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Research Paper

Heightened OAEs in young adult musicians: Influence of current noise exposure and training recency

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ABSTRACT

Otoacoustic emissions (OAEs) are a non-invasive metric of cochlear function. Studies of OAEs in musicians have yielded mixed results, ranging from evidence of diminished OAEs in musicians—suggesting noise-induced hearing loss—to no difference when compared to non-musicians, or even a trend for stronger OAEs in musicians. The goal of this study was to use a large sample of college students with normal hearing ($n = 160$) to compare OAE SNRs in musicians and non-musicians and to explore potential effects of training recency and noise exposure on OAEs in these cohorts. The musician cohort included both active musicians (who at the time of enrollment practiced at least weekly) and past musicians (who had at least 6 years of training). All participants completed a questionnaire about recent noise exposure (previous 12 months), and a subset of participants (71 musicians and 15 non-musicians) wore a personal noise dosimeter for one week to obtain a more nuanced and objective measure of exposure to assess how different exposure levels may affect OAEs before the emergence of a clinically significant hearing loss. OAEs were tested using both transient-evoked OAEs (TEOAEs) and distortion-product OAEs (DPOAEs). As predicted from the literature, musicians experienced significantly higher noise levels than non-musicians based on both subjective (self-reported) and objective measures. Yet we found stronger TEOAEs and DPOAEs in musicians compared to non-musicians in the ~1–5 kHz range. Comparisons between past and active musicians suggest that enhanced cochlear function in young adult musicians does not require active, ongoing musical practice. Although there were no significant relations between OAEs and noise exposure as measured by dosimetry or questionnaire, active musicians had weaker DPOAEs than past musicians when the entire DPOAE frequency range was considered (up to ~16 kHz), consistent with a subclinical noise-induced hearing loss that only becomes apparent when active musicians are contrasted with a cohort of individuals with comparable training but without the ongoing risks of noise exposure. Our findings suggest, therefore, that separate norms should be developed for musicians for earlier detection of incipient hearing loss. Potential explanations for enhanced cochlear function in musicians include pre-existing (inborn or demographic) differences, training-related enhancements of cochlear function (e.g., upregulation of prestin, stronger efferent feedback mechanisms), or a combination thereof. Further studies are needed to determine if OAE enhancements offer musicians protection against damage caused by noise exposure.

1. Introduction

Acute hearing is vital to musicians, who must rely on their ears to learn, fine-tune, express, and synchronize to music. Given the importance of hearing for musicians, it is perhaps not surprising that increased sound acuity has been observed in musicians across the auditory system. This phenomenon has been observed in various forms, from heightened ability to detect subtle nuances in sounds to smaller age-related changes to central auditory processing and heightened neural acuity to sound, in both active musicians and people with past musical training (past musicians) (Alain et al., 2014; Kraus et al., 2017; Yeend et al., 2017). Yet, as a group, musicians are also at a higher risk of hearing health problems

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(Jansen et al., 2009). Indeed, musicians at all training levels experience higher noise exposure than the general population (McBride et al., 1992; Miller et al., 2007; Tufts and Skoe, 2018), leading to an increased incidence of noise-induced hearing loss (NIHL) (Jansen et al., 2009). Most types of NIHL are caused by irreversible damage to cochlear hair cells and associated structures (cf. stereocilia) (Chen and Fechter, 2003). Outer hair cells (OHCs), one of two types of cochlear sensory receptors, help amplify low-intensity signals, giving them a vital role in expanding the dynamic range of human hearing (Davis, 1983). However, OHCs are highly susceptible to noise-induced damage, which often affects a particular region of the cochlea and results in frequency-specific hearing loss (Henderson et al., 2006). A loss of hearing acuity is a common clinical concern for musicians, as it can threaten their ability to perceive subtle musical elements, which may, in turn, increase mental distress and decrease social and occupational opportunities to perform (Vogel et al., 2014; Heckman et al., 2021).

1.1. Approaches to estimate noise-induced hearing loss and its risk

In clinical settings, audiological measures of NIHL are commonly limited to pure-tone audiometry. This approach finds the lowest sound intensity a person can hear (their threshold) across a set of frequencies. When hearing is measured through audiometry, NIHL is observed as a loss of sensitivity to frequencies in the 3–6 kHz range (McBride and Williams, 2001). Yet standard audiometry typically only tests as high as 8 kHz, well below the upper-frequency range of the human ear. When extended high-frequency (EHF) audiometry protocols are used to test the upper frequency range of hearing, decreased sensitivity to frequencies greater than 10 kHz are also common in noise-exposed populations (Wang et al., 2000).

While audiometry is currently deemed the gold standard in clinical hearing testing (Durch et al., 2006), it is subjective, requiring the listener to indicate whether they can hear the tone being played. This subjectivity complicates its use in young children or persons with cognitive impairments who may not understand the task (Naito, 2004). But even in healthy young adult populations, audiometry can be subject to response bias and false and exaggerated hearing loss (Peck, 2011). Objective measures are therefore an attractive alternative to conventional audiometry. One such method is otoacoustic emissions (OAEs) testing, an objective measure of OHC function that does not require a behavioral response, limiting the human perceptual and behavioral errors associated with audiometry (Lonsbury-Martin et al., 1991). OAEs are low-intensity (typically below audiometric threshold) sounds (i.e., emissions) that can be detected with a sensitive microphone in the ear canal as the result of non-linear cochlear activity (Kemp, 1978). The strength of the emissions, measured in decibels (dB) and/or signal to noise ratio (SNR), is a reliable indicator of OHC health (Lonsbury-Martin et al., 1991). OAEs can be elicited by various stimuli, with transient and tonal stimuli being common. Transient-evoked OAEs (TEOAEs) use a repeating transient sound such as a click or chirp tone burst to initiate broadband OHC activity. For distortion-product OAEs (DPOAEs), a tonal stimulus consisting of two frequencies is used; this stimulus complex sound produces emissions at non-stimulus frequencies that provide more frequency-specific indications of OHC activity. For both TEOAEs and DPOAEs, weak, absent, or low SNR OAEs may indicate NIHL. (There are some rare auditory pathologies, however, where OAEs are enhanced [Cheatham et al., 2014; El-Badry and McFadden, 2009]). With respect to NIHL and presbycusis, it has been proposed that OAEs provide an earlier indicator of hearing loss than audiometric thresholds (Abdala and Dhar, 2012; Hamdan et al., 2008), although supporting evidence is mixed (Jansen et al., 2009). Nevertheless, the earlier that precursors to NIHL can be detected, the more easily measures can be implemented to slow the progression of irreversible damage to the auditory system.

To help in the prevention of NIHL and to identify individuals at increased risk, various tools have been developed to estimate noise exposure. A quick method for estimating a person's noise exposure is to use a questionnaire, such as the Noise Exposure Questionnaire (NEQ) (Johnson et al., 2017). The NEQ is a roughly 5-minute survey that asks participants how often they engaged in different noisy activities such as power tool use, sporting events or nightclub attendance, musical instrument practice, music listening over earphones, and noisy jobs over the past 12 months. Responses to the NEQ are scored into an annual noise exposure estimate (Johnson et al., 2017). The NEQ has been used by other groups to assess noise exposure in a variety of populations, from college students to military personnel (Bernard et al., 2019; Bhatt, 2017; Brungart et al., 2019; Grinn et al., 2017; Washnik et al., 2016, 2020). Several recent studies have used the NEQ to evaluate noise exposure in student musicians (Washnik et al., 2016, 2020). A more time-intensive but objective approach to estimating personal noise exposure is personal noise dosimetry, which involves a small body-worn recording device that logs environment sound levels. In research on musicians, dosimetry measurements are often conducted during rehearsals or performances, which restricts dosimetry to a period of a few hours (Miller et al., 2007) or individual days (Washnik et al., 2016). Extending the dosimetry recording window to a longer period—a week in our case—can yield greater insight into routine exposure from social or other activities that may occur outside of scheduled rehearsals (Tufts and Skoe, 2018). Since each of these noise exposure measures has its own limitations, using both an objective and subjective measure can provide greater insight into individual noise exposure profiles and therefore better predict hearing risks.

1.2. Outer hair cell function in musicians

Studies of outer cell function have yielded mixed results when musicians are compared to non-musicians. Some have shown weaker or more variable OAE amplitudes in musicians (Hamdan et al., 2008; Høydal et al., 2017), presumably due to subclinical loss from increased noise exposure. Yet others have found no difference in OAEs amplitudes between musicians and non-musicians (Couth et al., 2020; Henning and Bobholz, 2016; Liberman et al., 2016; Møllerløkken et al., 2013; Reuter and Hammershøi, 2007), with some even finding a trend for musicians to have *stronger* OAEs on average (although to our knowledge there are no reports of this trend reaching a statistical significance) (Perrot et al., 1999; Wang et al., 2019). In studies that have recorded OAEs in the presence of a suppressor stimulus, musicians have been found to have finer cochlear tuning (Bidelman et al., 2016) and also stronger medial olivocochlear reflexes (MOCRs) (Bidelman et al., 2017; Brashears et al., 2003; Micheyl et al., 1995, 1997; Perrot et al., 1999; Perrot and Collet, 2014). (In the MOCR paradigms, reflexes are measured as the difference between the OAE amplitude with and without a contralateral stimulus, with a greater a difference indicative of stronger reflexes).

The heterogeneity in findings may be due to differing methodology and recruitment approaches. Some studies comparing OAEs between musicians and non-musicians focused on specific types of musicians such as rock musicians (Høydal et al., 2017) or professional musicians (Hamdan et al., 2008), whereas others did not target a specific group of musicians (Couth et al., 2020). Studies also varied in their sample sizes, with some having limited sample sizes ($n = \sim$12–30, e.g., Henning and Bobholz, 2016; Møllerløkken et al., 2013; Reuter and Hammershøi, 2007) and others having considerably larger sizes ($n = \sim$100–130, e.g., Couth et al., 2020; Emmerich et al., 2008; Yeend et al., 2017; $n > 300$, e.g., Jansen et al., 2009). Those with larger sample sizes generally have a wide age span (~20–60 years) creating the potential for confounding age effects (e.g., Emmerich et al., 2008; Jansen et al., 2009). While some studies measured noise exposure objectively via dosimetry (e.g., Emmerich et al., 2008) or through extensive interviews (e.g., Couth et al., 2020), others assumed higher levels of noise exposure in musicians without directly measuring it (Liberman et al., 2016).

1.3. Current study

To address the limitations of this prior work, we recruited a large sample of similarly aged college students (ages 18–23), all attending the same university and having audiometric thresholds in the clinically normal range (≤ 25 dB HL for frequencies up to 8 kHz). The study most comparable to the current study in size and age range is from Couth et al., 2020 (18–27 years), although they included a small number of musicians with unilateral hearing loss in the sample. To define "musicians," we followed the "six-year criterion" established by Zhang et al. (2020). In their meta-analysis of 90+ papers published between 2011 and 2017, Zhang and colleagues found a consensus point in the literature for "musicians" to be defined as having at least 6 years of musical experience. To encourage more standardization across studies and promote replicability, we followed this guideline and defined musicians as anyone with 6 or more years of musical training and non-musicians as anyone with 0–5 years of training.

The most novel element of our study is the inclusion of both active and past musicians in the musician sample. Including past musicians in the musician sample allowed us to examine differences in OAEs associated with musicianship while minimizing the effects of ongoing/recent noise risks to the auditory system from loud music activities. In all participants (n = 160), we estimated annual noise exposure levels using the NEQ, and in the active musicians and a small subset of the other participants, we used a combination of the NEQ and one week of personal noise dosimetry. In all participants, we also measured TEOAEs to a broadband chirp stimulus. This gave us an estimate of OHC integrity in the 1–5 kHz range, a range overlapping the frequency band where NIHL often presents in audiometry. Results over this frequency range were also investigated in a subset of participants on whom DPOAE data was available (n = 119). With the DPOAE protocol, emissions in the extended high frequency range—i.e. those not captured by the TEOAE protocol or the audiometry—were also available for exploratory examination. We predicted that active musicians would, as a group, have higher noise exposure estimates based on the NEQ and personal dosimetry than non-musicians. With respect to OAEs, we predicted that if any effects did emerge, OAE emissions would be weaker in the musician group by virtue of having higher levels of lifetime noise exposure.

2. Materials and methods

2.1. Study design

Testing was performed at the University of Connecticut (UConn) Storrs campus over several phases from fall 2018 through fall 2022, with a pause from spring 2020 to fall 2021 due to the COVID-19 pandemic. All participants provided written informed consent and were paid for participating in this study. The test protocol was approved by the Institutional Review Board at UConn. The test battery included an initial screening to confirm participants had "normal hearing." This screening was followed by OAE (TEAOE and DPOAE) measurements, noise exposure assessments (via NEQ and/or dosimetry), and a survey of musical training history.

To be included in the study, participants were required to have "normal hearing," as demonstrated by passing an otoscopic screening (to visually rule out outer and middle ear pathologies), passing an initial DPOAE screening, and having audiometric thresholds ≤ 25 dB HL at all test frequencies. The DPOAE screening was performed using the Madsen Alpha OAE Screener (Natus Medical, Inc.), which tests DPOAEs at f_2 = 2.5, 3, 3.5, 4, 5, and 6 kHz. Participants passed this component of the study inclusion criteria if they had an SNR ≥ 6 dB at a minumum of 4/6 test frequencies. Pure tone air conduction audiometry was performed using ER-2 inserts on a GSI-61 audiometer (Grason Stadler, Inc.) by testing octaves from 0.25 to 8 kHz. In a subset of participants (n = 41), the screening protocol also included tympanometry (GSI Tympstar Middle Ear Analyzer, Grason-Stadler Inc., Eden Prairie, MN) to evaluate middle ear function.

2.2. Participants

To obtain a broad sample across the university, study recruitment advertisements were placed in a daily email newsletter distributed to all students at UConn. In total, 170 college-aged (18–23 years old) individuals enrolled in the study, of which 10 were excluded because they did not meet the study inclusion criteria for normal hearing, did not meet group criteria (see Section 2.3), or had poor data quality. One of these 10 individuals was excluded because they had audiometric thresholds > 25 dB HL for at least one of our test frequencies. Three of these 10 individuals were excluded because they participated in a college music ensemble at the time of testing but had fewer than 6 years of musical training and, therefore, did not qualify as musicians based on our internal criteria (see Section 2.3). Four of the 10 were excluded because they provided inconsistent survey data regarding their music background, preventing us from confidently classifying them as musicians or non-musicians. Finally, two of the 10 were excluded because of poor quality OAEs (TEOAE and/or DPOAE composite SNR < 6 dB), indicating a potential middle or inner ear pathology not detected in our initial screening protocol or a data collection issue. With these exclusions, our working dataset comprised 160 people (114 female, 42 male, 4 non-binary) aged 18–23 years (mean = 19.73 years, SD = 1.35 years).

2.3. Group definitions

The final dataset consisted of 96 musicians (mean = 19.81 years, SD = 1.3 years) and 64 non-musicians (mean = 19.67 years, SD = 1.4 years; groups matched on age, $t(158) = 0.67$, $p = .50$). Musicians (n = 96; 74 female, 21 male, 1 non-binary) were defined as individuals with 6 or more years of musical training (self-reported) (Zhang et al., 2020), where training included taking private or group lessons and/or playing in an ensemble (professionally; recreationally; through a music school; or through a primary, secondary, or post-secondary school). The amount of training ranged from 6 to 19 years (mean = 10.65 years, SD = 2.74 years). Non-musicians (n = 64; 40 female, 21 male, 3 non-binary) were defined as individuals with 0–5 years of training (i.e., <6 years) who were also not actively involved in any musical training for at least 6 months before testing. The gender balance was similar between the musician and non-musician groups ($\chi^2(2, n = 160) = 4.94$, $p = .09$). Among the non-musicians, the amount of training ranged from 0 to 5 years (mean = 1.65 years, SD = 1.81 years). Note that nearly half of the non-musicians reported 0 years of musical training, and that the average amount of training is lower than non-musician group in the Couth et al., 2020 sample (which had a mean of 4.8 years of training, with a range of 0–22 years). In our sample, very few participants were close to the definitional cutoff: four non-musicians reported 5 years of musical training and two musicians reported 6 years.

As part of exploratory analyses, we sub-grouped musicians based on their current musical activity level (active vs. past musicians, results in Section 3.4). An additional exploratory analysis divided musicians with available dosimetry data (66 active musicians and 5 past musicians) based on risk of NIHL using NIOSH criteria (see definitions in Section 2.5 and results in Section 3.5). "Active musicians" (n = 69; 54 female, 14 male, 1 non-binary) were defined as individuals with 6 or more years of training who were actively involved (at least weekly) in musical activities at the time of testing. Activities included formal music ensemble rehearsals/performances, solo practicing, and/or gigging. "Past Musicians" (n = 27; 20 female, 7 male) were individuals who had not been actively engaged in musical activities for at least 6 months prior to testing but had accrued six or more years of training in the past. For past musicians, we do not have definitive estimates for all participants of when they stopped playing and so this information was not part of the analysis.

The musicians in our dataset reported between 6 and 19 years of music training. Active musicians (mean = 11.44 years, SD = 2.60 years) had ~2.81 more years of training than past musicians (mean = 8.63 years, SD = 1.94 years; $t(94) = 5.07$, $p < .001$). In the sample of active musicians, roughly half ($n = 34$) were studying music at UConn (including pursuing degrees in music performance, theory, education, composition, and history) and the remainder were studying other disciplines. Regardless of their curriculum, however, the active musicians were involved in group music ensembles such as the UConn marching band, pep band, concert bands, concert choirs, symphony orchestras. Most of the active musicians reported playing multiple instruments ($n = 44$); this overlap makes it difficult to make distinctions between instrument groups. For this reason, we treat the active musicians as a single category in the analysis presented here. See Table S1 for a detailed breakdown of individual music history and noise profile.

2.4. OAE test battery

All participants in the study were tested with the TEOAE protocol ($n = 160$). A total of 119 (49 non-musicians and 70 musicians, of whom 23 were past musicians and 47 were active musicians) were tested with the DPOAE protocol. The smaller sample for the DPAOE protocol is on account of this protocol being added after the initial study recruitment began. Both TEAOE and DPOAE testing was performed using the HearID system (Mimosa Acoustics, Inc.).

TEOAEs were measured using a chirp stimulus (bandwidth = 1–5 kHz, 10.5 ms) with the HearID default Chirp50_B2000_N60 protocol (Mimosa Acoustics, Inc.). The recording protocol was identical to that reported in Parker et al. (2021). The protocol was run four times for the right ear using a ER10C probe and insert. The left ear was used if calibration errors occurred for the right ear. For each run, a nonlinear sequence of four chirps was repeated at least 500 times (500 sweeps). Each individual chirp was 10.5 ms and the interval between the four chirps was 32.5 ms. The protocol exceeded 500 times when a minimum SNR of 6 dB was not reached. The first three chirps of the sequence were played at 50 dB SPL, with the fourth chirp played at 59.5 dB SPL in inverting polarity to minimize stimulus artifacts and middle ear components. Responses to individual chirps were averaged over a 14-ms time window. For each run, the recordings were bandpass filtered from 1 to 5 kHz (3 dB/octave roll off), making 721 to 5075 Hz the effective bandwidth of the response. During data collection, data frames were discarded if the instantaneous wideband noise level was above 55 dB SPL, the factory default. The TEOAE magnitude was automatically analyzed by the software in the frequency domain, and the noise floor was calculated as the TEOAEs' magnitude difference between successive stimulus presentations. From each run, the software calculated the TEOAE magnitude (dB SPL) and the TEOAE noise floor, from which the TEOAE SNR was calculated offline by subtracting the noise floor from the TEOAE magnitude. The four runs were then averaged offline. Participants with an SNR < 6 dB were excluded from the final dataset, as this may indicate a potential middle or inner ear problem or excessive noise during the recording (Dhar and Hall, 2011).

DPOAEs were measured from 119 participants at 17 f_1/f_2 pairs using the HearID + DP module (Mimosa Acoustics, Inc.). Measurements were taken from both ears. Each stimulus consisted of two primary tones, f_1 and f_2, with $f_2/f_1 = 1.2$, presented at levels $L_1 = 65$ dB SPL and $L_2 = 55$ dB SPL. The response was measured as the intensity of the emission signal at the frequency $2f_1 – f_2$. We tested an extended frequency range, which was plotted with respect to the f_2 frequency (516; 750; 984; 1500; 2016; 3000; 3984; 6000; 8016; 8719; 9516; 10,359; 11,297; 12,328; 13,453; 14,672; and 15,984 Hz). Measurements were made in the ear canal in 1-second data frames. The data frames were time-averaged up to a maximum duration of 10 s for a given frequency. Once this maximum duration was achieved, the next stimulus was presented. During the measurements, individual frames of 1 second were rejected if the noise level exceeded 10 dB. For a given frequency, the measurement terminated early if the stopping rule criteria were met. The early stopping rules were a noise floor of 0 dB SPL and SNR of 10 dB. No filtering was applied during measurement. For the purposes of comparing TEOAEs and DPOAEs, we focused on an f_2 range referred to here as the "DPOAE Composite." This range is commensurate with the effective bandwidth of the TEAOEs, since it takes the binned average of the measurements at $f_2 = 984$, 1500, 2016, 3000, and 3984 Hz. As with TEOAEs, participants with an SNR < 6 dB at any frequency in this range of interest were excluded from the final dataset. For both TEOAEs and DPOAEs, SNR was the primary dependent variable used in the statistical analysis. Noise floors and emission amplitudes were also considered in secondary analyses to understand the source(s) of potential differences in SNRs.

DPOAEs also provided a measure of EHF hearing not captured by our audiometric protocol, in addition to supplementing the standard range audiometry. For this reason, we opted to test each ear separately on the DPOAE protocol. When time permitted, each ear was tested twice, creating four measurements for each participant for each stimulus, that were later averaged. For the TEOAEs, where the effective bandwidth overlaps the standard frequency range, we tested only one ear because audiometric thresholds were symmetric in this range in all participants. Limiting TEOAE testing to one ear also shortened the test protocol. For TEAOEs, we defaulted to test the right ear, which aligns with the putative ear advantage for the transient sounds observed in neonates (Sininger and Cone-Wesson, 2006).

2.5. Personal noise dosimetry

Most of the active musicians ($n = 66$), a small number of non-musicians ($n = 15$), and a few past musicians ($n = 5$) wore an ER-200DW8 personal noise dosimeter for 7 consecutive 24-hour days. The dosimeter measured and logged environmental sound levels above 70 dBA every 3.75 min. For the complete methods and a discussion of the merits and limitations of personal noise dosimetry, see Skoe and Tufts (2018). For each measurement day, we calculated the participants' continuous sound levels, averaged over 24 h using a 3-dB exchange rate and A-weighted sound levels (LAeq24h). The LAeq24h was then averaged across measurement days. To apply NIOSH reference limits to our dosimetry data, the LAeq24h daily average was then normalized to an 8-hr period (LAeq8h). NIOSH exposure limits, which are typically applied to occupational settings, are based on an 8-hr workday, with the recommended NIOSH exposure limit being 85 dBA averaged over 8 hrs. Following NIOSH standards, individuals with exposures that exceed this limit are considered to be at increased risk of NIHL compared to those below this limit. In this study, LAeq8h is representative of noise exposure across the week the dosimeter was worn.

2.6. The noise exposure questionnaire (NEQ)

The NEQ (Johnson et al., 2017) was administered to all participants to obtain an estimate of their noise exposure over the past year (i.e., the 12 months preceding participation in the study). The short, 5-minute questionnaire asks about the frequency of engaging in common noisy activities such as using power tools, attending loud social events (such as bars and concerts), listening to music over earphones, and playing a musical instrument. It then estimates the annual noise exposure (ANE) using representative sound levels from the literature for each activity type. The NEQ noise exposure estimate is expressed in dB as the continuous sound level averaged over 8760 hr using a 3-dB exchange rate and A-weighted sound levels (LAeq8760h). The NEQ estimate of annual noise exposure is not restricted to working hours, and it is expressed over a period of a full year (8760 hr = 24 hr × 365 days). For the specifics of the LAeq8760h calculation, refer to Johnson et al. (2017).

For the purposes of applying a common NIOSH exposure limit criterion of 85 dBA for 8 h for both the dosimetry and NEQ data, the NEQ

LAeq8760h estimate was normalized to an 8-hr period, with the acknowledgement of the differences between task-based approaches like the NEQ and objective approaches like personal noise dosimetry. To facilitate comparison across other studies that have used the NEQ, the LAeq8760h is also presented.

2.7. Data analyses

The Kolmogorov-Smirnov test was used to evaluate the normality in our variables. All of our primary variables of interest except for the DPOAE composite and LAeq8h from weeklong dosimetry were not normally distributed (p-values: TEOAE < 0.001; LAeq8760h from NEQ $= 0.001$; years of training < 0.001). Although our data violate the assumption of normality, the robustness of our sample size motivated our use of parametric testing for group analyses (Nguyen et al., 2016). T-tests compared differences between non-musicians and musicians, and between the musician subgroups. Non-parametric Mann-Whitney U tests were also performed to reinforce the findings from parametric testing.

Since OAEs are known to differ between males and females (especially TEOAEs, McFadden et al., 2009), we also analyzed group differences covarying for gender. As we only collected information about gender identity, not sex assigned at birth, gender was used as a covariate. Given that transgender and non-binary people make up a relatively small portion of the population and our sample is sufficiently large, this can be considered a relatively accurate estimate of sex in this analysis. A chi-square test was used to test for a gender balance across groups. An analysis of covariance (ANCOVA), using gender as a covariate, was used to compare the OAE SNR of musicians and non-musicians. Repeated-measures analysis of variance (RMANOVA) was used to analyze OAE noise floors and amplitudes and, in the case of DPOAEs, frequency-specific effects. To examine the relationship between OAE SNR and musical training, we used years of musical training as a continuous measure of training. Non-parametric correlations were used since years of training was found not to be normally distributed. All statistical analyses were performed using JASP (Version 29 0.17.3) or SPSS (Version 28.0.1.1)

3. Results

3.1. Hearing thresholds are similar in musicians and non-musicians

All individuals included in the final dataset were required to have thresholds ≤ 25 dB HL at each octave frequency between 0.25–8 kHz. To analyze the audiometry data, the average of both ears was taken and used as an individual's threshold for each test frequency (Fig. 1e). To determine if there were statistically reliable audiometric differences between groups, these data were submitted to a 2×6 repeated-measures analysis of variance (RMANOVA: Musician vs. Non-Musician $\times$ Frequency). In addition to the expected main effect of frequency ($F(5, 790) = 59.43$, $p < .001$), there was an interaction between frequency and group ($F(5790) = 77.82$, $p < .001$), but not a main effect of group ($F(1158) = 1.12$, $p = .29$). At each test frequency between 0.25–4 kHz, average thresholds were roughly the same in musicians and non-musicians. However, at 8 kHz musician thresholds were, on average, 3.28 dB lower (better) than non-musician thresholds (musicians: $M = 0.00$ dB, SD $= 5.45$ dB; non-musicians: $M = 3.28$ dB, SD $= 5.54$ dB; SE $=0.75$, $t = 4.36$, Cohen's $d = 0.70$, $p < .001$, Holm *post-hoc* corrected).

3.2. Musicians experience higher levels of noise exposure than non-musicians

The NEQ revealed that musicians had higher noise exposure than non-musicians over the previous 12 months (Fig. 1a). The LAeq8760h of musicians ranged from 64.5 to 84.9 dB with an average of 75.53 dB (SD $= 4.40$ dB). For non-musicians, LAeq8760h ranged from 64.0 to 86.3 dB with an average of 73.46 dB (SD $= 5.05$ dB). By comparison, in their study of college students ($n = 75$), Washnik et al. (2020) reported an LAeq8760h mean of ~68 dB for non-musicians and ~76 dB for musicians. In the current dataset, the LAeq8h ranged from 70.50 to 90.86 dB with an average of 81.54 dB (SD $=$ 5.03 dB) for musicians. For non-musicians, LAeq8h ranged from 70.00 to 93.2 dB with an average of 79.47 dB (SD $= 5.03$ dB). This amounts to a roughly 2.0 dB difference between musicians and non-musicians ($t(158) = 2.75$, $p < .01$; U(158) $=$ 2321, $p < .01$). Thirty-three of 160 participants exeeded the NIOSH noise exposure limit; of these 33, 21 were musicians and 12 were

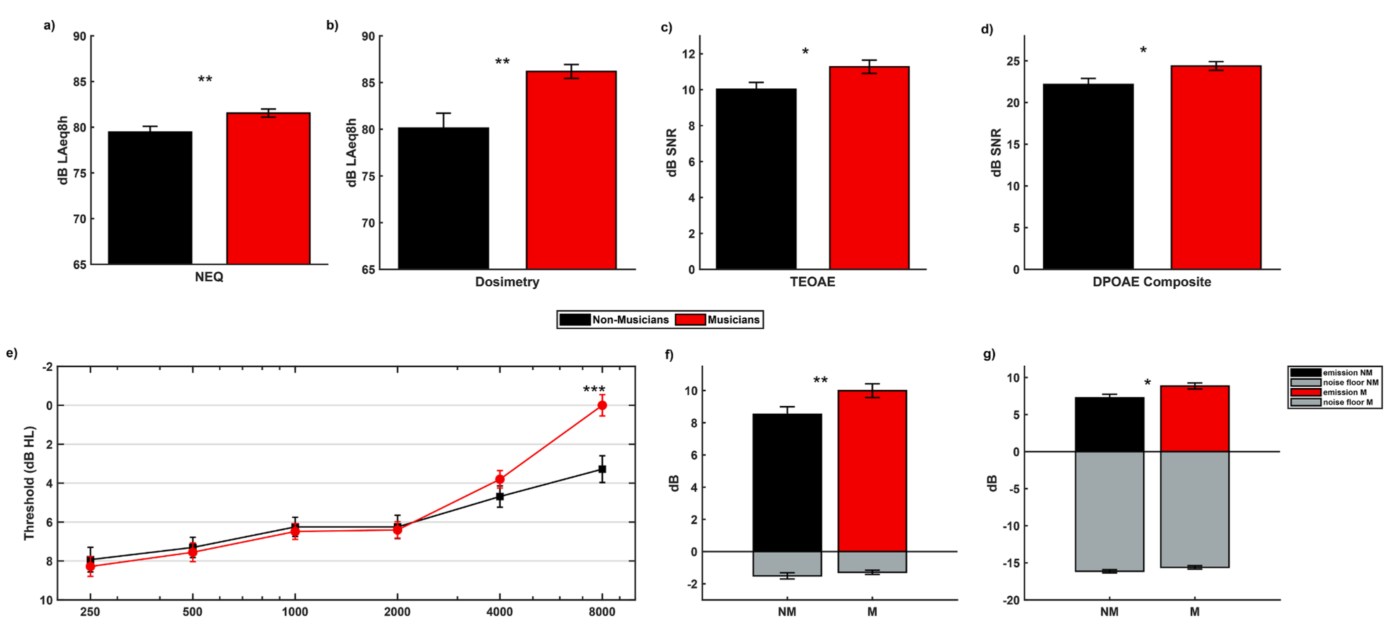

Fig. 1. Musician and non-musician audiometry, noise exposure, and OAEs. (a) – (d) show musicians (in red) on the right and non-musicians (in black) on the left. (a) and (b) show average LAeq8h from the NEQ and average LAeq8h from personal dosimetry (c) and (d) show average TEOAE and DPOAE SNRs respectively, both plotted in dB. (e) shows pure tone audiometry for the two groups. (f) and (g) show the emission and noise floor levels (gray) for TEOAE and DPOAE, respectively, for musicians (M) and non-musicians (NM). Error Bars = ±1 SE. *$p < .05$; **$p < .01$; ***$p < .001$. For noise floor statistics, refer to Results Section 3.3.

non-musicians.

Like with the NEQ, personal noise dosimetry also showed that musicians (n = 71; 66 active and 5 past musicians) had higher noise exposure than non-musicians (n = 15) (Fig. 1b). The dosimeter LAeq8h for musicians ranged from 68.15 to 102.4 dB with an average of 86.19 dB (SD = 6.30 dB). The dosimeter LAeq8h for non-musicians ranged from 70.0 to 91.5 dB with an average of 80.12 dB (SD = 6.40 dB). Personal noise dosimetry showed that musicians' daily average noise exposure was roughly 6.07 dB higher than non-musicians ($t(84) = 3.38$; $p = .001$). Using NIOSH criteria, 45 of 86 participants with dosimetry data had noise exposure levels that exceeded 85 dBA over an 8-hr period, of which 42 were musicians and 3 were non-musicians. By comparison, of these 45, the NEQ flagged 14 as having exceeded the NIOSH exposure limit.

In 86 participants, both NEQ and dosimetry data were available. In this subset, the two measures were correlated ($\rho = 0.40, p < .001$), such that those with higher NEQ LAeq8hs also generally had higher dosimetry LAeq8hs. However, while correlated, the dosimetry estimates were on average higher than the NEQ estimates (dosimetry LAeq8h $M = 85.13$ dB, SD = 6.70 dB; NEQ LAeq8h $M = 75.80$ dB, SD = 4.54 dB; $t(85) = 13.97$, $p < .001$; $W = 2909$, $z = 4.47$, $p < .001$). This is not surprising given that the NEQ estimate is derived from representative levels, whereas the personal dosimeter captures actual sound levels for an individual. So, for example, the NEQ would equate 1-hour playing the harp to 1-hour playing in a 100-piece band, whereas the dosimeter would be more sensitive to the actual sound level of the different musical environments.

3.3. OAE SNRs are enhanced in musicians vs. non-musicians

Musicians had enhanced OAEs as measured by both TEOAEs (Fig. 1c) and DPOAEs (Fig. 1d). The average TEOAE SNR for musicians was about 1.25 dB higher than for non-musicians (musicians: $M = 11.28$ dB, SD = 3.65 dB; non-musicians: $M = 10.03$ dB, SD = 3.04 dB; $t(158) = 2.26$; $p = .03$). Musician's higher SNR could be driven by differences in the amplitude of the TEOAE and/or the noise floor, prompting us to consider each component separately (Fig. 1f). For instance, it could be that musicians are less fidgety participants, leading to lower noise floors and resulting in stronger OAE SNRs. For TEOAEs, musicians, however, had a noise floor that was 0.22 dB higher than non-musicians (musicians: $M = -1.29$ dB, SD = 1.39 dB; non-musicians: $M = -1.50$ dB, SD = 1.54 dB). Musicians also had 1.47 dB higher emissions than non-musicians (musicians: $M = 9.99$ dB, SD = 4.17 dB; non-musicians: $M = 8.52$ dB, SD = 3.7 dB). To determine if there were statistically reliable differences in the actual or relative amplitudes of the noise floor and emission, these TEAOE metrics were submitted to a 2 × 2 repeated-measures analysis of variance (RMANOVA: Musician vs. Non-Musician × Noise Floor vs. Emission Amplitude). As expected, for both groups, the emission amplitude was higher than the noise floor ($F(1158) = 1490.31$, $p < .001$). Additionally, musicians had higher noise floors and emission amplitudes (main effect of group, $F(1158) = 5.11$, $p = .03$). Interestingly, there was a musicianship × TEOAE metric interaction, indicating the relative difference between the emission and noise floor was higher for musicians (11.28 dB) than non-musicians (10.03 dB; $F(1158) = 5.11$, $p = 0.03$). Thus, musicians appear to have enhanced TEOAE amplitudes despite a slightly higher noise floor. Note, though, the difference in the TEOAE noise-floor amplitude did not survive Holm-corrected *post hoc* tests ($t = -0.45$, $p = 0.65$), but the difference in TEOAE amplitudes did ($t = -3.02$, $p = 0.01$) (Fig. 1f).

For the DPOAE composite (over the ~1–5 kHz range), the SNR was roughly 2.22 dB higher in musicians than non-musicians (musicians: $M = 24.38$ dB, SD = 4.40 dB; non-musicians: $M = 22.16$ dB, SD = 5.17 dB; $t(117) = 2.52$; $p = .013$, $U(117) = 1378$, $p = .07$). For the DPOAE composite, musicians had a noise floor that was 0.52 dB higher than non-musicians (musicians: $M = -15.61$ dB, SD = 2.22 dB; non-musicians: $M = -16.14$ dB, SD = 1.75 dB). For the composite metric, musicians also had a 1.60 dB higher emission than non-musicians (musicians: $M = 8.85$ dB, SD = 4.00 dB; non-musicians: $M = 7.25$ dB, SD = 3.88 dB). To determine if there were statistically reliable differences in the actual or relative amplitudes of the noise floor and emission, these data were submitted to a 2 × 2 repeated-measures analysis of variance (RMANOVA: Musician vs. Non-Musician × Noise Floor vs. Emission Amplitude) (Fig. 1 g). As expected, the emission amplitude was higher than the noise floor for both groups ($F(1117) = 3689.06$, $p < .001$). Additionally, there was a main effect of group with musicians having reliably higher noise floors and emission amplitudes ($F(1117) = 5.97$, $p = 0.02$). Thus, for the composite measure, the DPOAE SNR enhancement in musicians is not due to lower noise floors. However, while the SNR was different between groups, the musicianship × DPOAE metric interaction was not significant ($F(1117) = 1.86$, $p = 0.17$).

3.3.1. Accounting for gender

These group differences for OAE SNR persisted when gender was added as a covariate. Although gender was a significant covariate for TEOAE SNRs ($F(1157) = 10.1$, $p < 0.01$), even when covarying for it, TEOAE SNRs were significantly larger in musicians compared to non-musicians ($F(1157) = 4.34$, $p = .04$). DPOAE composite SNRs were also larger when covarying for gender ($F(1117) = 6.33$, $p = .01$); however, gender was not a significant covariate ($F(1116) = 1.59$; $p = 0.21$).

3.3.2. Relationships between extent of music training, noise exposure, and OAE SNRs

To further analyze the relationship between musical training and OAEs, correlations were performed with years of training. This analysis included all participants (n = 160). We found that TEOAE SNRs increased significantly with years of training (ρ = 0.22; $p < .01$), and that this increase was driven by the amplitude of the TEOAEs ($\rho = 0.23$, $p < .01$) and not the noise floor ($\rho = 0.03$, $p = .67$). In addition, LAeq8760h was found to increase with greater years of training ($\rho = 0.30$, $p < .001$). However, the relationship between LAeq8760h and TEOAE SNR was not significant ($\rho = -0.03, p < .73$) and neither was the relationship between LAeq8760h and DPOAE composite ($\rho = -0.02, p < .85$).

3.4. Exploratory analysis 1: active musicians experience higher noise exposure than past musicians and have similar TEOAEs but smaller DPOAEs

In light of the group differences seen between musicians and non-musicians, we pursued follow-up exploratory analyses comparing past and active musicians. The groups were matched audiometrically, including at 8 kHz (no main effect of group [$F(1,94) = 0.1, p = .75$], nor a Group × Frequency interaction [$F(5, 470) = 0.88, p = .49$]). Regarding noise exposure, active musicians generally experienced higher levels than past musicians. Active musicians' LAeq8760h from the NEQ was, on average, 5.35 dB higher than that of past musicians (active musicians: $M = 77.04$ dB, SD = 3.35 dB; past musicians: $M = 71.69$ dB, SD = 4.47 dB; $t(94) = 6.38$; $p < .001$; $U(94) = 1549.5, p < .001$) (Fig. 2a). Based on the available data from personal noise dosimetry, daily average noise exposure for active musicians was about 6.06 dB higher than that of past musicians (active musicians: $M = 86.61$ dB, SD = 6.18 dB; past musicians: $M = 80.56$ dB, SD = 5.69 dB) (Fig. 2b), although dosimetry data is only available from 5 of the 27 past musicians, and so a statistical comparison was not performed.

TEOAEs generally did not differ between past and active musicians. TEOAE SNRs (Fig. 2c) in active musicians and past musicians were nearly equal (active musicians: $M = 11.27$ dB, SD = 3.76 dB; past musicians: $M = 11.28$ dB, SD = 3.43 dB; $t(94) = 0.01$; $p = .99$; $U(94) = 919.5$, $p = .92$). Additionally, active musicians and past musicians did not differ with respect to TEOAE noise floors and or TEOAE amplitudes (active vs. past musician × noise floor vs. amplitude RMANOVA: no main effect of musician group: $F(1,94) = 0.08$, $p = .78$; expected main

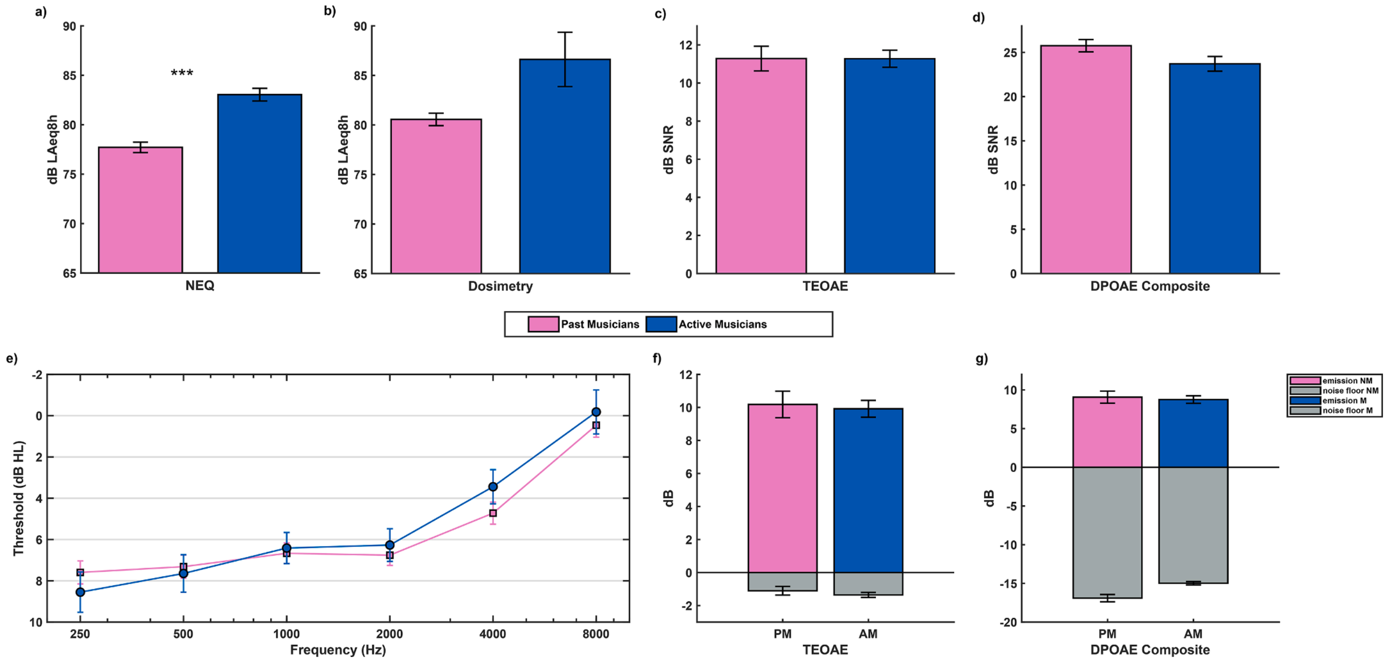

Fig. 2. Sub-analysis of past and active musician noise exposure and OAEs. (a) – (d)Past musicians are plotted in pink on the left and active musicians are plotted in blue on the right. (a) and (c) show average LAeq8h from the NEQ and average LAeq8h from personal dosimetry, respectively. (b) and (d) show average TEOAE and DPOAE SNRs respectively, both plotted in dB. (e) shows pure tone audiometry for the two groups. (f) and (g) show the emission and noise floor levels (gray) for TEOAE and DPOAE, respectively, for active musicians (AM) and past musicians (PM). Error Bars = ±1 SE. ***p* < .05; ***p* < .01; ****p* < .001. For noise floor statistics, refer to Results Section 3.4. Note that for the personal noise dosimetry, data was available for all active musicians and five past musicians.

effect of TEOAE metric: $F(1,94) = 965.95$, $p < .001$; no interaction: $F(1,94) = 0.09$, $p = .76$) (Fig. 2f). Similar to the TEOAEs, the DPOAE composite SNR (Fig. 2d) over the ~1–5 kHz range was not significantly different between past and active musicians ($t(68) = 1.862$; $p = .067$, $U(68) = 405$, $p = .09$), although, on average, past musician's DPOAE composite SNR was about 2.05 dB higher than active musicians (past

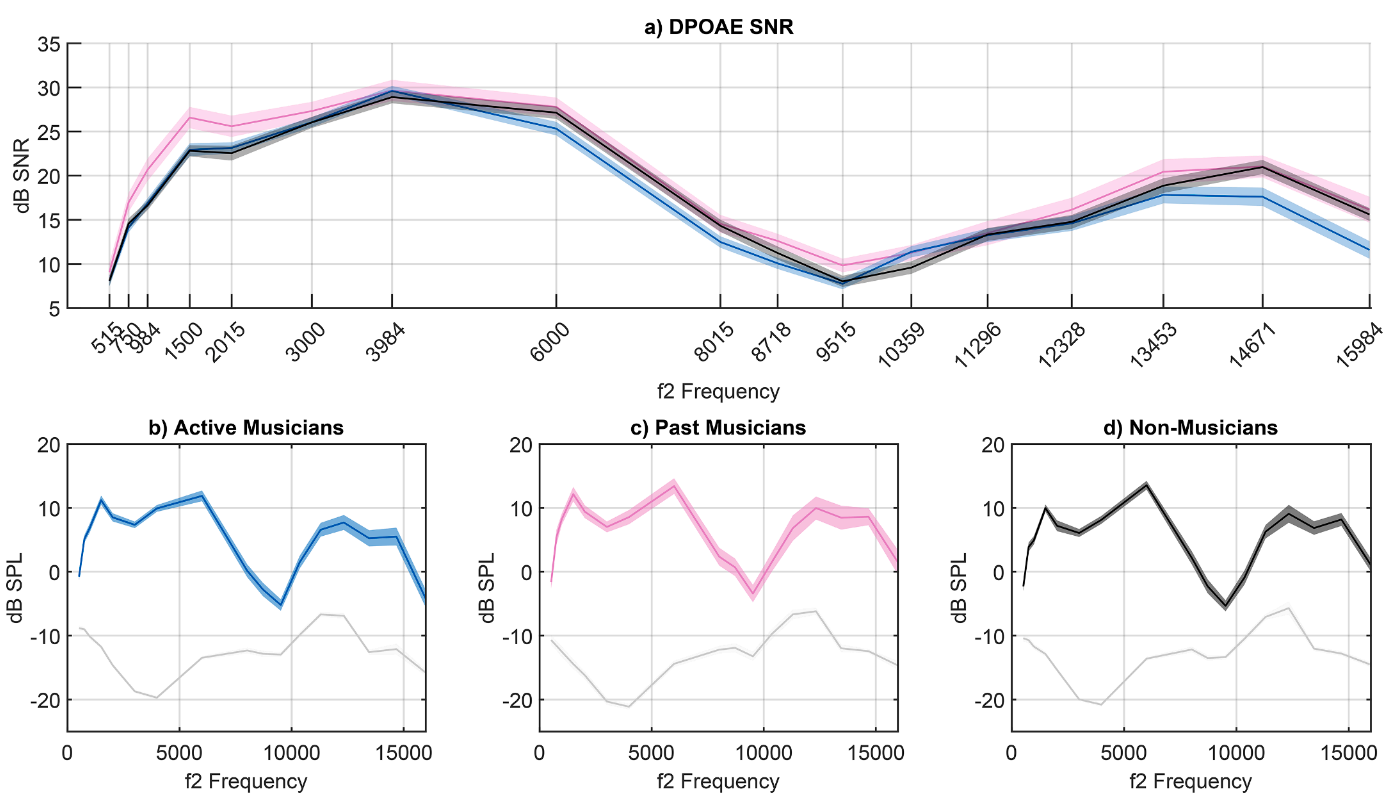

Fig. 3. DPGram of all three groups. (a) DPOAE SNRs are plotted at each test f_2 frequency in the extended high frequency range for non-musicians (black), past musicians (pink), and active musicians (blue). Shading = ±1 SE. In panels b, c, and d emission and noise floors amplitudes are plotted for current musicians, past musicians, and non-musicians, respectively.

musicians: $M = 25.76$ dB, SD = 4.89 dB; active musicians: $M = 23.71$ dB, SD = 4.02 dB). An analysis of the DPOAE composite noise floor and emission amplitudes showed a group by DPOAE metric interaction (active vs. past musician × noise floor vs. amplitude RMANOVA: no main effect of musician group: $F(1,68) = 0.15$, $p = .10$; expected main effect of DPOAE metric: $F(1,68) = 2153.52$, $p < .001$; interaction: $F(1,68) = 4.34$, $p = .04$). *Post-hoc* pairwise comparisons indicated that this interaction was driven by past musicians having lower noise floors ($t = 2.37$, $p = 0.04$) (Fig. 2 g).

Our primary interest was the DPOAE composite because it allowed for a comparison between TEOAEs and DPOAEs. However, as a follow-up to the DPOAE composite analyses, further exploratory analyses considered the full spectrum of the extended high frequency DPOAEs (Fig. 3). Note that around $f_2 = 9515$ Hz, there appears to be a "notch" or a sharp drop in the emission intensity. This frequency region is well known to have a suppressed measurement caused by standing waves in the ear canal (Siegel and Hirohata, 1994) so it is more a measurement artifact than an indication of impaired cochlear function at this frequency. Nevertheless, it was included in the analysis of the full spectrum of f_2 frequencies tested. When all DPOAE f_2 frequencies are included in the model, there was a significant group difference for DPOAE SNRs (active vs. past musician × f_2 frequency RMANOVA; main effect of active musicianship, $F(1,68) = 7.16$, $p < .01$). There was also the expected main effect of frequency $F(1,1088) = 96.62$, $p < 0.001$). Interestingly, a frequency-by-musician-group did not emerge, indicating the magnitude of the group difference was not frequency-specific ($F(16, 1088) = 0.99$, $p = .46$). To understand what drove the SNR differences, we once again analyzed DPOAE noise floors and amplitudes through RMANOVAs. A significant TEOAE metric by group interaction ($F(1,68) = 7.157$, $p < .001$) emerged due to past musicians having larger emissions (1.44 dB, $t = -1.89$, $p = .12$) but smaller noise floors (0.70 dB, $t = 9.23$, $p = .358$) than the active musicians.

3.5. Exploratory analysis #2: a comparison of active musicians with different noise exposure shows no OAE group differences

In this section, we focus only on active musicians ($n = 69$). Of the 66 active musicians on whom dosimetry data was available, 41 exceeded the NIOSH noise exposure limit of 85 dBA over 8 hr, and 25 fell below the limit. The NEQ identified an additional 5 who exceeded the exposure limit. Thus, we found that a total of 46 active musicians were above and 23 were below the limit, with the assumption that those above the limit are at greater risk of NIHL than those below it. TEOAE data was available for all participants. Active musicians below the limit had 1.71 dB higher TEOAE SNRs than musicians above the limit, although the difference was not statistically significant (below limit: $M = 12.11$ dB, SD = 3.64 dB; above limit: $M = 10.89$ dB, SD = 3.79 dB; $t(67) = 1.31$; $p = 0.19$; $U(67) = 631$, $p = .20$). Because the groups were not different with respect to SNR, a noise floor analysis was not undertaken. Of the 47 active musicians on whom DPOAE data was available, the DPOAE composite SNR was also not significantly different between musicians above and below the NIOSH limit (below limit: $n = 17$; $M = 23.70$ dB, SD = 3.61 dB; higher exposure: $n = 30$; $M = 23.71$ dB, SD = 4.29 dB; $t(45) = -0.01$, $p = .99$; $U(45) = 272.00$, $p = .72$). This extended across all frequencies (below vs. above limit × f_2 frequency RMANOVA: main effect of noise-exposure group, $F(1,45) = 0.32$, $p = .57$; expected main effect of DPOAE f_2 frequency, $F(16,720) = 71.30$, $p < .001$; no interaction, $F(16,720) = 0.85$, $p = .62$). Because the groups were not different with respect to SNR across the frequency spectrum, a noise floor analysis was not undertaken.

3.6. Exploratory analysis #3: comparing non-musicians, past musicians, and active musicians reveals that recency of training may differentially affect DPOAEs and TEOAEs

In this section, we compare all three groups (non-musicians, past musicians, and active musicians), and factor risk of NIHL into the analysis as a covariate. For the TEAOE SNR, there was a statistically significant musician group effect ($F(2, 156) = 3.26$, $p = .04$), but NIHL risk was not a significant covariate ($F(1, 156) = 19.60$, $p = .17$). *Post hoc* pairwise comparisons showed that active musicians differed from non-musicians ($t = 2.45$, $p = .05$, Holm corrected) (active musicians > non-musicians); however, the other pairwise comparisons were not significant. For the DPOAE composite there was also significant main effect of group ($F(2, 115) = 4.6$, $p = .01$), and risk was not a significant covariate ($F(1, 115) = 0.07$, $p = 0.80$). In this case, *post-hoc* testing showed that past musicians differed from non-musicians ($t = 2.98$, $p = .01$, Holm corrected) (past musicians > non-musicians), but the other pairwise comparisons were not significant. When factoring in all DPOAE frequencies (Fig. 3), the main effect of group was also significant ($F(2115) = 3.22$, $p = .04$) but the group x frequency interaction was not ($F(32, 1840) = 0.86$, $p = .69$). *Post-hoc* testing showed a difference between active and past musicians ($t = -2.5$, $p = .04$, Holm corrected) (active musicians > past musicians) but not the other groups.

3.7. Exploratory analysis #4: regression analysis

Finally, multiple regression evaluated how musical training (years), current activity level (active vs. not active; non-active in this case includes past musicians and non-musicians) and current noise exposure (NEQ LAeq8760h) combine to predict OAE SNRs. For the TEOAE, results showed a statistically significant regression ($R^2 = 0.06$, $RMSE = 3.5$, $F(3159) = 3.20$, $p = .03$), with years of musical training as the only significant predictor of TEOAE amplitude ($t = 2.49$, $p = .02$). The other two variables did not independently contribute to the model (NEQ, $t = -0.70$, $p = .49$; currently active, $t = -0.60$, $p = .54$), although the trend was for TEOAEs to decline with more noise exposure and an active musical practice. For the DPOAE composite, the model was not statistically significant ($F(3118) = 1.40$, $p = .25$).

4. Discussion

Our primary goal was to investigate the association between musical training, otoacoustic emissions and noise exposure in young adults with clinically normal hearing. Consistent with previous studies from our group and others, we found that musicians (people with 6+ years of musical training) had higher exposure to noise in the previous 12 months than non-musicians (e.g., Reuter and Hammershøi, 2007; Tufts and Skoe, 2018). Despite this increased noise exposure, the musician group had more robust cochlear responses (i.e., stronger OAE amplitudes and SNRs) in the 1–5 kHz range than the non-musician group, as measured by both TEOAEs and DPOAEs. This finding is suggestive of enhanced cochlear amplification in musicians. Importantly, heightened SNRs OAEs in the 1–5 kHz range could not be predicted from air-conduction hearing thresholds (see also, Glavin et al., 2021), as hearing thresholds were not different between groups in this range. However, enhanced cochlear function could explain both stronger OAEs and lower (better) hearing thresholds in the musicians at 8 kHz. (Although hearing thresholds at 8 kHz did not strongly correlate with either metric [TEOAE: $\rho = -0.05$, $p = .46$; DPOAE: $\rho = -0.17$, $p = .06$, respectively] and the relationship between hearing thresholds at 8 kHz and the emission corresponding to the 8 kHz f_2 stimulus was weak [$\rho = -0.22$, $p = .02$]).

Exploratory analyses compared OAEs between two musician subtypes: those who were currently active vs. those who were not (i.e., past musicians). Past musicians, a relatively understudied population (Skoe and Kraus, 2012), had comparatively lower noise exposure estimates than either the non-musicians or active musicians. Yet even in the face of past musicians having lower noise exposure in the previous 12 months, their TEOAE SNRs and DPOAE composite SNRs were similar to those of active musicians in the 1–5 kHz range. However, when the entire DPOAE frequency range was considered, active musicians had lower

SNRs than past musicians, consistent with a subclinical noise-induced hearing loss in active musicians that only is evident when active musicians are compared to a group with similar levels of musical training who are not experiencing ongoing risks of noise exposure from music making. Thus, stronger cochlear amplification in musicians may be impacted by ongoing noise exposure.

To further evaluate the effects of ongoing risks of NIHL, we created subgroups of active musicians based on a combination of personal noise dosimetry and a noise exposure questionnaire. The purpose of this analysis was to compare active musicians who exceeded the NIOSH noise exposure limit to active musicians who did not exceed the limit. With noise exposure being a major contributor to hair cell damage, weaker cochlear emissions in active musicians with higher levels of noise exposure would be a reasonable prediction. However, a statistically significant group difference did not emerge for either the TEOAE or DPOAE SNR composite, although SNRs were on average lower in the active musicians with higher average noise exposure levels. Our analysis of all three groups (non-musicians, past musicians, and active musicians) suggests that TEOAEs may potentially be more sensitive to the amount of training than DPOAEs and that DPOAEs may potentially help differentiate people with very quiet environments (i.e., past musicians).

The OAE SNR difference between musicians and non-musicians was about 1–2 dB. While small at face value, this is roughly the same magnitude as the decline in DPOAE amplitudes observed between young and middle-aged adults (Abdala and Dhar, 2012). If, as suggested by our findings, young adult college musicians have stronger cochlear amplifiers, what might account for this “musician enhancement”? Agedifferences between groups can be ruled out given the close age of the two groups (both 19 years old on average). Enhanced SNRs in musicians are also likely not due to lower noise floors (See Section 3.3). An alternative explanation is that individuals with stronger cochlear function are generally more inclined towards auditory activities and that the musician enhancement is not due to training per se but instead is related to demographic and idiosyncratic auditory factors that lead a person to start and continue playing a musical instrument for an extended period (at least six years in our case). Given the behavioral relevance of sound for a musician, it is also possible that musicians—whether because of pre-existing inclinations or training-related changes—are more attuned to the OAE stimulus and direct more attention to it. A potential mechanism for this could be through the efferent reflex that acts upon OHCs (Walsh et al., 2015), resulting in stronger OAEs (Bidelman et al., 2017; Brashears et al., 2003; Micheyl et al., 1995). Complicating this attention-based interpretation, however, is that the literature on the effect of attention and task on OAEs has yielded inconsistent findings (Meric and Collet, 1994). Another complication to interpreting the OAE enhancement in musicians is that tympanometry was only collected in about one-quarter of participants, so group differences in middle-ear attenuation cannot be completely ruled out.

An alternative explanation for this cochlear enhancement is that musicians have undergone plastic (experience-dependent) changes to the regulation of the cochlear proteome. Specifically, more robust OAEs could be due to an upregulation of prestin, a motor protein associated with the outer hair cells that is critical for cochlear amplification (Dallos et al., 2000). If this is the case, our findings here would lead us to predict higher levels of serum prestin in musicians compared to non-musicians. Upregulation of prestin could be adaptive, fortifying the inner ear to protect from NIHL, or compensatory, overcoming an incipient hearing loss. Our recent work suggests prestin might be actively regulated by environmental sound levels: in a group of (largely) non-musicians, we found that lower levels of routine noise exposure (measured by 3 weeks of noise dosimetry) correlated with higher levels of serum prestin (Parker et al., 2022). Whether the same processes apply to musicians is unknown. For past musicians, we predict a similar relationship (lower noise levels correlate with higher prestin) if they lead quieter lives than even non-musicians. But for active musicians, the opposite relationship is predicted (higher noise levels correlate with higher levels of serum prestin).

While the current analysis suggests that recent exposure to high levels of noise (measured via the NEQ or personal noise dosimetry) does not *strongly* influence cochlear amplification, we used noise exposure metrics that are time-limited and do not capture lifetime noise exposure (unlike the structured interview technique used in Guest et al., 2018). This leaves open the possibility that training-related differences in *lifetime* sound exposure have influenced the regulation of prestin or other cochlear processes that underlie OAE production.

While the mechanism(s) and factors underlying the “musician enhancement” remain open questions, the significant, albeit weak, relationship between years of musical training and TEOAEs argues against the enhancement being purely the result of pre-existing group differences. However, some caution should be applied here given that the relationship with DPOAEs was not significant and it is possible that people with higher innate OAEs start playing at a younger age or stick with it longer. Whether higher OAE levels in musicians are innate or are due music-dependent changes remains to be seen, but no matter the cause, the effect seems to persist even when the musician has not engaged in musical training for at least 6 months. To clarify whether cochlear enhancements pre-date training, are a consequence of training, have a potential developmental (age-dependent) component, or eventually fade with greater passage of time since stopping training (Skoe and Kraus, 2012), it would be necessary to recruit and study musically inclined children/adults before they start playing a musical instrument and follow them over an extended period. Greater clarity on training-related and demographic variables that have a positive influence on cochlear function may hold clinical value in developing more effective remediation programs for clinical populations.

Other reports of “musician advantages” for auditory-related processes can be found across the literature. Most, however, focus on central auditory processes and functions, not peripheral ones (Kraus and Chandrasekaran, 2010). There is a small literature showing that musicians have stronger central control over cochlear function. These studies measured medial olivocochlear reflexes, using a paradigm in which OAEs are recorded in the presence of contralateral noise (Bidelman et al., 2017; Brashears et al., 2003; Micheyl et al., 1995, 1997; Perrot et al., 1999; Perrot and Collet, 2014). In some of these studies, baseline OAE levels tended to be larger in musicians (although not statistically so) (Brashears et al., 2003; Perrot et al., 1999); however, ours is the first large-scale study to provide evidence for it. We believe the emergence of a statistically significant musician enhancement for OAE SNRs in our study, but not other studies, could arise from a combination of methodological factors. First, there is greater statistical power in having a large sample. We also attempted to minimize confounding age, lifestyle, health, and audiometric factors by targeting a narrow age range (18–23 years old) and by accounting for gender differences. Within a relatively narrow demographic (college students), we then cast our definition of musician broadly, using the “six-year” benchmark to differentiate musicians vs. non-musicians (Zhang et al., 2020). This broad definition allowed us to increase the range of noise exposure in the sample and capture a wide range of musical instruments and ensembles. Such an approach contrasts with other studies that have focused on more narrowly defined groups of musicians, such as musicians who play the same instrument or musical genre (professional vocalists, rock musicians), and/or musicians with different levels of noise exposure (Høydal et al., 2017; Jansen et al., 2009; Reuter and Hammershøi, 2007). In addition, we included past musicians in our musician sample; this is in contrast to other recent work that categorized them as non-musicians (Couth et al., 2020). Having a large, yet heterogeneous, sample of musicians with clinically normal audiometric thresholds may have been a key to detecting this subtle musician enhancement. The inclusion of both TEOAE and DPOAE data is another noteworthy feature of our study, as it allows for a comparison across stimulus types and frequency ranges. The TEOAEs and DPOAE composite converged in showing a musician enhancement in the 1–5 kHz range. A minor caveat to this comparison is the slightly reduced sample size for the DPOAE dataset, due to it being a later addition to our test protocol, and subtle differences between TEOAEs and DPOAEs in our exploratory analysis of the different subgroups.

Contrary to what may be predicted based on the musician enhancement of OAEs, our two measures of noise exposure, the NEQ and personal dosimetry, suggest that active musicians are routinely exposed to higher levels of noise within the range commonly considered detrimental to hearing health. Indeed, almost 2/3 of the active musicians exceeded the NIOSH limit. Yet, we did not see robust evidence for subclinical levels of outer hair cell damage in those who exceed NIOSH exposure limits. This could be a direct consequence of our targeted age range, or it could be due to limitations of not having extended-high frequency audiometry in the dataset. Incorporating extended high frequency audiometry into the analysis, alongside OAEs, could have enabled better differentiation of noise-exposed ears (Moore et al., 2017). (We note that EHF audiometry has been part of the original test battery but was removed due to equipment artifact affecting threshold estimates for the highest frequencies). The NEQ and personal noise dosimetry may also be limited in their ability to gauge true risk. For instance, the NEQ relies on representative levels for different activities (e.g., listening to music over earphones) to estimate noidse exposure over the past 12 months. By contrast, our dosimetry approach does not capture noise exposure from earphones, was time limited to one week, and was only administered to active musicians plus a small smattering of the past musicians and non-musicians.

Based on the pattern of results, we conclude that, in young adult musicians with clinically normal hearing, recent high-level noise exposure from music-making (as measured from the NEQ and weeklong noise dosimetry) may offset the musician enhancement of OAEs, albeit only slightly. Our findings inform the "tender" vs. "tough" ear argument for noise susceptibility (Bidelman et al., 2017; Maison and Liberman, 2000) by showing that certain listening experiences could help fortify (i.e., toughen) the ear from damage. In line with arguments made by Bidelman et al. (2017), our findings suggest that extended exposure to music during music practice/rehearsal may strengthen cochlear processes to decrease vulnerability to noise damage.

While this study is novel in showing an OAE SNR enhancement in college musicians, we do not view our findings are being wholly at odds with the previous, rather mixed findings, in musicians. If we factor in a possible “musician enhancement” for young adults but also take as a given that (1) sustained exposure to high-level noise will eventually adversely affect OAEs (especially if sustained across multiple years) and (2) that musicians are not all at the same risk of NIHL, with some being significantly more noise exposed than others (Tufts and Skoe, 2018), then this, collectively, could explain the mixed findings. In Fig. 4, we present a unified account of the literature. As modeled in Fig. 4, musicians’ heighted cochlear function could represent an enhanced/trained state. If noise-induced damage occurs, cochlear function may decline in the early stage of loss to a point where OAEs are matched between musicians and non-musicians (e.g., Couth et al., 2020; Henning and Bobholz, 2016; Liberman et al., 2016; Møllerløkken et al., 2013; Reuter and Hammershøi, 2007). If noise exposure accrues and damage progresses, OAEs are predicted to be weaker in musicians compared to non-musicians with lower noise exposure in the more advanced stage of loss (e.g., Hamdan et al., 2008; Høydal et al., 2017).

A challenge to drawing conclusions across studies on musicians, however, is that musicianship is multifaceted and can be defined from various dimensions, such as the total amount of training, the type of training, and the level of ability (Zhang et al., 2020). For the current study, we cast a wide net and defined musicianship broadly using the 6-year benchmark defined by Zhang et al. (2020). We then followed stricter criteria to define active musicianship. While, on average, the non-musicians had < 3 years of musical training, a small number had 5 years of training, placing them close to the definitional threshold. While we defined them as non-musicians for the purposes of this study, in

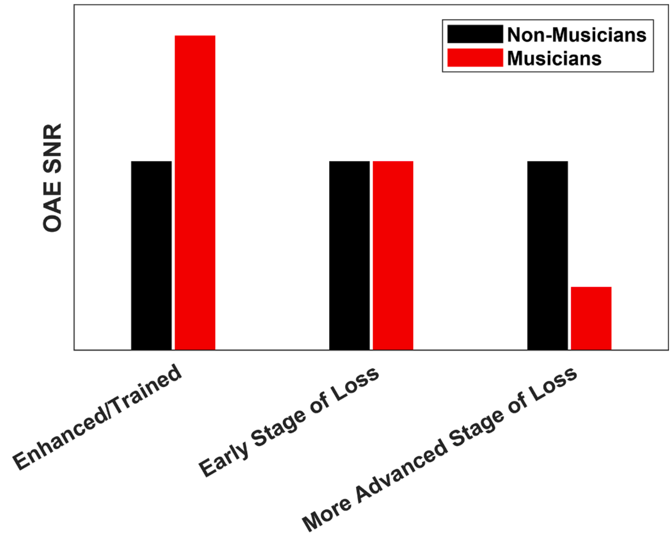

Fig. 4. Theoretical model of the effect of musical training and noise exposure on OAEs. Average OAEs of musicians (in red on the right) vs. non-musicians (in black on the left) are predicted in different stages of training and cochlear function.

truth, there is likely no bright line between 5 *vs.* 6 years of training. We acknowledge this as a limitation of the study. Whether the musician enhancements observed here generalize to other types of young musicians not captured here and/or is preserved into middle or old age are open questions. While the active and past musicians did not differ for either the TEOAE measurement or the DPOAE composite, the accumulation of noise exposure over time through continued engagement in music is likely to eventually differentiate the groups. In further support of this possibility, our exploratory, frequency-specific analysis of the DPOAE data shows that there is a tendency for active musicians to have lower OAEs than past musicians. These trends warrant subsequent investigations. Tracking active and past musicians longitudinally and comparing them to a noise-exposed control group would also help to test theories about the otoprotective role of musical training (Bidelman et al., 2017). These follow-up investigations may also help to elucidate whether the proposed capacity of musical training to enhance cochlear function and protect from noise damage and/or age-related loss (Alain et al., 2014) necessitates a specific amount, type, or duration of training—and whether continuation or even the secession of musical activities may be more beneficial to prevent significant cochlear damage.

A well-known challenge in audiological research of musicians is recruiting noise-exposed non-musicians with comparable noise exposure histories to musicians (Hamdan et al., 2008). While the lack of a noise-exposed non-musician group is a limitation in this study, this limitation is not unique. Further research is necessary to understand how noise exposure derived from musical training may differ in its effect on the auditory system from other forms of noise exposure. For active musicians the primary source of noise risk was from music activities. By contrast, the small number of non-musicians who fell above the NIOSH noise exposure limit varied in which activities were most risky. However, the NEQ is not designed to make subtle comparisons between or within groups. To better understand variability in active musicians, we used personal noise dosimeters to obtain an objective measure of noise exposure. However, because of the cost and time-intensive nature of personal noise dosimetry, noise dosimetry was restricted to active musicians and a subset of past and non-musicians. Therefore, we had no standardized objective measurement of noise exposure for our entire sample to more confidently assign risk level based on NIOSH criteria. Another challenge for studies of this nature is how to define and then recruit “non-musicians.” We defined “non-musicians” more broadly than some recent studies (Couth et al., 2020) and less broadly than others (Boebinger et al., 2015; Madsen et al., 2019). That said, the argument could be made that musicianship is not a binary construct. Historically, most of the college students that have replied to our study ads have had some musical training, either because they attended schools where music was compulsory or they came from more affluent families where involvement in extracurricular enrichment programs like musical training was the cultural norm. Put simply, in our experience American college students without *any* music experience are the exception, not the norm.

In summary, our findings reinforce the duality of musical training, i. e., its capacity to strengthen but also to weaken the auditory system. Our study adds a new, potentially important dimension to take into consideration when caring for the hearing health needs of musicians: stronger OAEs in young adult musicians than in non-musicians suggests that separate norms for musicians are needed to aid in the earlier identification of NIHL. The concern is that if musicians are compared against non-musician norms rather than musician norms or their own baseline, incipient hearing loss is more likely to be missed. However, an important future question to answer is how best to assess musicians' noise exposure (through dosimetry or a task-based approach like the NEQ) and its impact on hearing, whether through PTA or OAEs, some combination of both, or an alternative approach (e.g., serum levels of cochlear proteins).

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CRediT authorship contribution statement

Morgan Main: Conceptualization, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Visualization, Project administration, Funding acquisition. **Erika Skoe:** Conceptualization, Methodology, Software, Validation, Resources, Writing – original draft, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors have no conflict of interest to declare.

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Supplementary materials

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