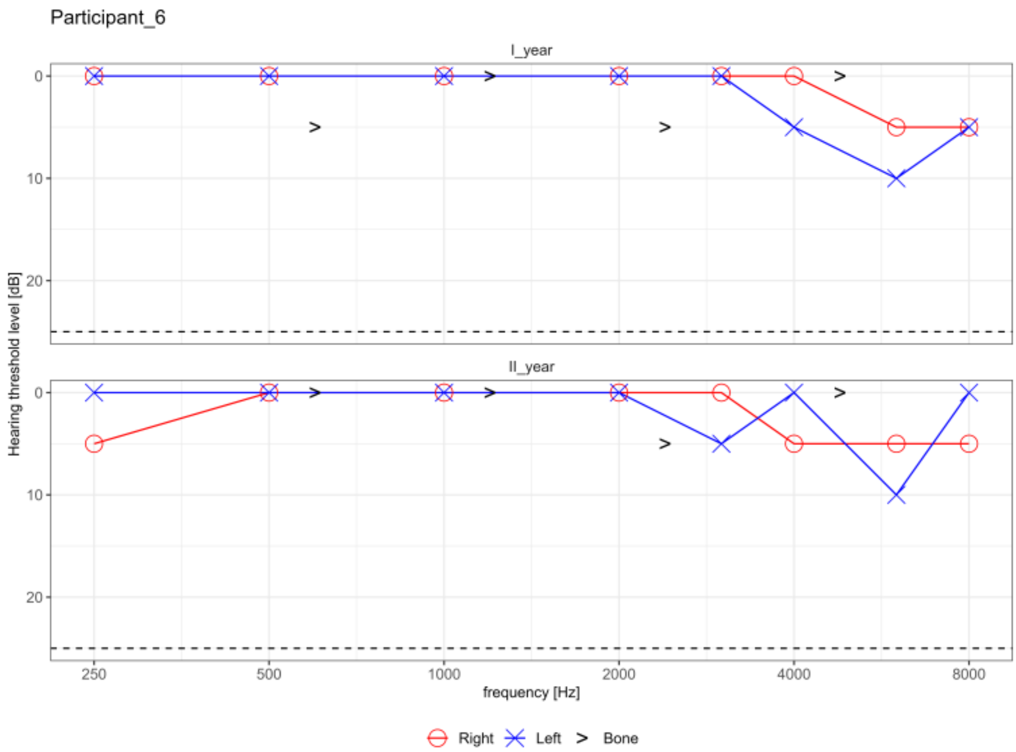

Figure A6. Yearly audiograms for Participant 6.

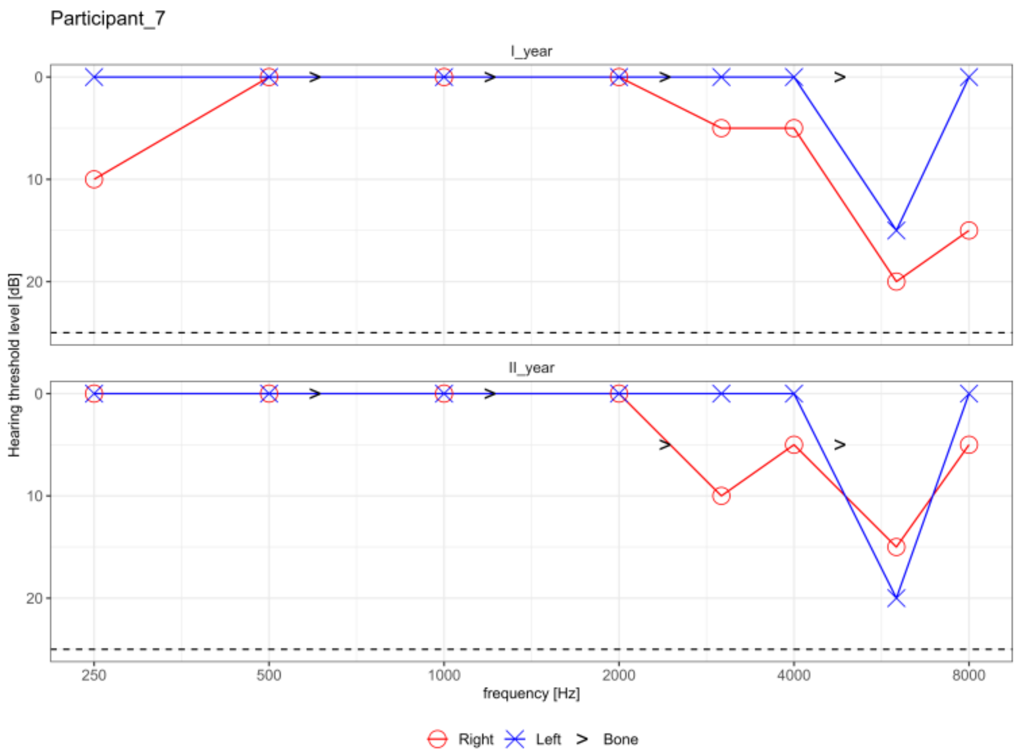

Figure A7. Yearly audiograms for Participant 7.

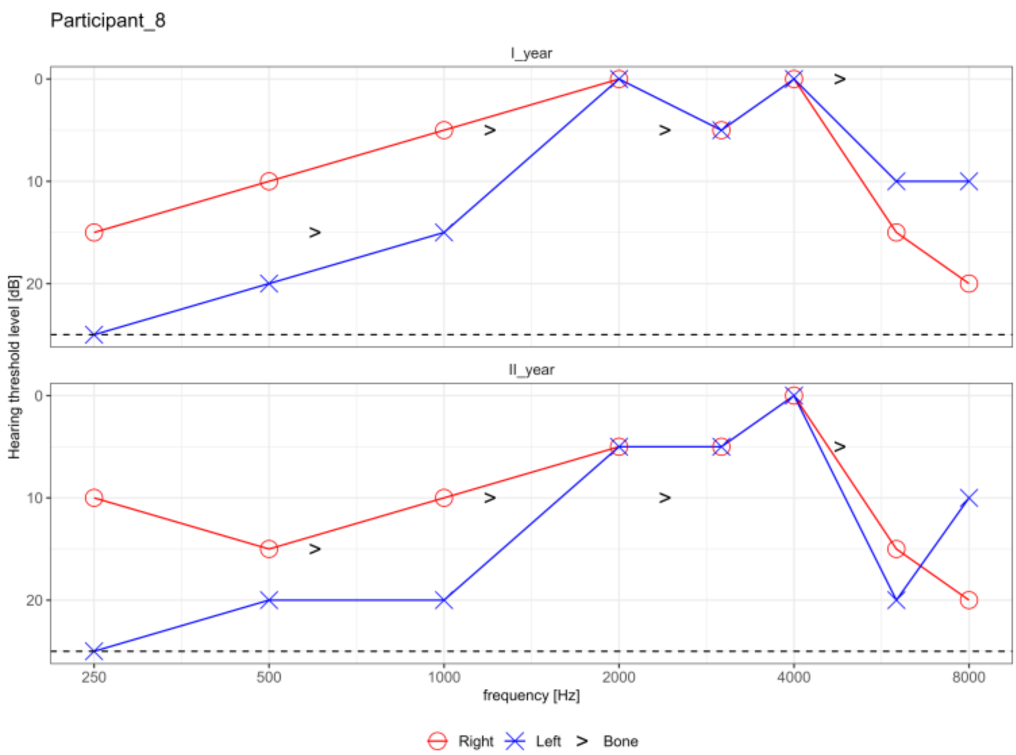

Figure A8. Yearly audiograms for Participant 8.

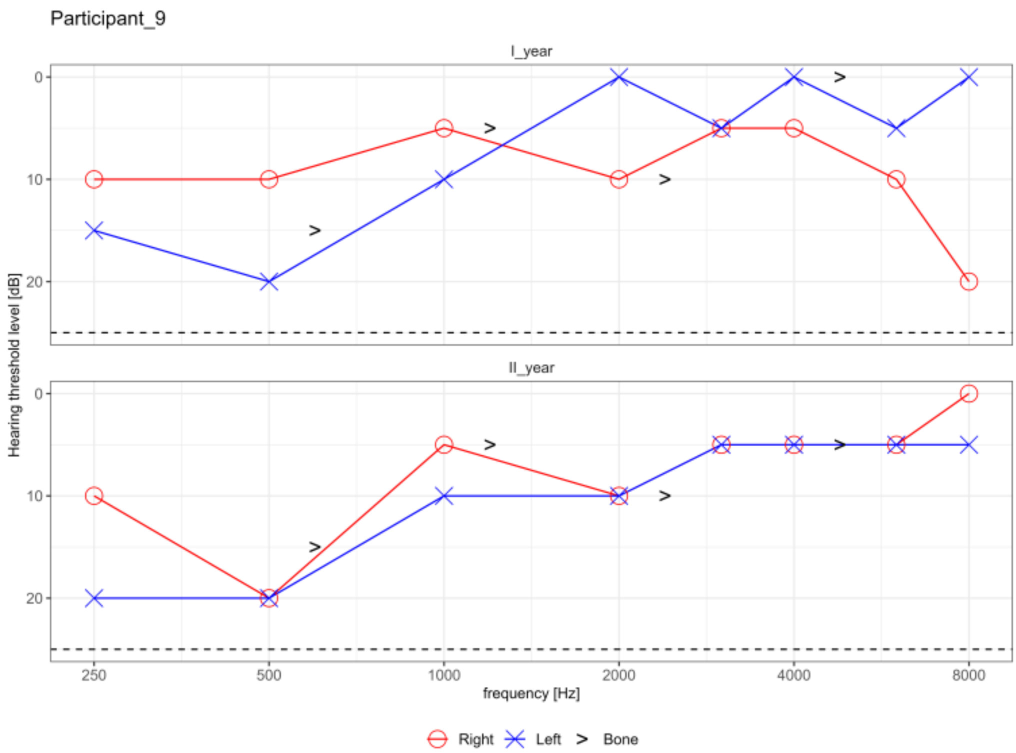

Figure A9. Yearly audiograms for Participant 9.

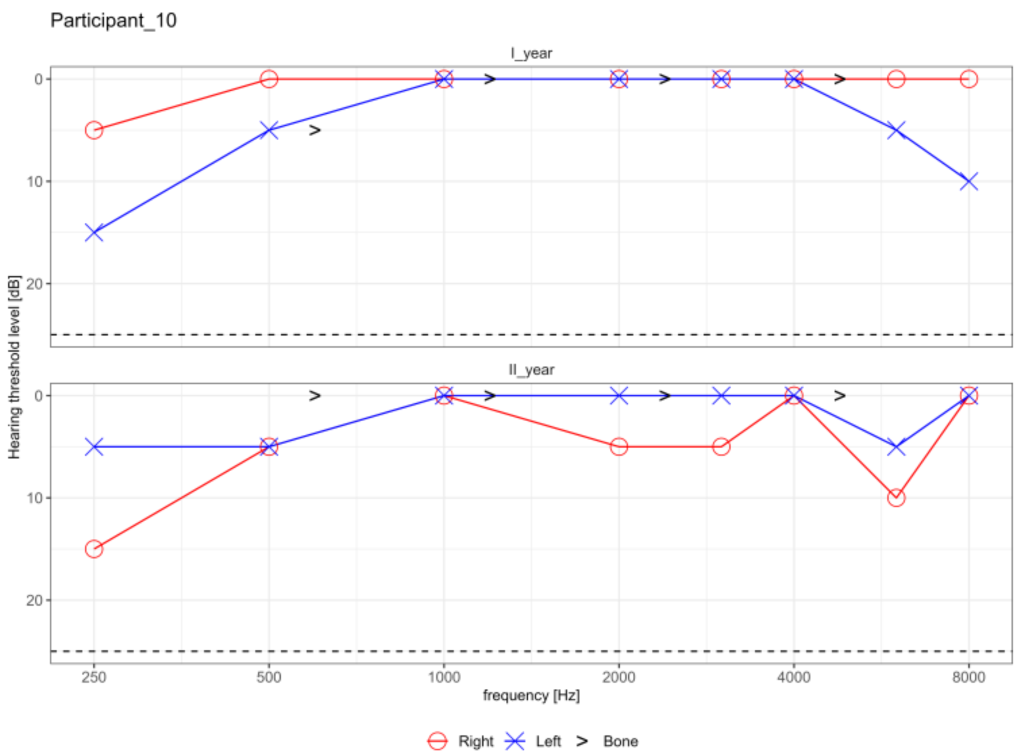

Figure A10. Yearly audiograms for Participant 10.

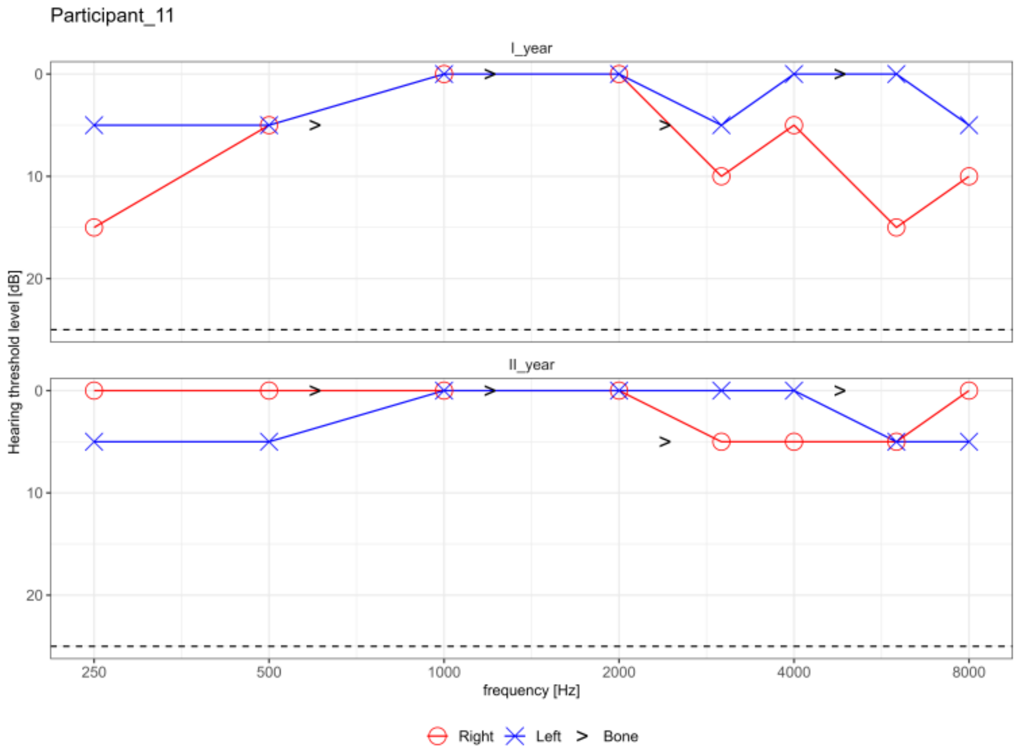

Figure A11. Yearly audiograms for Participant 11.

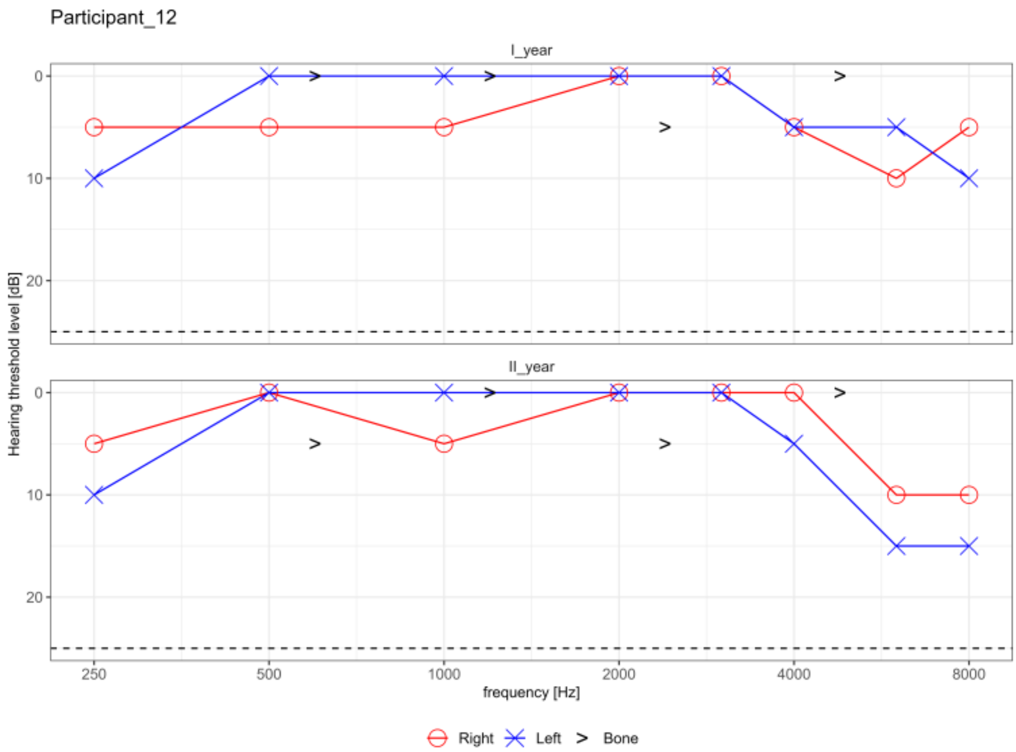

Figure A12. Yearly audiograms for Participant 12.

References

1. Rabinowitz, P.M. Noise-induced hearing loss. *Am. Fam. Physician* **2000**, *61*, 2749–2760. [PubMed]
2. Fink, D. A new definition of noise: Noise is unwanted and/or harmful sound. Noise is the new 'secondhand smoke'. *Proc. Meet. Acoust.* **2019**, *39*, 1–12. [CrossRef]

3. Hong, O.; Kerr, M.J.; Poling, G.L.; Dhar, S. Understanding and preventing noise-induced hearing loss. *Disease-a-Month* **2013**, *59*, 110–118. [CrossRef]
4. Kurabi, A.; Keithley, E.M.; Housley, G.D.; Ryan, A.F.; Wong, A.C.Y. Cellular mechanisms of noise-induced hearing loss. *Hear. Res.* **2017**, *349*, 129–137. [CrossRef]
5. Lake, A.B.; Stuart, A. The Effect of Short-Term Noise Exposure on Audiometric Thresholds, Distortion Product Otoacoustic Emissions, and Electrocochleography. *J. Speech Lang. Hear. Res.* **2019**, *62*, 410–422. [CrossRef] [PubMed]
6. Yost, W.A.; Killion, M.C. Hearing thresholds. In *Encyclopedia of Acoustics*; M.J. Crocker: Mahwah, NJ, USA, 1997; Volume 3, pp. 1545–1554.
7. Lees, R.E.; Roberts, J.H.; Wald, Z. Noise-induced hearing loss and leisure activities of young people: A pilot study. *Can. J. Public Health* **1985**, *76*, 171–173.
8. Palin, S.L. Does classical music damage the hearing of musicians? A review of the literature. *Occup. Med.* **1994**, *44*, 130–136. [CrossRef]
9. Earshen, J.J. Understanding noise exposure measurements. *Hear. Rev.* **1999**, *6*, 37–40.
10. Cook-Cunningham, S.L.; Grady, M.L.; Nelson, H.R. Hearing Dose and Perceptions of Hearing and Singing Effort Among University Choir Singers in Varied Rehearsal and Performance Settings. *Int. J. Res. Choral Sing.* **2012**, *4*, 1–19.
11. Švec, J.G.; Granqvist, S. Tutorial and guidelines on measurement of sound pressure level in voice and speech. *J. Speech Lang. Hear. Res.* **2018**, *61*, 441–461. [CrossRef]
12. Occupational Safety and Health Administration. *29 CFR 1910.95 OSHA. Occupational Noise Exposure and Hearing Conservation*; Occupational Safety and Health Administration: Washington, DC, USA, 1983.
13. National Institute for Occupational Safety and Health. *Reducing the Risk of Hearing Disorders Among Musicians*; National Institute for Occupational Safety and Health: Washington, DC, USA, 2015.
14. Henoch, M.A.; Chesky, K. Sound exposure levels experienced by a college jazz band ensemble: Comparison with OSHA Risk criteria. *Med. Probl. Perform. Artist.* **2000**, *15*, 17–22. [CrossRef]
15. American Academy of Audiology. Clinical Consensus Document for Audiological Services for Musicians and Music Industry Personnel. 2020. Available online: https://www.audiology.org/practice-guideline/clinical-consensus-document-audiological-services-for-musicians-and-music-industry-personnel/ (accessed on 12 November 2024).
16. Royster, J.D.; Royster, L.H.; Killion, M.C. Sound exposure and hearing thresholds of symphony orchestra musicians. *J. Acoust. Soc. Am.* **1991**, *89*, 2793–2803. [CrossRef]
17. Zhao, F.; Manchaiah, V.K.; French, D.; Price, S.M. Music exposure and hearing disorders: An overview. *Int. J. Audiol.* **2010**, *49*, 54–64. [CrossRef]
18. Phillips, S.L.; Mace, S. Sound level measurements in music practice rooms. *Music. Perform. Res.* **2008**, *2*, 36–47.
19. Schmidt, J.H.; Pedersen, E.R.; Paarup, H.M.; Christensen-Dalsgaard, J.; Andersen, T.; Poulsen, T.; Bælum, J. Hearing loss in relation to sound exposure of professional symphony orchestra musicians. *Ear Hear.* **2014**, *35*, 448–460. [CrossRef]
20. Ryan, A.F.; Kujawa, S.G.; Hammill, T.; Le Prell, C.; Kil, J. Temporary and permanent noise-induced threshold shifts: A review of basic and clinical observations. *Otol. Neurotol.* **2016**, *37*, e271–e275. [CrossRef]
21. Comeau, G.; Koravand, A.; Swirp, M. Prevalence of Hearing Loss Among University Music Students. *Can. Acoust.* **2018**, *46*, 37–51. Available online: https://piano.uottawa.ca/wp-content/uploads/2020/10/37.-Comeau_Koravand_Swirp_Hearing-loss-2018.pdf (accessed on 12 November 2024).
22. Di Stadio, A.; Dipietro, L.; Ricci, G.; Della Volpe, A.; Minni, A.; Greco, A.; de Vincentiis, M.; Ralli, M. Hearing loss, tinnitus, hyperacusis, and diplacusis in professional musicians: A systematic review. *Int. J. Environ. Res. Public Health* **2018**, *15*, 2120. [CrossRef]
23. Zeigler, M.C. The effects of a tinnitus awareness survey on college music majors' hearing conservation behaviors. *Med. Probl. Perform. Artist.* **2001**, *16*, 136–143. [CrossRef]
24. Rodrigues, M.A.; Amorim, M.; Silva, M.V.; Neves, P.; Sousa, A.; Inácio, O. Sound levels and risk perceptions of music students during classes. *J. Toxicol. Environ. Health* **2015**, *78*, 825–839. [CrossRef]
25. Hu, A.; Hofmann, E.; Davis, J.; Capo, J.; Krane, N.; Sataloff, R.T. Hearing loss in singers: A preliminary study. *J. Voice* **2015**, *29*, 120–124. [CrossRef] [PubMed]
26. Steurer, M.; Simak, S.; Denk, D.M.; Kautzky, M. Does choir singing cause noise-induced hearing loss? *Audiol. Off. Organ Int. Soc. Audiol.* **1998**, *37*, 38–51. [CrossRef] [PubMed]
27. Coleman, R.F. Dynamic intensity variations of individual choral singers. *J. Voice* **1994**, *8*, 196–201. [CrossRef] [PubMed]
28. Redman, Y.; Vercelli, C.; Cantor-Cutiva, L.C.; Bottalico, P. Work-related communicative profile of voice teachers: Effects of classroom noise on voice and hearing abilities. *J. Voice* **2022**, *36*, 291.e17–291.e31. [CrossRef] [PubMed]
29. Isaac, M.J.; McBroom, D.H.; Nguyen, S.A.; Halstead, L.A. Prevalence of hearing loss in teachers of singing and voice students. *J. Voice* **2017**, *31*, 379.e21–379.e32. [CrossRef]
30. Pawlaczyk-Łuszczynska, M.; Zamojska, M.; Dudarewicz, A.; Zaborowski, K. Noise-induced hearing loss in professional orchestral musicians. *Arch. Acoust.* **2013**, *38*, 223–234. [CrossRef]