# Weeklong Noise Exposure of 100 College Students Who Participate in Music Activities

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## ABSTRACT

**Objectives:** Musicians are routinely exposed to sound levels that place them at risk of hearing loss. Although the dangers of sound overexposure from music are well-known, less is known about which specific types of music activities contribute to this risk. Past study indicated that college musicians experience potentially hazardous sound levels during both musical and nonmusical activities. We now expand this line of investigation to a larger dataset to subtype musicians (based on instrument, ensemble type and number, and music-major status) and capture a wide array of musical engagement (total years of training, total hours of music engagement during the week).

**Design:** Descriptive study of college musicians with hearing thresholds <25 dB HL combining personal noise dosimetry, daily activity diaries, and musician subtyping.

**Results:** The college musicians in our sample showed a wide range of average daily sound exposure, spanning from 2 to 1638% of the National Institute of Occupational Safety and Health daily recommended exposure limit dose. It is important to note that ~70% of the cohort's average daily sound exposure exceeded the National Institute of Occupational Safety and Health recommended exposure limit dose. We found that total years of musical training did not predict daily dose, but weekly hours of music activities did. When subtyping musicians, we found that music majors and nonmajors experienced similar average daily sound exposure; that brass and woodwind players tended to experience more sound exposure than string musicians; that musicians in multiple ensembles experienced more sound exposure than those in only one ensemble; and that musicians in band ensembles experienced more sound exposure than those in orchestral ensembles. The musician subtypes at lowest risk were vocalists and string players. Musicians who engaged in more hours of musical activity during the week experienced higher levels of sound exposure. Marching band members were more likely to engage in high-sound-intensity nonmusic activities compared with music majors. But even within different musician subpopulations, average daily sound exposure varied across individuals and the type and extent of music engagement accounted for only about half of the variance in average daily sound exposure.

**Conclusions:** The college musicians in this sample varied widely in their sound exposure profiles. Musician subtype accounted for some of this variation, as did total hours of music engagement. However, neither variable captured the full range observed. As such, relying on musician subtype or total hours of engagement as a proxy measure for exposure could lead to erroneous conclusions about risk at the individual level. This finding highlights the need for individualized sound-exposure assessment to evaluate risk and provide appropriate recommendations to musicians to maintain their hearing health.

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**Key words:** Musicians, Noise-induced hearing loss, Personal noise dosimetry.

**Abbreviations:** CI = confidence interval; $L_{Aeq,T}$ = time-equivalent A-weighted sound level; NIHL = noise-induced hearing loss; NIOSH = National Institute for Occupational Safety & Health; REL = recommended exposure limit.

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## INTRODUCTION

Musicians are routinely exposed to sound levels that exceed the National Institute of Occupational Safety and Health (NIOSH) recommended exposure limit (REL), both during rehearsals and performances (Phillips & Mace 2008; Phillips et al. 2010; Gopal et al. 2013), placing them at considerable risk for noise-induced hearing loss (NIHL). The negative repercussions of sound exposure likely precede measurable hearing loss. Indeed, overexposure to sound may undermine some of the potential benefits of musical training, including benefits to speech perception in noise (Skoe et al. 2019; Main & Skoe 2024), even when audiometric thresholds are within normal limits.

To better characterize—and, ultimately, mitigate—the hearing health risks faced by musicians, personal noise dosimeters have been used to measure sound levels during music rehearsals and performances (Behar et al. 2004; Miller et al. 2007), an approach advocated by the American Academy of Audiology's clinical consensus guidelines on musicians and the music industry (Santucci et al. 2020). More recent studies have extended personal noise dosimetry to capture sound levels for all activities within a college musician's typical routine, including musical and nonmusical activities, with protocols ranging from 2 days to a full week (seven 24-hr days) (Washnik et al. 2016; Skoe & Tufts 2018; Tufts & Skoe 2018; Camera et al. 2019; Smith et al. 2019). Using a weeklong approach in a dataset of 22 college musicians and 40 nonmusicians, unsafe levels of sound exposure were found to not be limited to musical environments (Tufts & Skoe 2018). Indeed, some musicians were also exposed to unsafe levels during nonmusic activities (such as social events, exercise, and academics), suggesting that restricting personal dosimetry to music activities gives an incomplete picture of NIHL risk. Within this sample, 77% of the musicians exceeded the NIOSH REL of 85 dBA for the week, with a wide range in sound exposure dose (25 to 1600%). The sample was heavily biased toward university marching band members, and only two were music majors. These findings motivate the need for a more comprehensive study of individual differences in sound exposure among college musicians and a deeper understanding of the factors that contribute to variation in exposure. Indeed, Smith et al. (2019) found reliable differences in sound-exposure levels during

rehearsals and music practice as a function of instrument type in a study of 43 college musicians, but nonmusical environments were not compared.

The present study examines a sample of 100 college musicians with a range of musician subtypes and experiences. The dataset combines weeklong noise dosimetry, daily activity diaries, and a music activity questionnaire to investigate individual variation in daily sound exposure. We subtyped musicians based on their status as a music major, the number and type of current ensembles, and the instruments they played to identify how different subtypes predict risk, as measured by the average daily sound exposure. In addition to these musician subtypes, we examined the extent of engagement in music and nonmusic activities, with our primary interest being in the total years of training and the total hours of music and nonmusic activities during the week of personal noise dosimetry.

## MATERIALS AND METHODS

### Overall Approach

Our goal was to estimate the sound exposure a college musician experiences in a typical week of the academic term. We recruited musicians from the University of Connecticut, Storrs campus. We accepted any student who self-identified as a "musician." The study protocol took 8 calendar days. On the first day, participants completed a battery of hearing screening tests and other auditory tests (these varied depending on which specific study they enrolled in) and were briefed on dosimeter use. Then, they were given dosimeters to wear for 8 days, after which they returned the dosimeters to the lab.

This article combines data from multiple research studies our lab conducted from 2016 to 2021. Procedures were consistent except as noted. The University of Connecticut Institutional Review Board approved all study activities.

### Recruitment

Self-reported musician participants were recruited from the undergraduate student body of the University of Connecticut, Storrs campus. Students were invited to participate if they regularly engaged in formal music activities—beyond that, there were no provisos or limitations vis-à-vis musical experience or activities. Exclusionary criteria were air-conduction hearing thresholds >25 dB HL at 0.25, 0.5, 1, 2, 4, and/or 8 kHz bilaterally, measured with ear inserts (ER2) in a double-walled audiometric sound booth (IAC Acoustics, Winchester, United Kingdom), using the modified Hughson-Westlake procedure on a clinical audiometer (GSI 61 Audiometer; Grason-Stadler, Inc) calibrated annually by a certified technician. Audiometry was performed by audiology students under the training and supervision of a clinical audiologist.

Participants provided written consent and were paid for study participation. Once enrolled, participants completed a questionnaire on their demographics and music activities, including instruments, music ensembles, whether they were a music major, and how long they had practiced music (see Supplemental Materials, Supplemental Digital Content, https://links.lww.com/EANDH/B889). Note that across-study music profile variation was expected because our recruitment and enrollment strategy evolved over time to target different musical variables (instruments, ensemble types, etc.; see Tables S1 and S2, Supplemental Digital Content, https://links.lww.com/EANDH/B889).

### Dosimetry

Each participant wore an ER-200DW8 personal noise dosimeter for eight consecutive calendar days. The dosimeters were configured with an 85 dBA criterion level, a 3 dB exchange rate, a 70 dBA threshold, and an upper limit of measurement at 130 dBA. Dosimetry for the first 22 musicians collected in the 2016 to 2017 period was conducted with a 75 dBA threshold. For subsequent years, our protocol evolved, and the threshold was lowered for subsequent years to 70 dBA, the lowest threshold the software interface allowed. This threshold change does not affect estimates of risk. If someone spent the whole day at <75 dBA, then with a threshold of 70 dBA, you could see some small doses that would otherwise appear to be 0% with a 75 dBA threshold. But once they spend time in levels above 75 dBA, any differences in dose due to the different thresholds would start to go away rather fast, and the higher the dose, the less the threshold difference matters. So, where the risk is highest, with larger doses, the threshold does not make a difference.

Dosimeters obtained sound levels on a continual basis every 220 msec. Values were summed over a 3.75 sec interval, and summed values were saved to memory, yielding 16 logged values per hour. The on/off button was disabled so participants could not accidentally shut off the dosimeter. We also disabled the dose indicator lights on the dosimeters so that they would not influence participants' behavior. Participants were instructed to keep the devices on their person for the week (except during sleep, bathing, or sport, during which time they were asked to keep the dosimeter nearby). The dosimeter was not paused or turned off during these activities. Once the experimenter turned them on, the devices collected data continuously for 168 hr unless there was a battery failure or, in rare cases, the participant returned the dosimeter before the end of the 168-hr period. If they were doing an activity where the device might be damaged, they were asked to put the device nearby. Otherwise, participants were asked to wear the dosimeter as close to their ears as possible, ideally clipped to their collar or on the shoulder. They were told the dosimeters would measure the sound level, but not the content, of their environments.

Dosimeters were calibrated periodically by generating a 1000 Hz narrowband signal at 90 dB SPL in an Audioscan Verifit test box, then measuring the signal's level with a calibrated sound level meter (Larson-Davis 824 sound level meter or 2250 Light-G4 B&K sound level meter) and with the dosimeter in "QuickCheck" mode. These calibration measurements consistently were within 2.5 dB of the mean of three sound level meter measurements, which aligns with the manufacturer's calibration specifications.

Dosimetry data were exported as text files from the dosimeter using the ER-200D Utility Suite v4.04 (Etymotic, Inc.) and then analyzed using custom MATLAB scripts developed by the lab (available from the corresponding author under reasonable request). The data were split into 2 partial days and 6 full, 24-hr days, totaling a maximum of 168 hr of dosimetry. This data split (i.e., across days) was necessary because participants did not begin recording at 12:01 AM on their first day in the study. For example, if they enrolled at 10:00 AM on a Monday, the dosimetry data resulted in 2 partial days: the first Monday from 10:00 AM

to 11:56:15 PM; and the second Monday (their last day of participation) from 12:00 AM to 9:56:15 AM. These two partial days were "stitched together" for a seventh full 24-hr day. Thus, the dosimeter recordings comprised up to 7 full, 24-hr days that spanned 8 calendar days. The recordings were less than 168 hr in rare cases where there was a battery failure or when the participants' schedule required that they return before the end of the 168-hr period.

For each day, the A-weighted equivalent sound level (dB $L_{EQ,T}$) was calculated using the following equation:

$$\mathrm{dBL_{Aeq},}_T = 10\log\left[\left(\frac{1}{T}\right)\sum t_i 10^{\frac{L_{\mathrm{Ai}}}{10}}\right], \quad (1)$$

where $T$ is the total duration of each calendar day in hours (24 hr, except for the 2 partial days), $i$ is the increment number, $t_i$ is the duration of the increment (3.75 min), and $L_{\mathrm{Ai}}$ is the A-weighted sound level for that increment Royster et al. (2003).

Next, the A-weighted levels were transformed into daily doses re: the NIOSH (1998) REL as:

$$\text{Daily Dose}\,(\%) = 100 \times \left(\frac{T}{T_c}\right) 2^{\frac{L_{\mathrm{Aeq},T} - L_c}{Q}}, \quad (2)$$

where $T$ is the total duration of each calendar day in hours, $T_C$ is the criterion duration (8 hr), $L_{\mathrm{Aeq},T}$ is the cumulative listening level for that day, $L_C$ is the criterion level (85 dBA), and $Q$ is the exchange rate (3 dB) (Roberts & Neitzel 2022). A 100% daily dose is the REL, equivalent to a continuous exposure to 85 dBA over 8 hr, such that 100% reflects the daily recommended limit of sound exposure, 50% reflects half the daily limit, etc. Finally, each daily dose was arithmetically averaged to derive the average percent of daily sound exposure re: the NIOSH REL. Using the NIOSH REL allows us to maintain consistency with previously published work in this area and facilitates comparison with other published dosimetry studies (Flamme et al. 2012; Washnik et al. 2016; Tufts & Skoe 2018).

For each day, the 8-hr A-weighted equivalent dB LAeq,8hr was calculated from the day's dose, using this formula:

$$\mathrm{dB\ LAeq_{,8hr}} = \frac{3}{\log_{10}2} \times \log_{10}\frac{\text{Daily Dose}}{100} + 85 \quad (3)$$

The dB LAeq,8hr for each day was arithmetically averaged to derive the average daily sound levels expressed in decibels (Roberts & Neitzel 2022).

## Daily Activity Diaries

To link daily sound exposure to specific types of activities, participants kept daily time-stamped activity diaries. Our diary method evolved over the course of this project, as we learned we could simplify, standardize, and automate the journaling process.

- A paper diary method was used here for the 40 participants enrolled between 2016 and 2017.
- In 2018, we moved from paper diaries to an online survey administered in Qualtrics, where participants logged their activity in 15-min intervals. This method was used here for the 10 participants enrolled in 2018.
- Finally, for the remaining participants in 2021, we adopted a Google calendar system where participants logged time, choosing from a pre-set list of activities.

In the current analysis, we were interested in two broad activity categories: music activities and nonmusic activities. We operationally define music activities as any event where the participant was playing their instrument or at a rehearsal or performance for an ensemble in which they participated; anything else was a nonmusic activity. Listening to music—live or recorded—outside of the context of music rehearsal or performance was treated as a nonmusic activity. By cross-referencing the diaries and dosimetry data, we also quantified the total number of minutes of activities during the week that occurred at or above 85 dBA Leq in a 3.75 min. sampling period, operationally defined as "high sound intensity" activities.

## Statistical Approach

Part 1 presents descriptive statistics characterizing variation in average daily sound exposure across participants. Descriptive statistics are reported for both average daily sound exposure doses (%) and average daily sound exposure levels (dB LAeq,8hr).

Part 2 evaluates different musical variables to determine which are associated with higher or lower average daily sound exposure. The dependent variable for all statistical models in Part 2 was a log transformation of individuals' average daily dose. Primary variables of interest included musician subtype and total hours of music activity during the 8-day collection period. Musicians were subtyped based on their status as a music major, the number and type of ensembles, and playing specific instruments. Hours of music or nonmusic activity were extracted from activity diaries.

First, using $\chi^2$ tests, we compared the proportion of individuals engaging in a specific musical activity whose average daily sound exposure levels, expressed as dose (%), exceeded the NIOSH REL to those not engaged in the activity. Next, we tested for associations between activity type and average daily sound exposure using linear mixed-effects models. The advantage of this linear mixed-effects approach is that we can account for individuals engaged in multiple activities by dichotomizing these activities as participant/nonparticipant and modeling them simultaneously as dummy-coded variables (examples: an individual who plays trumpet and violin or a participant in both marching and concert band). The other advantage is that the mixed-effects models allowed us to include the study cohort as a variable to account for potential across-cohort variation. Note that across-cohort variation was expected because our recruitment strategy evolved over time to target different musical variables. Fixed effects were the musical variable of interest (such as ensemble, instrument, etc.; see Table 1) and study-year cohort was the random effect (see Table S1, Supplemental Digital Content, https://links.lww.com/EANDH/B889).

Finally, we created linear models to use musician subtype and engagement variables (ensemble type, extent of practice, etc.) to predict average daily sound exposure and a binary logistic regression to predict if individuals exceeded the NIOSH REL dose.

**TABLE 1. Study cohort**

| | Total (N = 100) |
|---|---|
| Demographics | |
| Age (SD) | 19.4 (1.3) |
| No. female | 76 |
| Characteristics of musical engagement | |
| Number who are music majors | 44 |
| Average years playing music (SD) | 11.1 (2.6) |
| Average no. of instruments currently played (SD) | 1.4 (0.7) |
| Average no. of ensembles currently participating (SD) | 1.9 (1.0) |
| No. in multiple ensembles | 57 |
| Participates in… | |
| Marching band | 51 |
| Pep band | 20 |
| Wind ensemble | 13 |
| Drumline | 4 |
| Concert or symphonic band | 19 |
| Choir | 20 |
| Orchestra | 20 |
| Plays … | |
| Brass instrument(s) | 25 |
| Woodwind instrument(s) | 42 |
| String instrument(s) | 12 |
| Percussion instrument(s) | 6 |
| Guitar | 17 |
| Piano | 33 |
| Voice | 34 |
| Quantity of musical activities | |
| Hours | 10.8 (7.4) |
| High intensity hours (>85 dBA) (SD) | 5.0 (4.6) |
| Percent musical hours that were loud (SD) | 42% (27%) |
| | Total (N = 100) |

*Descriptive statistics and musical engagement for each study cohort. Descriptive statistics are shown for the total sample, including a summary of musical activities. See Table S1, https://links.lww.com/EANDH/B889, for breakouts for each recruitment bloc.*

All analyses were conducted in R (version 4.2.2). In all parametric analyses, average daily sound exposure doses were log-transformed because their raw distribution as percentages was not normally distributed ( Cohen et al. 2013); however, for descriptive statistics, we report daily sound exposure levels in decibels (dB LAeq,8hr) and percentages for ease of understanding and reference to the NIOSH REL dose. Where possible, we replicate parametric analyses using average daily sound exposure doses without a log-transform via nonparametric analyses (Mann-Whitney *U* tests for group comparisons and Spearman correlations). For all analyses, $\alpha = 0.05$. We did not correct for multiple comparisons, given that we replicated our findings in an omnibus model at the end of the article.

## RESULTS

This article reports on 100 young adult college students, all of whom self-identified as musicians. Ages ranged from 18 to 22 yrs (mean, 19.4 yrs; SD, 1.3 yrs) and 76 were women. On average, participants reported they had engaged in music activities 11.1 yrs (SD, 2.6 yrs), that they were currently playing an average of 1.4 instruments* (SD, 0.7), and that they currently participated on average in 1.9 organized music ensembles (SD, 1.0). Instruments varied widely and included all Western orchestral families (brass, keyboard, percussion, string, and woodwind instruments). Based on the diaries, participants reported an average of 10.8 hr of music activities (SD, 7.4) during the weeklong dosimetry period.

The dosimetry was interrupted in 4 participants due to equipment malfunctions. In these cases, the 8 days of dosimetry were nonconsecutive—in all 4 cases, the two multiday periods were combined to equate to 8 days, so these participants could be included in all analyses. For another three participants, fewer than eight calendar days of dosimetry were collected because their schedule required that they return before 8 days (5 days for 1 participant, ~6.5 days for the other three), and so, in these 3 cases, daily average sound exposure was calculated over the days available so these participants could be included in all analyses.

Table 1 reports full descriptive statistics and the categories on which musicians were subtyped. Of the 100 musicians, 44 were music majors, 51 were in marching band, and 57 participated in multiple ensembles. These were three of the most frequently occurring categories in the sample; other categories (e.g., percussionists) had lower representation in the dataset. Note that some musicians, for example, those who play multiple instruments, may be counted multiple times in Table 1.

Table S1, Supplemental Digital Content, https://links.lww.com/EANDH/B889, divides the dataset into three research cohorts based on the year of enrollment. With each new cohort, we sought to diversify our sample of college musicians, and the breakout shown in Table S1, Supplemental Digital Content, https://links.lww.com/EANDH/B889, confirms that we did so successfully. However, this also means the study-year cohorts differed in specific characteristics of interest, such as which ensemble(s) an individual engaged in most commonly. We also note that in some cases (such as the age distribution), the across-cohort differences may not be meaningful even if they reach a threshold of statistical significance (for example, while there is a significant difference in average age across cohorts, the actual difference is only up to 1.3 yr on average). Still, due to this variation, we included the study-year cohort as a random factor in all analyses. In Table S2, Supplemental Digital Content, https://links.lww.com/EANDH/B889, the academic major(s) for each of the 100 musicians is listed.

### Part 1: Daily Sound Exposure Varies Widely Among Musicians

Individual dosimetry data are shown in Figure 1 and illustrate variation in sound exposure observed across the sample. Data are plotted by day of the week, starting with Monday at 12:01 AM. The top four panels show sound levels for four representative musicians throughout the week, chosen by the authors to show a variety of sound-exposure patterns. In the top panels, the vertical red bars denote periods of music activities. The bottom panel shows all 100 musicians'

*There was some variation in how participants reported on the number of instruments they currently play. Some individuals counted variants within an instrument family as distinct instruments (e.g., alto and tenor saxophone are two instruments). Others consolidated them into one (e.g., alto and tenor saxophone are one instrument). We accepted either approach and report here as participant reported in questionnaires—our view is that this reflects participants' individual experience of the scope of their own musical practice. We focused only on instruments participants reported currently playing while enrolled in the study, not any they had played in the past.

dosimetry data as a heatmap, with warmer colors indicating higher sound levels. Time periods that fell below the dosimeter threshold appear black.

Examining Figure 1 shows both general trends and individual differences. For example, most high-sound activities are biased towards the second half of the day. Most music activities appear concentrated in the afternoons and evenings, consistent with anecdotal reports from the participants. (For example, marching band rehearsals fell on Tuesday, Thursday, and Friday evenings with performances on Saturday morning.) Note the concentration of relatively high sound levels for afternoons and evenings in the upper half of the heatmap (indicated with green and yellow colors).

Still, there is notable variation between individuals. Some musicians engaged in music consistently throughout the week (left panel 3), whereas others show more concentrated patterns in which activities are limited to a few days of the week (left panels 1 and 2). Some musicians experience their highest sound intensity activities during musical practice (left panel 4), whereas others experience high intensity sounds during musical and nonmusical activities (panel 2). There is also variation in the overall, maximum, pattern, and range of sound levels throughout the week.

Average daily sound exposure also varied widely across the 100 college musicians, from 2 to 1638% of the NIOSH REL dose. This translates to 68.07 to 97.10 dB LAeq,8hr. The average daily sound exposure dose for all participants is shown in Figure 2. This figure illustrates that roughly one-third of musicians averaged at or below the daily REL. Another third ranged from 100 to 300% of the daily REL dose, and the final third averaged >300% the daily REL. Five musicians averaged more than 1000% the daily REL dose—that is, doses exceeding 1000% of the recommended daily maximum. Thus, ~70% of the musicians in the sample fell above the REL dose, albeit to varying degrees.

## Part 2: While Some Musical Subtypes Correlate With Sound Exposure, They Do Not Account Fully for Individual Variation

Next, we consider different musician subtypes and their interaction in predicting average daily sound exposure.

### 2A: Music Majors Versus Nonmajors: Music Majors Are More Likely to Exceed the NIOSH REL But Do Not Experience Higher Levels of Sound Exposure Dose on Average Than Music Nonmajors

Music majors' (N = 44) daily sound exposure averaged 298% of the daily REL dose (range, 12 to 1387%; median 241%; SD, 299%) and nonmajors averaged 346% of the NIOSH REL dose (range, 2 to 1638%; median, 205%; SD, 369%). The music major's average dose corresponds to 89.72 dB LAeq,8hr, and the nonmajors corresponds to 90.37 dB LAeq,8hr. Music majors were more likely to exceed the REL, that is, have >100% dose: as shown in Figure 3, 75% of majors experienced average daily sound exposure exceeding the NIOSH REL compared with 61% of nonmajors ($\chi^2 = 4.5$, $p = 0.03$), but majors and nonmajors did not differ in average daily sound exposure dose ($t(98) = 0.47$, $p = 0.63$). There was also no difference between majors' and nonmajors' average daily sound exposure using the (raw, nonlog transformed) dose in a nonparametric test ($W = 1210$, $p = 0.88$).

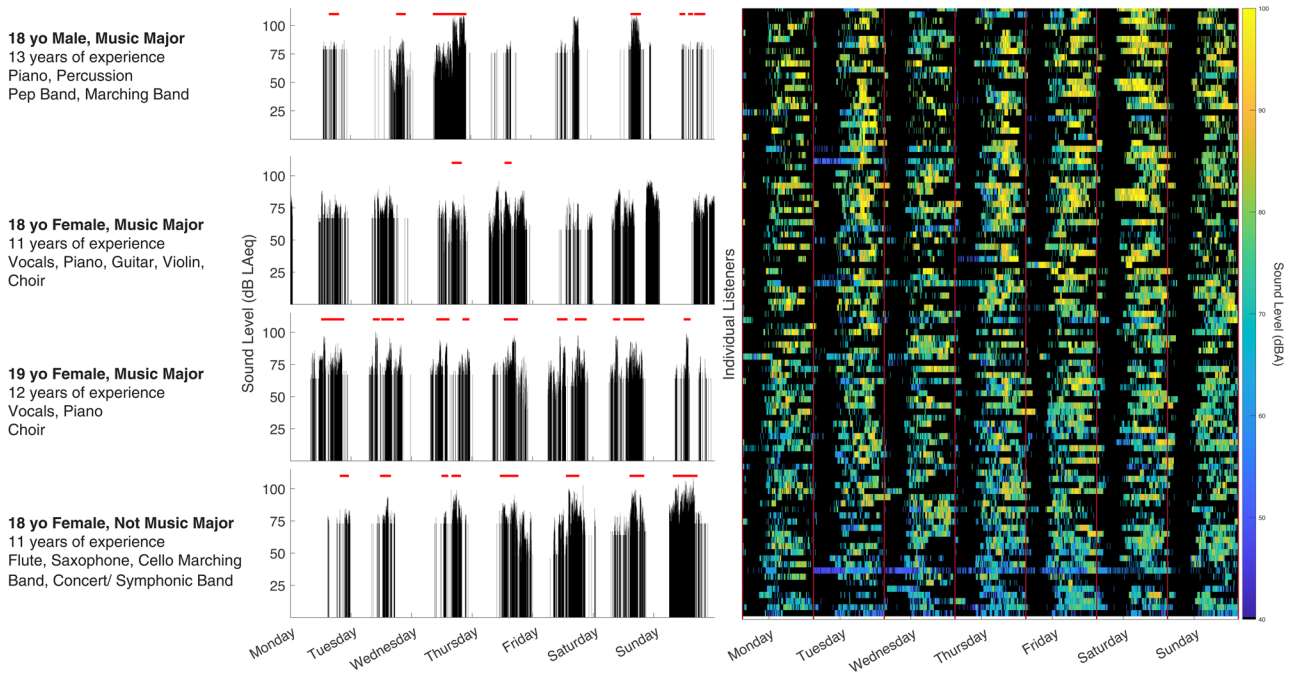



Fig. 1. Weeklong dosimetry data. (Left 4 panels) Time series showing representative individual musicians' weeklong dosimetry data from four participants. The black bars show the dosimeter reading (dB LAEq) at each time point in the week. The red horizontal lines superimposed on the time series indicate periods of music activity. (Right) Individual data on all 100 musicians plotted as a heatmap, with warmer colors indicating higher sound levels in dB LAeq. Sound levels at or above 100 dB LAeq appear yellow. Black indicates sound levels below the dosimeter threshold. Thin red vertical lines denote midnight; each participant appears on the graph as a separate horizontal line and musicians are scaled according to exposure level, with higher levels on top.

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 2 | 8 | 11 | 12 | 14 | 15 | 20 | 21 | 22 | 26 | |
| 30 | 30 | 31 | 35 | 35 | 38 | 41 | 42 | 46 | 53 | Below NIOSH REL |
| 55 | 58 | 63 | 75 | 79 | 83 | 85 | 85 | 87 | 88 | |
| 96 | 97 | 98 | 104 | 108 | 109 | 111 | 114 | 121 | 121 | |
| 143 | 158 | 166 | 176 | 178 | 188 | 193 | 199 | 218 | 237 | 1-3x REL |
| 237 | 242 | 245 | 245 | 248 | 248 | 249 | 252 | 263 | 267 | |
| 278 | 288 | 290 | 317 | 334 | 345 | 353 | 357 | 365 | 365 | |
| 373 | 387 | 400 | 418 | 425 | 450 | 474 | 490 | 540 | 590 | 3-10x REL |
| 594 | 620 | 623 | 640 | 704 | 760 | 772 | 779 | 781 | 786 | |
| 794 | 800 | 885 | 902 | 968 | 1115 | 1149 | 1256 | 1387 | 1638 | >10x REL |

Fig. 2. Average daily sound exposure doses for each of the 100 musicians. Average daily sound exposure, expressed as percent of the NIOSH REL dose, is illustrated for each participant. Colors illustrate different ranges of the average daily sound exposure levels, with green shades representing less risky sound exposure levels that fall below the REL and red illustrating exposures averaging >3× greater than the REL dose. Roughly one-third of musicians were at or below REL dose, one-third ranged from 1 to 3× REL dose, and the remaining third were >3× REL dose. NIOSH indicates National Institute of Occupational Safety and Health; REL, recommended exposure limit.

Music majors had slightly more years of music training on average (major mean = 11.7 yrs, SD = 2.9 yrs; nonmajor mean = 10.6 yrs, SD = 2.3 yrs; $t(98) = 2.1$, $p = 0.04$). Still, there was no systematic relationship between average daily sound exposure dose and total years of music training ($\beta = -0.60$, 95% confidence interval [CI] = −1.63 to 0.40), status as a music major ($\beta = -0.60$, 95% CI = −1.63 to 0.40), or their interaction ($\beta = 0.06$, 95% CI = −0.03 to 0.15) in the full cohort of 100 musicians. Put differently, majors and nonmajors, on average, experienced similar average daily sound exposure dose when accounting for differences in total years of musical experience. While this might seem at odds with the observation that majors are more likely to exceed the NIOSH REL, that analysis applied a blunt cutoff (below 100% NIOSH REL dose) and, as shown in Table 2, 75% of music majors are above the NIOSH REL compared with only 60% of nonmajors. The model, including only years of musical experience, major status, and their interaction, explained only 2.5% of the variance in daily sound exposure.

### 2B: Number of Music Ensembles: Musicians Engaged in Multiple Music Ensembles Experience Higher Average Daily Sound Exposure Than Musicians in Only 1 Ensemble

Figure 3 and Table 2 show individual musicians' average daily sound exposure broken out by the number of ensembles musicians reported participating in.

- 56% of the 43 musicians who participated in 1 ensemble exceeded the REL. They averaged 242% of the NIOSH REL, which corresponds to 88.82 dB LAeq,8hr (dose range, 2 to 902%; median, 158%).
- 66% of the 35 musicians who participated in 2 ensembles exceeded the REL. They averaged 325% of the NIOSH REL, which corresponds to 90.10 dB LAeq,8hr (dose range, 8 to 1149%; median, 237%; 1 ensemble versus ensembles: $\chi^2 = 2.10$, $p = 0.18$).
- 91% of the 22 musicians who participated in 3+ ensembles exceeded the REL, averaging 506% of the NIOSH REL, which corresponds to 92.02 dB LAeq,8hr (dose 22 to 1638%; median, 283%; 2 ensembles versus 3+ ensembles: $\chi^2 = 18.5$, $p < 0.001$).

Indeed, individuals who reported participation in more ensembles experienced a higher average daily sound exposure dose ($\beta = 0.18$, 95% CI = 0.06 to 0.31). This finding held when accounting for the total years of music practice, music major status, and the number of instruments they played. When treating ensemble participation linearly, each additional ensemble an individual participated in was associated with an additional 1.5× the NIOSH REL. For example, if a musician participated in just one ensemble and had an average daily sound exposure of 100% REL, an otherwise identical musician who participated in two ensembles would be expected to have an average daily sound exposure of 150% REL. Modeling multiensemble status explained 8.5% of the variance in daily sound exposure. The trend for increasing daily sound exposure with participation in more ensembles was confirmed by a nonparametric correlation on the un-log transformed dose (Spearman's $\rho = 0.28$, $p < 0.001$).

### 2C: Ensemble Type: Marching Band, Pep Band, and Wind Ensemble Players Experience Higher Average Daily Sound Exposure Than Those Participating in Other Music Ensembles

In Figure 4A, average daily sound exposure dose is plotted by type of musical ensemble for each participant. Table 2 reports the proportion of participants in each ensemble exceeding the NIOSH REL, relative to college musicians who do not participate in each specific ensemble (also known as nonparticipants). With respect to specific ensembles in isolation:

- Marching band participants were more likely to exceed the REL: 83% of participants were over REL compared with 61% of nonparticipants (marching band participants range, 22 to 1638%; median dose, 357%; median LAeq,8hr, 90.50; nonmarching band participants range, 2 to 760%; median dose, 105%; median LAeq,8hr, 85.211; $\chi^2 = 20.9$, $p < 0.001$).

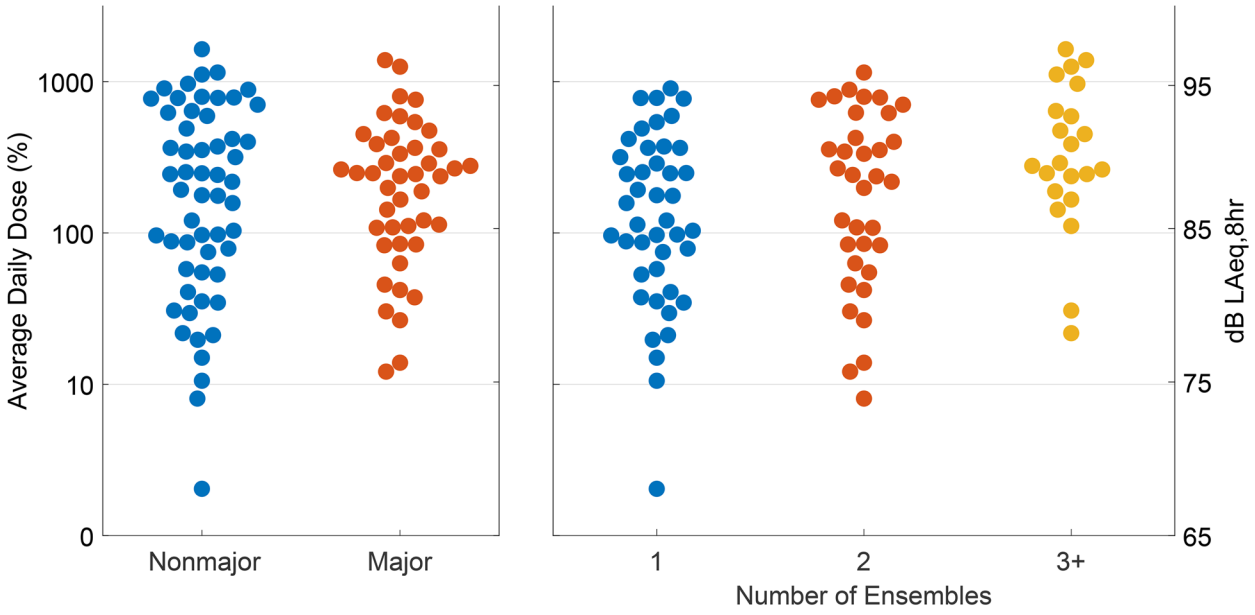



Fig. 3. Average daily sound exposure grouped by major and number of ensembles. Average daily sound exposure is shown for each individual in the subgroup. (Left) Individuals are grouped as music majors or nonmajors. (Right) Individuals are grouped based on the number of musical ensembles they participated in at the time of the study. Note that the y axis is labeled according to both dose (on a logarithmic scale) and dB LAeq,8hr.

**TABLE 2. Percentage of participants in each grouping that exceed the NIOSH REL**

| Grouping | % Participants Over NIOSH REL Dose of 100% (N) |
|---|---|
| Major | 75.0% (33) |
| Nonmajor | 60.7% (34) |
| 1 Ensemble | 55.8% (23) |
| 2 Ensembles | 65.7% (23) |
| 3+ Ensembles | 90.9% (20) |
| Marching band | 82.4% (42) |
| Pep band | 90.0% (20) |
| Concert or symphonic band | 84.2% (19) |
| Wind ensemble | 100.0% (13) |
| Drumline | 50.0% (2) |
| Choir | 50.0% (10) |
| Orchestra | 60.0% (12) |
| Brass | 88.0% (22) |
| Woodwinds | 80.9% (42) |
| Percussion | 83.3% (5) |
| Strings | 33.3% (4) |
| Guitar | 47.1% (8) |
| Piano | 61.8% (34) |
| Voice | 54.5% (18) |

*For each grouping—majors, number of musical ensembles, instrument, and specific ensembles—the percentage of participants engaged in that activity who exceeded the REL is reported (raw numbers are shown in parentheses). Given the prevalence of multi-instrumentalists and multi-ensemblists in the sample, the same person may be counted multiple times in the table.NIOSH, National Institute of Occupational Safety and Health; REL, recommended exposure limit.*

- Pep band participants were more likely to exceed the REL (pep band participants range, 22 to 1638%; median dose, 632%; median LAeq,8hr, 93; nonpep band participants range, 2 to 902%; median, 171%; median LAeq,8hr, 87.32; 90% of participants over REL compared with 61% of nonparticipants; $\chi^2 = 22.7$, $p < 0.001$).
- Wind ensemble participants were more likely to exceed the REL (wind ensemble participants range, 111 to 590%; median dose, 263%; median LAeq,8hr, 81.18; nonwind ensemble participants range, 2 to 1638%; median dose 177%; median LAeq,8hr, 90.86; 100% of participants over REL compared with 62% of nonparticipants; $\chi^2 = 46.9$, $p < 0.001$).
- Concert and symphonic band participants were more likely to exceed the REL (concert/symphonic band participants range, 22 to 1638%, median dose 387%; median LAeq,8hr, 90.50; nonconcert/symphonic band participants range, 2 to 1386%, median dose 193%; median LAeq,8hr, 87.85; 84% of participants over REL compared with 64% of nonparticipants; $\chi^2 = 5.3$, $p = 0.02$).
- Drumline members were less likely to exceed the REL, yet they did have higher median daily sound exposure (although this represents a small sample of 4 individuals; drumline participants range, 22 to 968%; median dose 334%; median LAeq,8hr, 90.22; nondrumline participants range, 2 to 1,638%; median dose, 237%; median LAeq,8hr, 88.73; 50% of participants over REL compared with 63% of nonparticipants; $\chi^2 = 5.9$, $p = 0.01$).
- Choir participants were less likely to exceed the REL (choir participants range, 8 to 620%; median dose, 96%; median LAeq,8hr, 84.82; nonchoir participants range, 2 to 1638%; median dose, 251%; median LAeq,8hr, 89; 50% of choir participants over REL versus 71% of nonparticipants; $\chi^2 = 9.2$, $p < 0.01$).
- Orchestra participants and nonparticipants were equally (un)likely to exceed the REL (orchestra participants range, 2 to 590%; median dose, 136%; median LAeq,8hr, 86.33; nonorchestra participants range, 8 to 1638%; median dose, 245%; median LAeq,8hr, 88.88; 60% of participants over REL versus 69% of nonparticipants, $\chi^2 = 1.4$, $p = 0.24$).

When considering participation in each ensemble together in a mixed-effects model, participation in marching band (N = 51; $\beta = 0.53$, 95% CI = 0.25 to 0.81), pep band (N = 20; $\beta = .35$, 95% CI = 0.07 to 0.62), or wind ensemble (N = 13; $\beta = 0.50$, 95% CI = 0.18 to 0.82) was associated with higher average daily sound exposure dose, whereas participation in orchestra

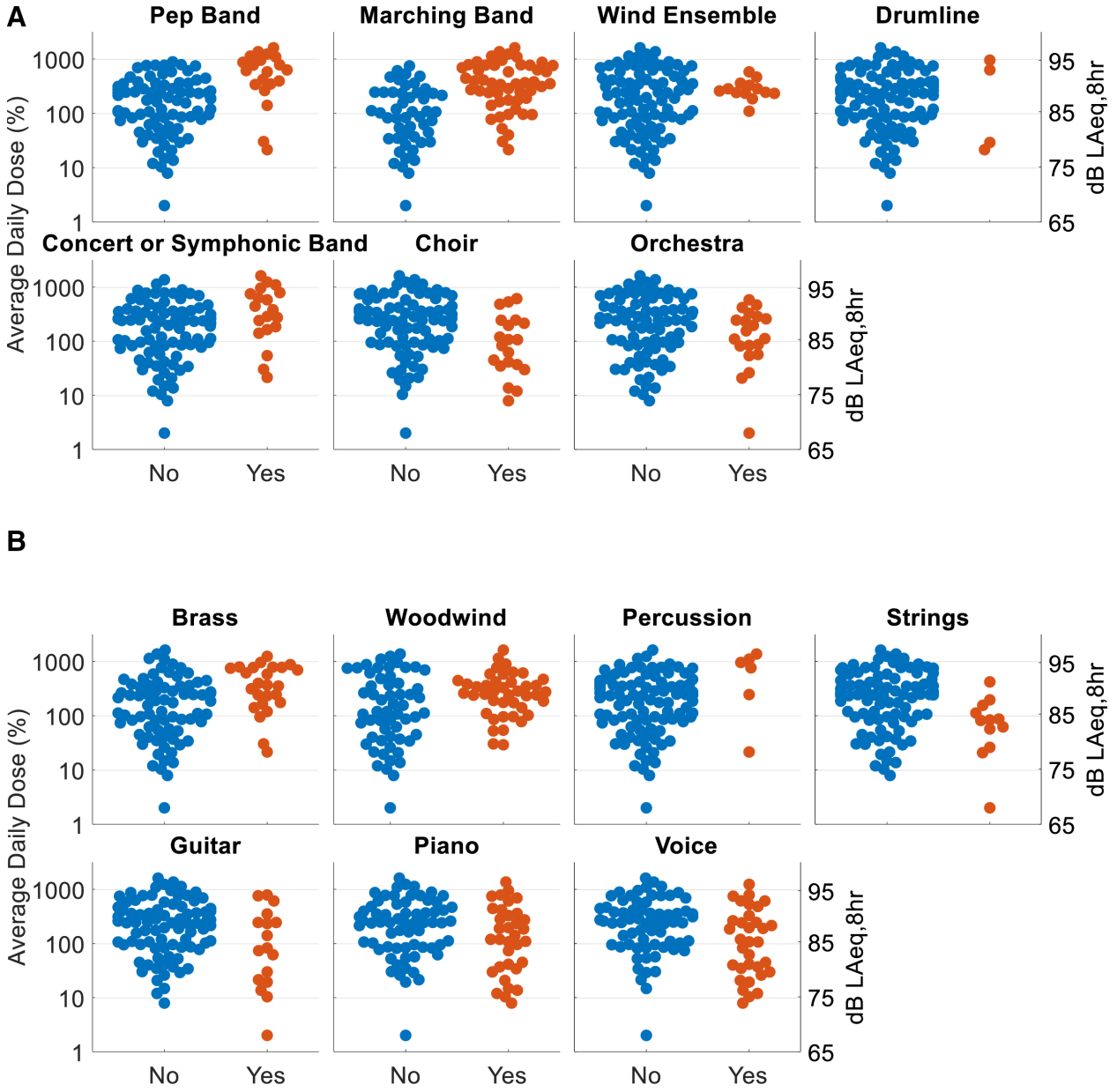



Fig. 4. Average daily sound exposure grouped by ensemble (A) and instrument (B). A, Average daily sound exposure is shown for each individual participating in the ensemble. Navy dots indicate an individual does not participate in that ensemble ("No") and the dark orange dots indicate an individual does ("Yes"). B, Individual average daily sound exposure is shown split by each instrument class. Navy dots indicate an individual does not play an instrument in that class ("No") and dark orange dots indicate an individual does ("Yes"). For both panels, the y axis is labeled according to both dose (on a logarithmic scale) and dB LAeq,8hr.

(N = 20), choir (N = 20), concert/symphonic band (N = 19), or drumline (N = 4) was not. We note, however, the small number of drumline participants. Still, this means that, when controlling for all other ensembles musicians participated in, marching band participants experienced an additional 3.4× the NIOSH REL over non–marching-band participants. Pep band participants experienced an additional 2.2× of the NIOSH REL and wind ensemble participants experienced an additional 3.2× over nonparticipants in those respective ensembles. Keep in mind that these are average daily sound exposure doses and many individuals participate in several types of ensembles. The slopes ($\beta$'s) from our models indicate that participation in each of the three ensembles (marching band, pep band, and wind ensemble) is independently associated with experiencing 2 to 3× the daily maximum NIOSH REL during the week of dosimetry. For example, a participant in both pep band and wind ensemble would be predicted to experience $2.2 \times 3.2 = 7.0\times$ the NIOSH REL. Overall, modeling ensemble types explained 34% of the variance in daily sound exposure dose.

We validated these group comparisons using nonparametric statistics on the nontransformed average daily dose. These comparisons were broadly consistent with our main analysis. Daily sound exposure levels, measured in dose, were higher in individuals who participated in marching band ($U = 529$, $p < 0.001$), pep band ($U = 300$, $p < 0.001$), or concert/symphonic band ($U = 499$, $p = 0.02$). There were no differences for

participants in wind ensemble ($U = 452$, $p = 0.25$), orchestra ($U = 973$, $p = 0.14$), or drumline ($U = 195$, $p = 0.96$). Finally, Choir participants had lower daily average dB LAeq,8hr levels ($U = 1110$, $p = 0.008$).

### 2D: Instrument Class: Brass Players Experience Higher Average Daily Sound Exposures; String Players Experience Lower Levels

Average daily sound exposure is shown for each individual musician sorted by musical instrument class in Figure 4B, and Table 2 reports the proportion of each instrument's players exceeding the NIOSH REL. With respect to specific instruments:

- Brass, woodwind, and percussion players were more likely to exceed the REL: 88% of brass players exceeded REL compared with 60% of nonbrass players ($\chi^2 = 30.4$, $p < 0.001$). Moreover, 81% of woodwind players exceeded the REL compared with 57% of nonwoodwind players ($\chi^2 = 13.4$, $p < 0.001$), and 83% of percussionists exceeded the REL compared with 66% of nonpercussionists ($\chi^2 = 7.6$, $p = 0.006$).
- String players, vocalists, and guitar players were significantly less likely to exceed the REL (string players: 33% over REL versus 72% of nonstring players, $\chi^2 = 30.5$, $p < 0.001$; vocalists: 55% over REL versus 73% of nonvocalists; $\chi^2 = 7.0$, $p = 0.008$; guitar players: 47% over REL versus 71% of nonguitar players, $\chi^2 = 17.0$, $p < 0.001$).
- Pianists and nonpianists were equally likely to exceed the REL: (61% of pianists over REL versus 70% of nonpianists, $\chi^2 = 1.4$, $p = 0.23$).

When considering instrument type together in a mixed-effects model, playing a brass instrument was associated with a higher average sound exposure dose—even when controlling for marching band participation, which was included as a predictor in this model due to the high number of brass players in marching band (N = 25; $\beta = 0.28$, 95% CI = 0.01 to 0.55). This corresponded to experiencing an additional 1.9× of the daily REL. In addition, playing a percussion instrument was associated with experiencing a higher average daily sound exposure (N = 6; $\beta = 0.48$, 95% CI = 0.02 to 0.93), with percussionists averaging an additional 3.0× of the REL. In contrast, playing guitar was associated with a lower average daily sound exposure (N = 33; $\beta = -0.32$, 95% CI = −0.60 to −0.04). This corresponded with experiencing 2.1× less of the REL. Although playing a woodwind trended toward significance, the bootstrapped CIs included 0, indicating there was not a reliable association (N = 42; $\beta = 0.24$, 95% CI = −0.03 to 0.53). Playing strings, piano, or being a vocalist was not a significant predictor of sound exposure in this model. Together, modeling marching band and instrument types explained 32% of the variance in daily sound exposure.

We validated these group comparisons using nonparametric statistics on the nontransformed daily average doses. These comparisons were broadly consistent with our main analysis. Daily average doses were higher in individuals who played a brass instrument ($U = 561$, $p = 0.003$), woodwind instrument ($U = 931$, $p = 0.04$), or who were percussionists ($U = 132$, $p = 0.04$). Daily average doses were lower in individuals who played a string instrument ($U = 783$, $p = 0.007$), were vocalists ($U = 1451$, $p = 0.01$), or were guitarists ($U = 921$, $p = 0.04$). Finally, there were no differences in daily average doses between pianists and nonpianists ($U = 1344$, $p = 0.107$).

### 2E: Extent of Musical Practice: Individuals Who Spend More Hours Engaged in Music Activities Experience Higher Average Daily Sound Exposure

In addition to wearing dosimeters and providing information about their instruments and ensembles via questionnaire, the musicians in our study kept an activity diary during the week of dosimetry. This allowed us to identify specific times, measured in 3.75-min intervals, during the week individuals practiced or performed music. By linking journaled activities to the week-long dosimetry data, we could also calculate the total time that an individual participated in high-sound-intensity activities, that were either musical or nonmusical. For this analysis, we identified the total number of 3.75-min intervals in the dosimeter record that exceeded 85 dBA, summed the total, and reported the total in minutes.

As shown in Figures S1 and S2, Supplemental Digital Content, https://links.lww.com/EANDH/B889, there was a wide range of total music activity hours, ranging from 0 to 29 hr of music in the week (mean, 10.8 hr; SD, 4.7 hr) and 0 to 16.8 hr of music ≥85 dBA (mean, 5.0 hr; SD, 4.7 hr). Relative to the total time in music activities, the percent of time participants spent in music activities ≥85 dBA ranged from 0 to 97% (mean, 43%, SD, 27%). That is, some musicians were almost never engaged in music activities ≥85 dBA; for others, practically all of their music activities were ≥85 dBA, with a wide variation between these 2 extremes.

Both total hours spent engaged in music ($\beta = 0.03$, 95% CI = 0.02 to 0.04) and total hours engaged in music ≥85 dBA ($\beta = 0.08$, 95% CI = 0.06 to 0.09) correlated with average daily sound exposure dose. Specifically, every hour engaged in music activity was associated with an additional 1.1× the REL and every hour engaged in music activities ≥85 dBA was associated with an additional 1.2× the REL. Hours engaged in music accounted for 14% of the average daily sound exposure dose, whereas hours engaged in music ≥85 dBA accounted for 35%. This finding emphasizes that not all music activities are high intensity, and that simply asking a person to report their total hours of music engagement via a diary or questionnaire does not fully capture the individual variation in sound exposure dose estimated by personal dosimetry. These correlations were replicated with nonparametric approaches: daily average doses (unlog transformed) correlated positively with total hours spent engaged in music ($\rho = 0.35$, $p < 0.001$) and total hours engaged in music ≥85 dBA ($\rho = 0.59$, $p < 0.001$).

One might argue that waking hours in general, rather than music activities in particular, account for higher sound exposure levels in multiday dosimetry protocol. For example, perhaps some individuals lead more active lives, participating both in more hours of musical activities and other high-sound-intensity recreational and occupational activities. We addressed this possibility in two ways. First, we examined the proportion of musical activity, measured in 3.75 intervals, that exceeded ≥85 dBA. This approach controls for variance in the total quantity of musical activity. For example, a musician who only had 2 hr of music in a week, but it was all during a marching band performance, might experience more unsafe sound levels than another musician who only engaged in solo practice during the week. Indeed, the proportion of music activities ≥85 dBA was an even stronger predictor of average daily sound exposure than total hours of music activities ($\beta = 1.22$, 95% CI = 0.86 to 1.56). This model accounted for 33% of the variance in average daily sound

exposure dose. This correlation was replicated with a nonparametric approach: daily average doses (un-log transformed) correlated positively with the proportion of musical activity hours ≥85 dBA ($\rho = 0.58$, $p < 0.001$).

Second, we used the diary data to examine how individuals spent their time more broadly. We found there was no correlation between total activity hours (time spent out of the house regardless of whether it involved musical activities) and average daily sound exposure dose ($\beta = 0$). There was also no correlation between hours spent in musical activity and hours in nonmusical activities during the week ($\beta = 0$). Thus, being more musically active is not associated with less (or more) engagement in nonmusic activities. There was, however, an inverse association between nonmusical activity hours and average daily sound exposure dose ($\beta = -0.007$, 95% CI = −0.012 to −0.002), accounting for 8% of variance in daily sound exposure dose. In other words, spending more time in the week engaged in activities besides music was associated with a lower average daily sound exposure dose. Thus, average daily sound exposure dose is not necessarily a simple byproduct of waking hours: it is how an individual spends those hours—and particularly the extent to which they engage in high-sound-intensity music activities, relative to the total amount of music activity hours—that correlates with average daily sound exposure dose. But, still focusing on sound exposure dose assessments only on music activities will still likely underestimate the total risk.

One might also argue that there are selection biases baked into certain aspects of musicianship that predispose individuals to engage in additional noisy nonmusical activities. For example, based on anecdotal data, marching band is as much a social experience as it is a musical activity. So, perhaps the social drive that leads an individual to marching band also increases their propensity to attend other high-sound-intensity events; or perhaps an interest in sports leads an individual to participate in marching band and attend additional, high-sound-intensity sports events even if they are not performing. Conversely, perhaps musicians are more sensitive to hazardous sound exposure, particularly in nonmusical contexts.

To address this, we created a two-by-two median split of the dataset, based on the minutes of music activities ≥85 dBA and minutes of nonmusic activities ≥85 dBA indicated by cross-referencing the dosimetry data with activity journals. If a participant fell below the median for both types of activities, they were placed in the low-low quadrant. If they fell above the median for both activity types, they were placed in the high-high quadrant, etc. There tended to be more music minutes ≥85 dBA than nonmusic minutes ≥85 dBA (music minutes ≥85 dBA median, 200.2 min, mean, 300.4, SD, 279.2; nonmusic minutes ≥85 dBA median, 153.9 min, mean, 200.1, SD, 192.7; $t(98) = 3.3$, $p = 0.001$).

Results are shown in Table 3, which reports the proportion of music majors and marching band participants, respectively, falling into each quadrant. These two groups were selected because of little overlap in membership (only two of the majors are in marching band). Among marching band participants, 54% of the group fell in the high-high quadrant, indicating that they were in the top half of the cohort for both music and nonmusic time ≥85 dBA logged. By contrast, only 23% percent of the music majors fell into this quadrant.

### 2F: Putting It All Together: Combining Hours of Musical Engagement With Musician Profiles Produces a More Accurate Model of Musicians' Average Sound Exposure Than Hours Alone

As a final step, we examined how the variables we identified as predictive of average daily sound exposure jointly account for individual variation in average daily sound exposure. We were mindful, though, that the personal noise dosimeters we used here may be impractical for most research and clinical applications. Thus, we asked how much variance in sound exposure we could explain using simple questions that do not require any specialized equipment, such as those reflected in our musician profile variables and the hours of music an individual musician engages in over the week. We remodeled the average daily sound exposure dose in a linear model from the total of musical activity and all profiling data, omitting study-year cohort as a random factor because it is not generalizable beyond our study, and omitting information about the proportion of musical activities that were ≥85 dBA because this metric requires dosimetry.

Our model accounted for 49% of the variance in average daily sound exposure (Fig. 5, top panel). It should be emphasized that we are operating in a log scale, meaning small model errors may translate to large differences in average daily sound exposure dose (Fig. 5, middle panel). To this end, as a last step, we used the same variables, and we found that a binary logistic regression model reliably predicted whether musicians' average daily sound exposure doses were above or below the NIOSH REL (Tjur's $R^2 = 0.43$, $p < 0.001$). An receiver operating characteristic (ROC) curve analysis on this model indicated an area under the curve (AUC) of 0.89 (95% CI = 0.82 to 0.95; Fig. 5, bottom panel), indicating the model classified individuals as high or low risk, based on NIOSH criteria, with good accuracy. To ascertain if the musicianship profiling variables, such as ensembles and instruments, added value in predicting sound exposure risk above and beyond the number of hours spent in music activities, we constructed a similar model predicting sound overexposure risk group solely from the hours of music an individual engaged in during the week. As shown in Figure 5, this was a poorer predictor (grey ROC curve; AUC = 0.69, 95% CI = 0.61 to 0.83) compared with the comprehensive model (purple ROC curve; $Z = 2.7$, $p = 0.007$).

## DISCUSSION

We used a multiday dosimetry protocol to measure daily sound exposure in 100 college musicians with varied musical experiences and engagement, but with normal audiograms. Personal noise dosimeters were worn during all waking hours for eight calendar days, thereby capturing soundfield exposure levels from all daily activities not just scheduled or unscheduled music activities. Participants ranged in their total years of musical training, academic curriculum, ensembles in which they participated, instruments they played, and the total hours they played their instrument during the week. We found considerable variability in their average daily sound exposure, ranging from 2 to 1638% of the NIOSH REL. About one-third of the musicians' average sound exposure was at or below the REL, one-third were 1 to 3× the REL, and one-third were >3× the REL.

### Multiple Aspects of Musical Practice Correlate With Sound Exposure

We sought to understand sources of variation in sound exposure and to identify which musician variables predicted sound overexposure risk. First, we considered individual variables. We found that being a music major was not predictive of higher average daily sound exposure dose compared to nonmajors, although majors were more likely to exceed the NIOSH REL. Musicians in the marching band, the largest ensemble on campus, experienced higher average sound exposure than those who were not in the marching band. Given that sound exposure dose is based on sound level and duration, this is perhaps not surprising because sound intensity is predicted to scale with more sound sources (more instruments). Consistent with this finding, Washnik et al. (2021) measured personal noise dosimetry in six marching-band participants during their practice and showed that sound levels exceeded recommended limits for all participants, and were higher during performances than rehearsals. In a similar vein, we also found that musicians in any kind of band (marching band, pep band, concert band, symphonic band), or who played band instruments (brass and woodwinds), had a higher average daily sound exposure dose than those who did not display these characteristics (Figs. 4 and 5). Miśkiewicz and Rakowski (1994) argue that brasswinds have a larger dynamic range than string instruments due to variations in the brass-winds' spectral envelopes, which may contribute to the relatively high average daily doses in the musicians who play them.

Musicians who played in multiple ensembles were also more likely to experience higher average daily noise exposure doses, as playing in multiple ensembles is expected to increase the total practice time during the week. Indeed, individuals in 1 ensemble averaged 541 min of music activity during the week (SD, 380 min); individuals in 2 ensembles averaged 710 min of music (SD, 436 min); and individuals in 3+ ensembles averaged 748 min (SD, 545 min). Weekly average sound exposure dose was particularly high in individuals who participated in 3 or more ensembles (Fig. 3). Similarly, we found that total hours of music practice during the week were predictive of higher average daily sound exposure.

It should be emphasized that we are examining average daily sound exposure across a week, with measurements taken on the individual, not group, level. That is, we measured the cumulative sound exposure for each day, and then arithmetically averaged across days to derive the daily average. Different techniques have been used to measure musicians' sound exposure, including positioning microphones at fixed locations within a music space (Sabesky & Korczynski 1995; Rodrigues et al. 2014; Powell & Chesky 2017; Smith et al. 2019). Such "area" monitoring can provide valuable information about group-level risks; however, individual risk is more accurately estimated with a personal monitoring approach that uses personal noise dosimeters or other wearable devices (Washnik et al. 2016). For a holistic estimate of individual risk, in our study, dosimeters were worn for 1 week across all daily activities, from which we calculated the average daily sound exposure for the week. A novel element of our design is that we measured sound exposure across an entire week, only a subset of hours of which might have been dedicated to music rehearsal or performance. Our results indicate that, for the purposes of evaluating individual risk, it is important to consider the combination of all activities, musical or not. In fact, while we could reliably predict average daily sound exposure dose from the total hours of music activities and music profile variables, only half of the variation in sound exposure was accounted for using these variables. Thus, the average daily sound exposure dose and the differences noted between musicians cannot be solely attributed to sound levels experienced during music activities alone. Indeed, Skoe and Tufts (2018) found that some musicians experience sound levels above the NIOSH REL during musical and nonmusical activities. We expand on this finding here. When comparing college musicians with respect to the total minutes of nonmusic activities ≥85 dBA, we find the marching band members are considerably more likely to fall above the median compared with music majors (68% of marching band members versus 46% of music majors). This reinforces that musicians are also potentially exposed to high-intensity sound outside of musical contexts, and the importance of considering the extent and nature of these activities in a comprehensive evaluation of sound overexposure and NIHL risk.

### Musician Profiling Predicts Daily Sound Exposure

Next, we turned to understanding the collective impact of all music profile variables including total hours of music activities in predicting average daily sound exposure dose. These variables were extracted from simple questions and did not require specialized equipment, like noise dosimeters, to obtain.

Collectively, these profile variables accounted for 51% of the variance in the average daily sound exposure and had good predictive power in identifying whether musicians were above or below the NIOSH REL. On its own, the total hours of music activities were less reliable in predicting whether the musicians' average daily sound exposure dose was above or below the NIOSH REL. This is noteworthy as the Noise Exposure Questionnaire (Johnson et al. 2017), a tool for estimating annual sound exposure that is growing in popularity, uses these total hours to estimate risk. Finally, while we could classify musicians accurately and reliably as above or below the NIOSH REL based on ensemble and instrument variables, models including these variables accounted for only 40 to 45% variance in daily sound exposure. Indeed, for all the models tested, roughly half (if not more) of the variance was unaccounted for. And, of

**TABLE 3. Loud musical vs. loud nonmusical activities during the week**

| **Music Majors (N = 44)** | Nonmusic Minutes | | **Marching Band Participants (N = 50)** | Nonmusic Minutes | |
|---|---|---|---|---|---|
| | High | Low | | High | Low |
| Music minutes | | | Music minutes | | |
| High | 23% | 20% | High | 54% | 22% |
| Low | 23% | 34% | Low | 14% | 10% |

*The entire cohort of musicians was divided using a median split along two dimensions: the number of minutes in the week engaged in loud musical vs. loud nonmusical activities. The proportion of music majors and marching band participants, respectively, falling into these quadrants is reported.*

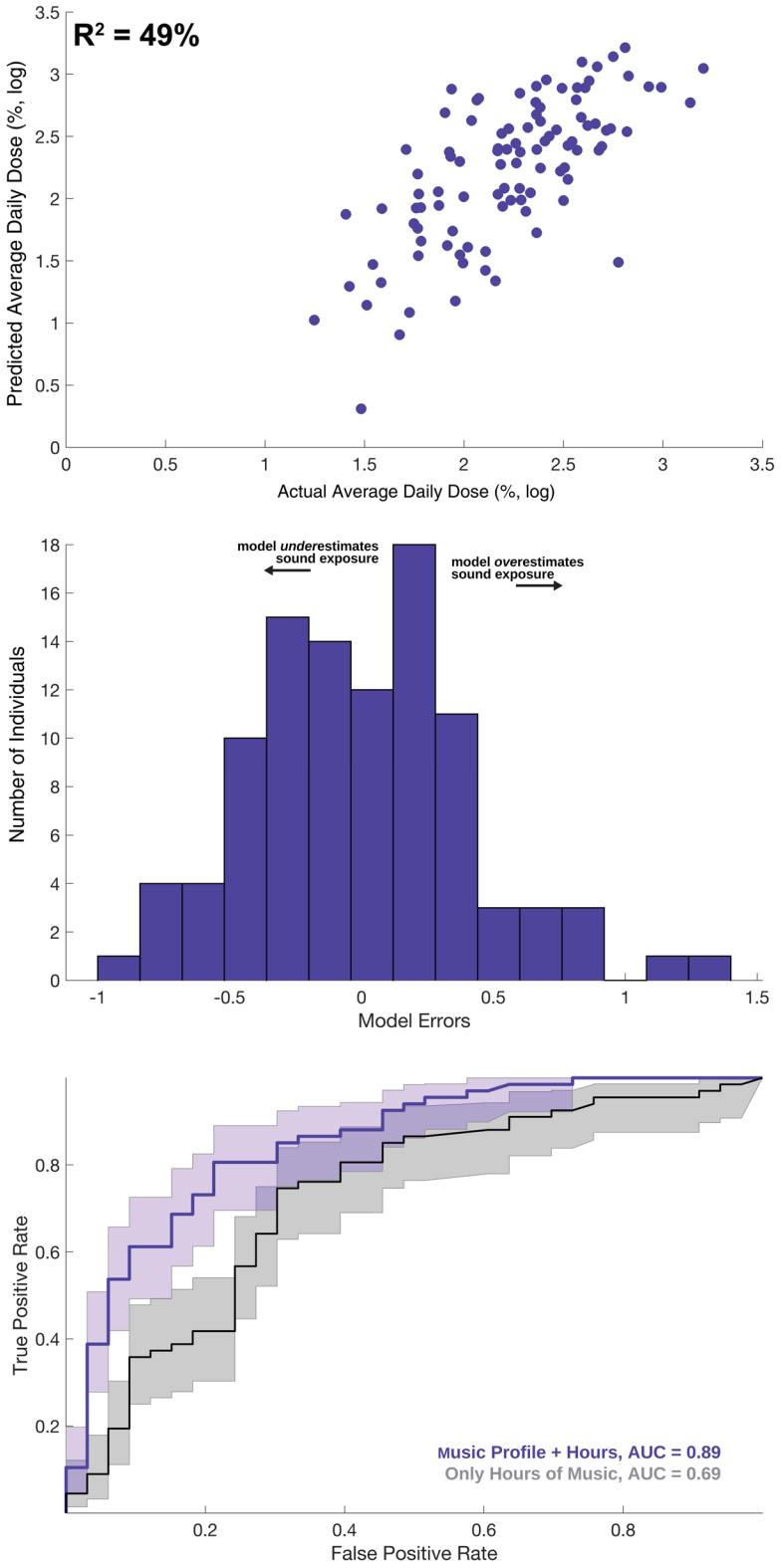



Fig. 5. Predicting average daily sound overexposure risk from musician subtyping. Average daily sound exposure was modeled by profiling musical activities. (Top) Actual vs. predicted average daily sound exposure, demonstrating good model fit. (Middle) Errors between musicians' actual and predicted sound exposure are plotted as a histogram. Note that the model is on a log scale, meaning small discrepancies between actual and predicted average daily sound exposure can reflect large differences in doses. (Bottom) Model accuracy to predict whether individuals exceeded the NIOSH REL (purple) compared with using weekly hours of music (grey), both plotted as receiver operating characteristic (ROC) curves with 95% bootstrapped confidence intervals. NIOSH indicates National Institute of Occupational Safety and Health; REL, recommended exposure limit.

course, sound exposure is not the only potential environmental contributor to hearing loss; this is addressed by a recent questionnaire developed by Griest-Hines et al. (2021).

It is important to point out the substantial across-individual variation in both average daily sound exposure and hours of musical activity in the sample. As shown in Figures S1 and S2, Supplemental Digital Content, https://links.lww.com/EANDH/B889, there was a wide range of musical activity during the week participants kept activity diaries, ranging from 0 to 34 hr. It is particularly interesting to examine the participants with 0 hr of music and/or 0 hr of music ≥85 dBA. As shown in Figure S1, Supplemental Digital Content, https://links.lww.com/EANDH/B889, some of the individuals with no musical activity during their week of participation in the study still experienced very high sound exposure levels—up to 6× the NIOSH REL. This reinforces our weeklong experimental design and why hearing risk during musical and nonmusical activities should be assessed. This finding also reinforces our view that musicians' sound exposure profiles should be conceptualized as traits and not states. That is, we think our week of dosimetry is representative and generalizable of their weekly risk, not circumscribed to the week they participated in our study.

One might ask why we included individuals who did not engage in music during the study week (n = 2). Because our goal was to capture various music subtypes, we thought including them would be the most veridical representation of the college musician population—some musicians take breaks from music activities for any number of reasons. In addition, our analysis shows that hours of music and more general musician profiling (instrument, ensembles, etc.) both add value to explaining variance in sound exposure and estimating risk.

### Limitations and Future Directions

There are several caveats to consider when interpreting our results. First, we rely on a descriptive, natural-history design. While this approach reflects participants' ecologically valid experiences, it is fundamentally correlational. Without random assignment, we cannot ascribe causal effects of specific music activities—or musicianship in general—to sound exposure. Second, our sound exposure assessments consisted of a single week of dosimetry. A recent study suggests that 1 week is representative of longer periods of dosimetry (Jorgensen et al. 2025), but this question requires further investigation. Third, although our sample is the largest to our knowledge to conduct individual-level weeklong sound-exposure assessments in college musicians, it still consisted of only 100 participants. There were also some types of musicians, such as percussionists, that were sparsely represented in our study. Our sample is also relatively small for the predictive modeling we conducted (and was insufficient for out-of-sample validation), so these specific results should be interpreted cautiously. Fourth, and related to the limited sample size, our cohort reflects college students at a single university and may not generalize to other musician populations.

While personal noise dosimeters have the advantage of providing highly individualized data, there are drawbacks to our dosimetry protocol and analytical approaches. One limitation of our multiday, daylong protocol is that the placement and use of the noise dosimeter was not verified at all times. Also, by focusing on average daily sound exposure, we are obscuring day-to-day variation in doses. A musician whose average sound exposure is at or below the average daily NIOSH REL, for example, may still experience one or two days of sound levels exceeding the REL. A recent study showed that 1 week of dosimetry correlates highly with dosimetry measured in other weeks during the semester (Jorgensen et al. 2025). Still, the extent to which 1 week is representative of a year or more is an open question. We also acknowledge that the NIOSH REL assumes a 5-day workweek for 40 yrs. We also did not correct for hearing protection. In addition, there is some margin of error in the dosimeter measurement due to the ±2.5 dB calibration accuracy of the devices. The upper limit of 130 dBA for the devices also means that high-impact noises may not be accurately measured. Finally, the dosimeters do not measure sound exposure from headphones or earphones, which themselves may be sufficient to cause high-frequency hearing loss (Le Prell et al. 2013). Thus, if anything, we are likely underestimating daily sound exposure in our cohort. Similarly, our approach to quantifying dosimetry relative to the NIOSH REL may underestimate the potential impact of percussive high-level sounds, such as those experienced by percussionists and other musicians who practice or perform adjacent to them.

We also have an incomplete characterization of music activities and experience. There are additional factors that may bear on sound exposure such as musical genre(s) and use of electronic amplification, frequency of public performance, and occupational or nonoccupational activities (such as performing music for pay versus pleasure or working versus exercising at a gym), or academic course of study (such as music performance versus music education versus nonmusic). We likewise have not explored interactions between sound exposure, music activities, and gender. Widén et al. (2011) reported on attitudes regarding sound exposure and risk in a large cohort of Swedish adolescents. They identified several gender differences in attitudes to susceptibility to and risk of sound overexposure; It is important to note that they did not identify gender differences in protective behavior regarding sound exposure. While this is only one study, it suggests gender differences may not have constrained our participants' engagement in music activities—at least with regard to the risk of sound overexposure.

In addition, while we focused on contemporaneous music activities to try and understand current sound exposure, the week sampled may not be fully representative of all current activities. For example, when asked to list all music ensembles they were currently in, it is possible that some or all the ensembles listed did not meet during the week of dosimetry, which again could potentially underestimate sound exposure and limit the value of predicting sound exposure from the number of ensembles in which a musician participates. A musician's long-term music activity history should also be considered when characterizing hearing health risk. Here, we focused on total years of music activity and found that total years did not predict the current average daily sound exposure. Guest et al. (2018) introduced a structured, adaptable interview to estimate lifetime sound exposure that may be better suited to capture music history. We also note that the NIOSH REL is not designed to detect the risk of other otopathies that can occur in musicians' exposure, such as tinnitus, hyperacusis, or diplacusis.

Another consideration that we did not investigate is whether ensemble practices were indoors or outdoors. This is particularly relevant for marching band, which performs at

outdoor sporting events such as football and may distinguish it from pep band, which tends to perform at indoor sports such as basketball. Anecdotally, the marching band at UConn tries to hold performances and practices outdoors, however due to weather or specific needs of the ensemble, rehearsals may occasionally be moved indoors. Given our sampling was done throughout the semester, with varying start dates for participants, we suspect our dataset reflects this variation in practice location. However, we do not have specific data on whether certain rehearsals/performances were indoors versus outdoors, as this was not included in the coding for our daily activity diaries. Unfortunately, we cannot draw any conclusions about the appropriateness of hearing protection in these settings. This may be an appropriate consideration for recommending hearing protection: for example, should personal sound exposure levels indeed be higher indoors, hearing protection may be even more warranted when practicing indoors.

Despite these limitations, we think the musician subtyping we used here still has its benefits. Our modeling showed that we could more accurately predict sound exposure using both musician subtyping and hours of music rather than just hours alone, emphasizing that the type and quantity of music activities are important factors to consider in assessing risk. This highlights the potential limitations of alternative methods of measuring sound exposure. For example, the Noise Exposure Questionnaire treats all music activities equivalently to estimate annual noise dose (Johnson et al. 2017). Our findings suggest that simple survey questions about the type and number of ensembles and instrument class may predict whether a musician is likely to be above or below the NIOSH REL. This has important implications for future large investigations of sound exposure in musicians for which personal noise dosimetry is not practical or feasible. Our findings also have important implications for education and intervention among college musicians about their risk for hearing loss. Still, we acknowledge gaps in our subtyping of musicians and that we could only explain up to about half of the individual differences in average daily sound exposure.

A study is currently underway by our group to address these limitations and further our understanding of musicians' sound exposure. This ties into a broader point, which is the practical challenges of performing ecologically valid sound-exposure assessments. For one, we relied on personal noise dosimeters in a carefully controlled study that took multiple years to complete, but the dosimeters we used are not practical or scalable in the long term because they are an additional device individuals would have to remember to wear. A promising alternative is to incorporate dosimeters into multipurpose devices such as smartwatches. Second, we tried to parameterize highly individualized musical experiences to capture musician subtypes. We believe a fuller understanding of sound exposure in musicianship will require both new technologies to make it more feasible to capture longer timescales and a multi-method approach, including both large-scale survey studies and smaller ethnographic studies to fully characterize the breadth of music activities and their sound level attributes—and, ultimately, how music activities might elevate the risk for hearing loss from sound overexposure. These questions are especially salient for older musicians, whose lifelong sound exposure may compound presbyacusis.

It is worth noting that the most susceptible individuals could still develop a hearing loss due to sound overexposure even if their exposures never exceed the NIOSH REL (Prince et al. 1997). To protect virtually everyone, the World Health Organization (Berglund et al. 1999) recommends a limit of 70 dBA for a 24-hr LAeq. In addition, the NIOSH REL was developed under the assumption that the exposure would occur over a working lifetime of 5-day weeks for 40 yrs. Nevertheless, we used the NIOSH REL to characterize risk because it is the metric most commonly seen in the literature, including dosimetry studies of nonoccupational exposure (Flamme et al. 2012; Washnik et al. 2016; Tufts & Skoe 2018), and is considered protective of >90% of individuals depending on model assumptions (Prince et al. 1997). Using the NIOSH REL allows us to maintain consistency with previously published studies in this area and facilitates comparison with other published dosimetry studies.

## CONCLUSION

In a sample of 100 college musicians, we showed that students engaged in music activities were very likely to experience high sound-exposure levels. It is important to note that most musicians' average daily sound exposure exceeded the NIOSH daily REL. At the same time, we saw wide across-individual variation in average daily sound exposure. That is, some musicians were almost never engaged in high-sound-intensity music activities; for others, practically all of their music activities were high intensity, with a wide variation between these two extremes. Certain music activities, such as participating in band ensembles, engaging in multiple ensembles, and playing a brasswind instrument, were associated with higher average daily sound exposure. In addition, individuals who engaged in more hours of music activities experienced higher sound exposure. Yet because our dosimetry was limited to sound field exposure and did not account for listening with earbuds or headphones, we are likely underestimating young adult musicians' daily sound exposure.

Our findings underscore the hearing health hazards of music activities and the need for fine-grained individualized measures to assess risk. They also highlight that music activities are not the only source of hearing health risk for musicians. A comprehensive hearing health risk assessment should include considerations of music in addition to other occupational and recreational sources. This study supports the need to educate college musicians on specific risk factors so they can be active participants in, and take ownership of their hearing health.

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