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The daily auditory environments of people with tinnitus

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This study characterized typical noise exposure patterns in people with tinnitus relative to a control group. For a week, participants wore a personal noise dosimeter, with instructions to wear during all waking activities. The sample ($n=108$) included both Tinnitus and Control groups. Data were analyzed first using summative metrics of daily sound exposure followed by functional data analysis (FDA) to reveal finer temporal differences in sound exposure between groups. We found that daily personal sound exposure, measured using the time-weighted average sound pressure levels (LAeq,8h), was lower for the Tinnitus relative to the Control group. Based on the dosimeter data, neither group was at ongoing risk of noise-induced hearing loss, as average daily sound levels did not exceed 75 dB LAeq,8h for either group. However, the Tinnitus group spent less time engaged in noisy activities (>85 dBA) compared to the Control group, with notable differences for home environments. FDA revealed that group differences tended to be maximal around noon and evenings, periods where an individual is likely to have more control over their environment. Overall, we find that people with tinnitus had quieter environments, suggestive of leading quieter lives. Differences between groups may be explained by greater awareness of the risks of noise exposure or decreased sound tolerance in the Tinnitus group.

Keywords Tinnitus, Noise exposure, Personal noise dosimetry, Functional data analysis

Tinnitus is the sensation of sound in the absence of an external stimulus. Often experienced as ringing or buzzing, tinnitus can range from a mild condition to a disabling ailment that negatively impacts a person's livelihood. The global prevalence of tinnitus is estimated at ~14%, with the prevalence being higher in older adults[1]. There is currently no agreed-upon diagnostic or objective biomarker of tinnitus, so diagnosis is typically based on the subjective classification of self-reported symptoms. Adding to the complexity, tinnitus is a highly individualized condition with no universally accepted approach to assessing the biological severity of the condition and no one-to-one correspondence between the condition's biological basis and the psychological and emotional difficulties experienced due to the tinnitus.

Although tinnitus is a complex condition with many contributing factors, one frequent cause of tinnitus is noise exposure, which, depending on the nature of the exposure, leads to either a sudden or gradual onset of symptoms.Tinnitus severity has been associated with increased exposure to noise across the lifetime[2]. More lifetime noise exposure is also associated with increased occurrence of tinnitus[3–7]. However, people with high levels of lifetime noise exposure do not necessarily have tinnitus[8], suggesting that lifetime noise exposure alone is not sufficient to explain tinnitus. While the connection between long-term noise exposure and tinnitus has been the target of many studies[7–11], little attention has been given to sound exposure patterns *after* the onset of tinnitus. That is, while a history of noise exposure may put people at risk for developing tinnitus, whether people with tinnitus show distinctive patterns of sound exposure relative to a Control group without tinnitus has not been studied. A deeper understanding of the sound exposure patterns of people with tinnitus may aid the clinical management of tinnitus and give greater insight into the environmental conditions associated with disordered sound perception.

The goal of this study was to use wearable technology to objectively study the daily sound levels of people with self-reported tinnitus relative to a Control group, using one week of data as a snapshot of routine environmental sound levels. An appeal of using wearable technology is that it can provide more accurate and objective measures of sound exposure compared to self-report or interview[12]. Self-report can be prone to errors of recall and may be

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limited in its ability to capture fine-grained individual differences in sound exposure because of coarse temporal sampling windows and/or assumptions made about what constitutes loud activities and how to estimate sound levels from self-report[12]. A secondary goal of this study was to link daily sound levels to how tinnitus impacts a person's daily life. To assess the daily psychological and emotional response to tinnitus, the Tinnitus group completed the Tinnitus Handicap Inventory[13].

We used a body-worn noise dosimeter (ER-200DW8 personal noise dosimeter [Etymotic Research, Inc.]) to continually measure sound levels across a week. From the dosimeter log, we estimated time-weighted sound exposure levels for each day of the week. Our recent study showed that differences between college musicians and age-matched controls were not uniform across the week[14]. Instead, group differences were concentrated on specific days of the week when musical activities were highest. In that earlier study, data were aggregated across day of the week, but time of day effects were not analyzed. Other recent work investigating different time scales showed strong time of day effects, with sound levels increasing from the early morning to the evening and then decreasing again[15]. Here we employ functional data analysis (FDA) to identify time windows during the week of maximal difference between the Tinnitus and Control groups. This more granular time-series approach is likely to identify more subtle group differences that would be missed if only day-level effects were considered.

We had two alternative hypotheses for how the two groups might differ vis-à-vis their daily sound levels. The first was that the Tinnitus group would have higher daily sound levels. If noise exposure is a precursor to tinnitus and people with tinnitus have more lifetime noise exposure than a Control group, their environments may remain noisier even after developing tinnitus, and they may be at greater risk for hearing damage (or continued damage). Given that tinnitus severity increases with increased noise exposure, people with more severe tinnitus may have greater noise exposure post-tinnitus onset if occupational and recreation activities that contributed to tinnitus are still ongoing or replaced by other risky activities. The alternative hypothesis is that the Tinnitus group would lead generally quieter lives, and that their daily sound levels therefore would be lower than the Control group. This outcome could arise if having tinnitus creates greater awareness of the risks of noise exposure. It is also possible that the Tinnitus group would be more likely to avoid sound, not because of its risks to hearing, per se, but because of hyperacusis, a condition often comorbid with tinnitus, in which commonplace sounds are perceived as excessively loud[16]. The tinnitus group may also avoid loud sounds because tinnitus inherently fluctuates in perceived intensity and loud exposures may influence the severity of tinnitus[17].

We tested these alternative hypotheses in a dataset of 108 adults aged 18 to 80 years and found converging evidence that people with tinnitus lead quieter lives.

Methods

Testing was completed at the University of Connecticut (UConn) Storrs campus and the UConn Health Center (UCHC) Farmington campus from February 2022 through September 2023. Participants were recruited via advertisements in an online newsletter circulated to all University students and staff. The UConn Health Clinical Registry for Conditions of the Ear, Nose, and Throat served as an additional recruitment avenue for the Tinnitus group. All procedures were approved by institutional review boards at UConn and UConn Health and all methods were performed in accordance with the relevant guidelines and regulations. Written informed consent was obtained from all participants. Participants were paid for their participation. All the Control group participants were tested at UConn, as part of a larger ongoing study of noise exposure and aging. Four of the tinnitus participants were tested at UConn, and the remaining members of the tinnitus group were tested at UConn Health. To limit variability between sites, the audiometric testing environments were standardized, the same model of personal noise dosimeters was used, and one of the testers was common across sites.

Noise dosimeter data was collected over the span of one week and required that the participant visit the lab for two sessions separated by one week, first to pick up the dosimeter and then return to the dosimeter. At the first session, all participants underwent a hearing assessment via pure-tone air conduction audiometry. If they self-reported having tinnitus, they also completed the Tinnitus Handicap Inventory[13]. Prior to enrollment, participants were screened for a negative history of chronic ear infections, tympanic membrane rupture, ear-related surgery, neurological or ontological disorder, and use of medications known to affect hearing. The tinnitus participants tested at UConn Health were also screened to exclude for a history of hyperthyroidism, barotrauma, and vertigo. Participants were not excluded based on hearing status, as subjective tinnitus has been reported in both normal and hearing-impaired populations[18,19].

Participants

A total of 108 adults (18–80 years old, 63 female) completed the study. Participants were classified into one of two groups, a Tinnitus group and a non-tinnitus Control group, based on self-report of tinnitus. The Tinnitus group included 61 adults (18–80 years old, mean = 51.39, SD = 16.38), and the Control group included 47 adults (27–72 years old, mean = 44.23, SD = 12.03). The Tinnitus group was on average older than the Control group (Mann Whitney $U(106) = 1025$, $p = 0.01$, rank biserial correlation (rbb) = -0.28, rbb 95% CI = [-0.07, -0.40]).

In the Tinnitus group, roughly half the sample was female (52%, N = 32), compared to 65% of the Control group being female (N = 31). Although the gender distribution was not statistically different between groups ($X^{22} = 1.99$, $p = 0.16$), we included gender as a covariate in the analysis because the samples were not perfectly gender matched. Studies also suggest that men are more likely to be exposed to loud noise than women and that they are also at greater risk of noise-induced hearing loss than women[20,21].

Audiometry

Air-conducted monaural pure tone thresholds were obtained for the right and left ears under ER-3A (Etymotic Research, Inc.) insert earphones using a GSI-61 (Grason-Stadler) at UConn Storrs and an Interacoustics Affinity 2 AC440 clinical audiometer (e3 Diagnostics) at UConn Heath. Thresholds were obtained at standard clinical test frequencies (0.25, 0.5, 1.0, 1.5, 2.0, 3.0, 4.0, 6.0, 8.0 kHz) using a Hughson-Westlake procedure (Carhart and Jerger, 1959). The bilateral pure tone average (PTA) was calculated for each participant for the purposes of group comparisons and so PTA could be added as a statistical covariate.

At both test sites, audiometric testing was completed in standard sound insulated testing booths with maximum permissible ambient noise verified in accordance with ANSI standard S3.1–1999 (R 2008). Audiometric equipment was calibrated annually and in accordance with ANSI S3.6–2010 and ANSI S3.13–1987 (R 2012). Calibration and ambient noise control standards were maintained across testing sites.

Tinnitus handicap inventory (THI)[13]

The THI is a 25-item questionnaire that assesses the degree of difficulty a person is experiencing because of their tinnitus, with a focus on how tinnitus impacts social, emotional, and psychological functioning[13]. For each question, respondents reply "Yes" (4 points), "Sometimes" (2 points), or "No" (0 points). Scores are tallied into a THI total score (maximum of 100, minimum of 0), with higher scores associated with a more severe handicap. The scores are categorized by level of handicap: slight or no handicap (0–16), mild 18–36), moderate (38–56), severe (58–76), and catastrophic (> 78). THI scores were not available for four participants because of either leaving answers blank or giving multiple answers for a given question.

Weeklong personal noise dosimetry

Participants wore an ER-200DW8 personal noise dosimeter (Etymotic Research, Inc.) for a full week, after receiving training on how to use the device at session 1. The start time of the dosimeter log was recorded by the experimenter, rounding to the closest minute. A typical recording spanned 8 calendar days, with the first and last being partial days (< 24 h). The weeklong period began on a weekday, with Tuesday and Thursday being the most common start days for both groups. Wednesday was also a common start date for the Control group.

The time series dosimeter data log spanned all hours of the day, including waking and sleeping hours, without any a priori assumptions about the days or times when the participant would be more active. We have used this same dosimetry protocol in multiple prior studies and have shown that a week is representative of longer time scales[15].

As part of the training, participants were instructed to clip the dosimeter to the collar of their clothing to keep the microphone port exposed and with a consistent proximity to their ears. They were also instructed to wear the dosimeter during all waking hours and to keep the device nearby while they slept. During the week, participants kept a journal of their activities so that noisy periods (periods ≥ 85 dBA) could be mapped to specific activities. We used 85 dBA as a benchmark for defining noisy periods, to match our previous work in college musicians[14] and federal guidelines. In occupational settings, the National Institute for Occupational Health (NIOSH), advises taking hearing protection precautions for sound levels 85 dBA or higher. However, we note that sound levels below 85 dBA are not necessarily safe if sustained for long periods.

As part of our analysis, we also tallied the total time the participants' environments exceeded 85 dBA during the week.

Activities were coded into 17 broad categories: Sleep, Social, Travel, Errands, Coursework, Home, Job, Work from Home (WFH), Physical Activity, Yardwork, Shopwork, Solo Music Practice, Music Performance, Music Rehearsal, Attend Concert, Religious Service, and Other. The "Other" category included activities that did not fall into the prescribed categories. The Solo Music Practice, Music Performance, and Music Rehearsal categories required that person had the role of musician (and not attendee) in the performance or rehearsal. The Social category refered to any social activity, such as eating at a restaurant, going to a bar or party, or spending time with friends or family (either inside or outside of their home). When participants listed more than one code for an activity, the activity was recategorized with the primary code of that activity. For example, if a participant combined the codes "Errands/Travel" to indicate that they were traveling from one errand to another, the activity was coded as "Errands." If a participant combined the codes "Social/Physical Activity" to indicate that they were taking an exercise class with friends, the activity was recoded as "Physical Activity." If a participant combined the codes "Home/Sleep" to indicate that they were at home sleeping, the activity was recoded as "Sleep." The WFH, Shopwork, Yardwork, and Religious Service codes were not part of the original codes provided to the participants but were created post-hoc as these activities were reported by multiple participants in the notes section of their journals.

Device configuration matched those outlined in Parker et al.,[22]. In brief, the dosimeters were set to a 70 dBA threshold with an 85 dBA criterion level and 3 dB exchange rate. Environmental sound-level measurements were logged in equally spaced 3.75-min increments over the collection period, yielding 16 data points per hour and a maximum of 2688 data points per participant (16 points per hour *24 h *7 days). Each data point represents the summed energy of 1022 samples measured over 3.75 min. For each 3.75-min interval, samples below the threshold (70 dBA) are treated as zero by the device when summing dB levels.

At the conclusion of the weeklong personal noise dosimetry protocol, the dosimeter data logs were extracted using the Etymotic Research Utility Suite (version 4.04), saved as a text file, and processed through a lab-authored MATLAB script that plotted the data, generated the cumulative sound level for each full and partial calendar day, and saved the data in a time series format. Data for the two partial days that fell on the same day of the week were later combined into a single value. A second lab-authored MATLAB script identified noisy time windows that equaled or exceeded 85 dBA and then outputted the window timestamps into an Excel file. EThe activity associated with each noisy time stamp was then manually entered into the Excel file using the journals as reference.

Quality control process

We followed a rigorous protocol to ensure data quality. To be included in the analysis, we required a minimum of 6 calendar days of dosimeter data, which translates to 2304 dosimeter samples per participant. The average number of samples logged was 2681.28 points (SD = 14.67) for the Tinnitus Group and 2642.10 points (SD = 170.50) for the Control group ($t(106) = 1.78$, $p = 0.07$). Due to scheduling and the availability of participants, the interval between session 1 and session 2 was abbreviated for two of the Control participants, contributing to the Tinnitus group having, on average, slightly more points in the dosimeter time series log.

During the weeklong period between sessions, participants were instructed to contact the study team if the green light on the dosimeter stopped blinking, as this was an indication of malfunction. For the ER-200DW8 personal noise dosimeter, the most common form of failure is power disruption when the batteries become unseated. When this happens, the dosimeter log is automatically terminated. To minimize premature termination of the dosimeter log, the dosimeter battery door was taped shut before the participant left the lab.

After the devices were returned, the data logs were reviewed again for evidence of device malfunction and to confirm compliance. We followed a multi-step process: First, we confirmed that the total number of samples logged matched the scheduled wear period and met the 6-day minimum wear time requirement. If it did not, this was an indication of device failure. Device failure occurred for three Tinnitus participants, who opted not to repeat the weeklong protocol; they are not counted in the Tinnitus sample size reported above. Device failure occurred for two Control participants who repeated the protocol. For these two Control participants, only the second run was included in the analysis.

Second, to check for compliance with wearing the dosimeter, we visually inspected the dosimeter plot to identify three elements: (a) the presence of daytime vs. nighttime trends, (b) evidence of extended exposure to a constant noise source (fan), and (c) extended periods when the device was not worn (10 + consecutive hours). The expected trend is an increase from early morning to afternoon and a decrease towards bedtime[15]. In cases where the sound level fluctuations did not match this cyclical pattern or the plot revealed periods where the device might have been near a constant noise source for an extended period (e.g., fan), we consulted the participant and/or journals and were able to resolve that the reported activity data explained the sound level data patterns. In all cases, the constant noise occurred overnight and was consistent with the person sleeping near a fan or air conditioner. No exclusions were made on the basis of (a) and (b). Based on a review of the dosimeter plot and journals, seven participants (3 in the Control group, 4 in the Tinnitus group) were identified as having not worn the dosimeter for an extended period on a single given day. These days were omitted when calculating the average daily sound exposure level and when comparing dB LAeq,8h across days. For the Control, the missing data fell on a Sunday, Monday, and Thursday. For the Tinnitus group, the missing data fell on a Saturday, Sunday, Monday and Wednesday.

Third, if gaps in the journals were identified such that no activity was entered in the journal for any of the noisy windows, the participant was consulted to fill in missing data for the noisy windows.

Fourth, once the full dataset was collected, we reviewed the journals in detail and corrected any coding errors so that the activities were captured by the 17 activity categories described above. Journal data is not available for 5 Tinnitus participants, one because the journal information was undecipherable and the others due to a lack of compliance with completing the journal. These participants were omitted from analyses that are specific to the activity data.

Analysis

Summative measures: Assessing noise risk and calculating daily sound exposure levels. patterns. Personal noise dosimeters can be used to obtain objective data on whether a person is at risk of hearing damage from extended periods of noise exposure[23–27]. For this, we followed NIOSH recommended exposure limit (REL) guidelines that state that exposure should not exceed 85 dBA averaged over an 8-h workday (85 LAeq, 8h)[28]. Levels at or above this are considered risky to hearing. To compare personal sound exposures to the NIOSH REL, sound exposure estimates for each calendar day were normalized to an 8-h day (LAeq,8h) for each participant; that is, we calculated the equivalent continuous sound level for an 8-h period that would contain the same sound energy as the full or partial day. For each participant, the dB LAeq,8h was averaged to create a measure of the average daily sound exposure level for the week the dosimeter was worn. Statistical analysis of the summative measures of sound exposure was conducted using JASP (Version 0.19.2).

Functional data analysis (FDA)

In addition to summative metrics, the dosimeter data was analyzed using functional data analysis (FDA). FDA is a branch of statistics that models continuous functions and thus can potentially reveal time-dependent patterns within noisy and discrete dosimetry data[29]. Unlike traditional approaches to analyzing dosimeter data that analyze single measurements at specific points or summative measures, we adopted FDA methods[29] that analyze discrete dosimeter data through their underlying continuous functions. By modeling each participant's sound exposure as a smooth trajectory, FDA allows for a more detailed examination of when and how the Tinnitus and Control groups diverge in their sound exposure patterns across the week. In this study, we first imputed missing data, then fit mean functional curves separately for the Tinnitus and Control groups. Next, we derived each participant's individual exposure curve by adding the fitted residual curve to the group mean curve. This approach effectively smoothed the raw data. To pinpoint time windows of significant difference between groups, we applied both multiple testing and simultaneous inference approaches, i.e., Pointwise Wilcoxon Tests with false discovery rate control and simultaneous confidence bands[30,31].

A. Data extraction and imputation

As a precursor to statistical modeling, each day of the week was exacted from the dosimeter log and ordered by day of the week from Monday to Sunday, before being concatenated into a single (2688 × N) matrix for each group. In the time series matrix, the first data point began on Monday at midnight (12:00 a.m.), with equally spaced intervals of 3.75-min thereafter. Re-ordering the dosimeter data by day of the week was necessary, as the dosimeter collection did not begin on the same day of the week for all participants. The start time also varied across participants and did not necessarily start at the top of the hour. In generating the times-series matrixes, the actual start time was shifted to align with the closest 3.75 interval. If the first and the last day of the recording occurred on the same day of the week, the two partial days were concatenated. Given that the recording capacity of the dosimeter cannot exceed 2688 points, the time stamps of the two partial days did not overlap. In cases where the participant returned the dosimeter before logging a full 2688 points, the missing time points were coded as NaN (not a number).

For this analysis, measurements below the 70 dBA threshold were adjusted to a single conservative value, 60 dBA, to maintain continuity. The value is midpoint between typical quiet home background levels (≈50 dBA) and the device threshold of 70 dBA. The same constant-value approach was adopted in our earlier work[14]. We also conducted sensitivity checks using 55 dBA and 70 dBA, which yielded identical statistical conclusions (data not shown). After this adjustment, some data remained missing due to instances where the dosimeter was returned before a full run (2688 points). On average, the percentage of missing data was 6.0% for both the Control and Tinnitus groups. The maximum missing percentages was 7.2% for the Control group and 8.3% for the Tinnitus group. To address these temporal gaps, we applied the Seasonally Decomposed Missing Value Imputation method 32 using the imputeTS package (v 3.3) in R[32]. The method involves decomposing the time series into trend, seasonal, and remainder components, followed by linear interpolation to estimate missing values based on the linear relationships in the decomposed components. The assumption of this method is that the remainder component is stationary, which was confirmed by performing the Augmented Dickey-Fuller (ADF) test. All p-values were below 0.01, leading to the rejection of the null hypothesis and confirming the stationarity of the remainder component. Supplemental Fig. S1 shows examples of the imputation *results*, with red lines representing the imputed values and the black line representing the raw series.

B. Fitting mean and functional curves for Control and Tinnitus groups.

Following the imputation method, each participant had a time series length of 2688 points, with no missing values. Using this imputed data, the main patterns of variation were extracted from the time series for each group, using the B-Spline curve fitting method with R packages *splines* and *glmnet*[33,34] . Specifically, the basis construction process identified a set of mathematical functions (polynomials) that can effectively represent a complex curve, such as the dosimeter time series. This is achieved by dividing the time series into smaller intervals defined by knots, which serve as the boundaries of these intervals. A cubic B-Spline (degree 3), widely recognized for its balance between flexibility and smoothness, was selected for the analysis.

To avoid potential overfitting, a penalized linear regression incorporating a ridge regularization term was employed. The optimal values for the number of knots k and the regularization parameter λ were determined by the Bayesian Information Criterion (BIC), which balances goodness of fit with model complexity. Based on the results, the optimal number of knots was determined to be 84, corresponding to one knot every two hours. The fitted mean functions for the Control group and Tinnitus group are shown in Supplemental Fig. S2.

C. Fitting individual sound exposure curves.

To test whether the two groups showed different functional patterns, we derived each participant's individual sound exposure curve. This serves as a denoising (i.e., smoothing) step that aims to remove the random fluctuations from the data and reveal the underlying pattern. (Note that "denoising" in this context does not refer to noise in an acoustic sense or in reference to sounds levels that might damage hearing.) Specifically, each individual exposure curve can be decomposed into two parts, the group mean curve (fitted from the previous step collectively by all participants in each group) and the individual residual curve.

We calculated the residuals by subtracting the fitted group mean curves from the original imputed time series data for each individual. The residual series were then fitted with cubic splines with the same number of knots (84) and with the regularization parameter λ selected by cross validation. For each individual, the smoothed exposure curve was then obtained by adding its fitted residual curve to the fitted group mean curve. Examples of smoothed exposure curves are shown in Supplemental Figure S3.

D. Detecting time windows of significant differences.

To pinpoint time windows of significant difference between the two groups, we applied two complementary approaches: pointwise multiple testing and simultaneous confidence bands. On both the raw data and the smoothed data, point wise comparisons were conducted by performing two-sample Wilcoxon tests between the Control and Tinnitus groups at each time point from Monday 12:00 a.m. to the following Sunday at 11:56:15 p.m. The p-values are adjusted based on the Benjamini–Hochberg procedure to control the false discovery rate (FDR) at 10%. Our study tests multiple correlated hypotheses over time points. In such a context, using the Benjamini–Hochberg procedure with $q = 0.10$ is a common compromise in functional-data and environmental-exposure research because it preserves adequate power for detecting moderate effects[30] and yields an effective (realized) FDR well below 10% when test statistics are positively dependent[32] . Choosing $q = 0.05$ would result in the same qualitative conclusions, though the number of significant intervals would be smaller.

With the smoothed data, we also performed simultaneous confidence band comparisons between the Tinnitus and Control groups by constructing simultaneous confidence bands of the two groups based on David

Degras (2011)[31], with implementation provided by the R package *fregion (v 0.0934, 27 Apr 2017, GitHub hpchoi/fregion)*, developed by Hee Park Choi (2021)[35].

Results

A. Hearing thresholds

The tinnitus group had poorer hearing thresholds (Fig. 1)

As shown in Fig. 1, the Tinnitus Group had higher hearing thresholds on average than the Control Group. The bilateral pure tone average (PTA) for all test frequencies was 12.95 dB HL (SD = 5.65) for the Control group compared to 21.75 dB HL (SD = 10.05) for the Tinnitus Group (U(106) = 625, $p < 0.001$, rbb = -0.56, rbb 95% CI = [0.07 0.47]).

B. Average daily sound exposure as a function of age, PTA, and gender

Before comparing groups with respect to sound exposure, we evaluated how average daily sound levels related to age, bilateral hearing thresholds (PTA), and gender in the full sample of N = 108. We found that PTA increased in an expected way with age (rho = 0.43, $p < 0.001$), but average daily sound levels did not relate to age (rho = -0.004, p = 0.96) or PTA (rho = -0.079, p = 0.42). In this sample, men had an average daily sound exposure of 74.62 dB LAeq,8h compared to 71.76 dB LAeq,8h for women. This did not constitute a statistically significant difference (U(107) = 1631, p = 0.18, rbb = 0.16, rbb 95% CI = [-0.07 0.36]).

C. Average daily sound exposure in Tinnitus vs. Control Groups

Average daily sound exposure was lower for the Tinnitus goup (Fig. 2A, Table 1).

For the Control group, the mean average daily sound level was 75.08 dB LAeq,8h (SD = 9.12, range = 44.62 – 91.82, median = 75.27) compared to 71.34 LAeq,8h (SD = 8.86, range = 51.76 – 95.13, median = 70.97) for the Tinnitus group (U(106) = 1837, p = 0.01, rbb = 0.28, rbb 95% CI = [0.07 0.47]).

The group difference in average daily sound exposure level held even when controlling for hearing thresholds (bilaterial PTA of all test frequencies), age, and gender ($F(1,103) = 4.79$, p = 0.03, $\eta^2 = 0.04$). Thus, the Tinnitus group having lower daily sound levels cannot solely be explained by the group being older and having poorer hearing, or by an effect relating to gender.

D. Risk of noise-induced hearing loss

A small number of participants in each group had average daily exposures > = 85 dB LAeq,8h, but the number was similar across the two groups (4 in the Control group, 5 in the Tinnitus group), and the average daily sound exposure was less than 85 dB LAeq,8h for both groups. As such, as a whole, neither group is considered at a high risk of noise-induced hearing loss**.**

E. Tinnitus group analysis: Tinnitus Handicap Inventory

In the Tinnitus sample, the THI scores ranged from 0 to 72, with a mean of 27.36. The mean value falls within the Mild handicap range. The THI score distribution was *N* = 20, 22, 12, and 3 for Slight, Mild, Moderate, and Severe tinnitus handicap, respectively.

There was a negative correlation between THI score and the average daily sound exposure level (rho = -0.31, p = 0.02), where higher self-perceived handicaps were associated with lower sound levels (Fig. 2D). A regression model indicated that 8.1% of the variance in daily sound levels was explained by the THI score ($R^2 = 0.08$, Adjusted $R^2 = 0.06$, $F(1, 56) = 4.82$, p = 0.03). Adding gender, hearing thresholds (PTA), and age increased the explanatory power to 12% but did not yield a statistically significant model ($R^2 = 0.12$, Adjusted $R^2 = 0.05$, $F(4, 56) = 0.18$, p = 0.51), and only THI was a significant predictor within the model (THI standardized $\beta = -0.31$, t = -2.19,

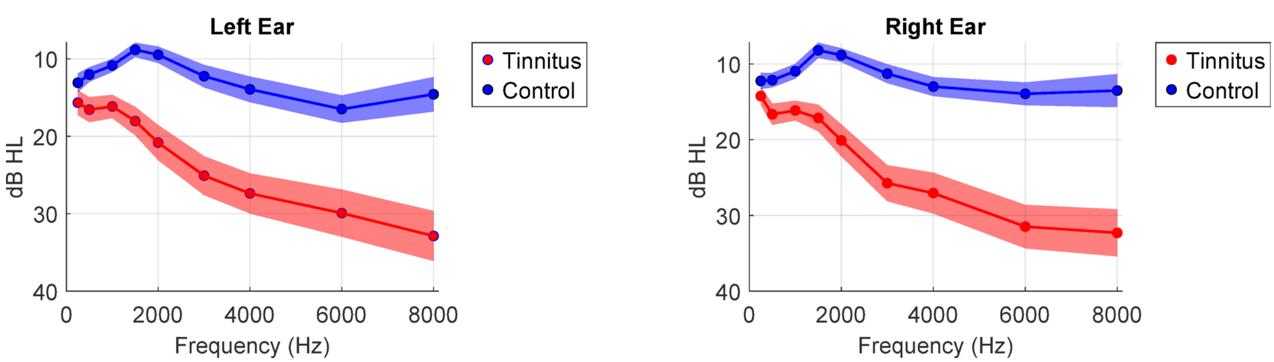

Fig. 1. Audiogram for the Tinnitus (red) and Control (blue) groups. Shading represents + /- 1 standard error of the group mean.

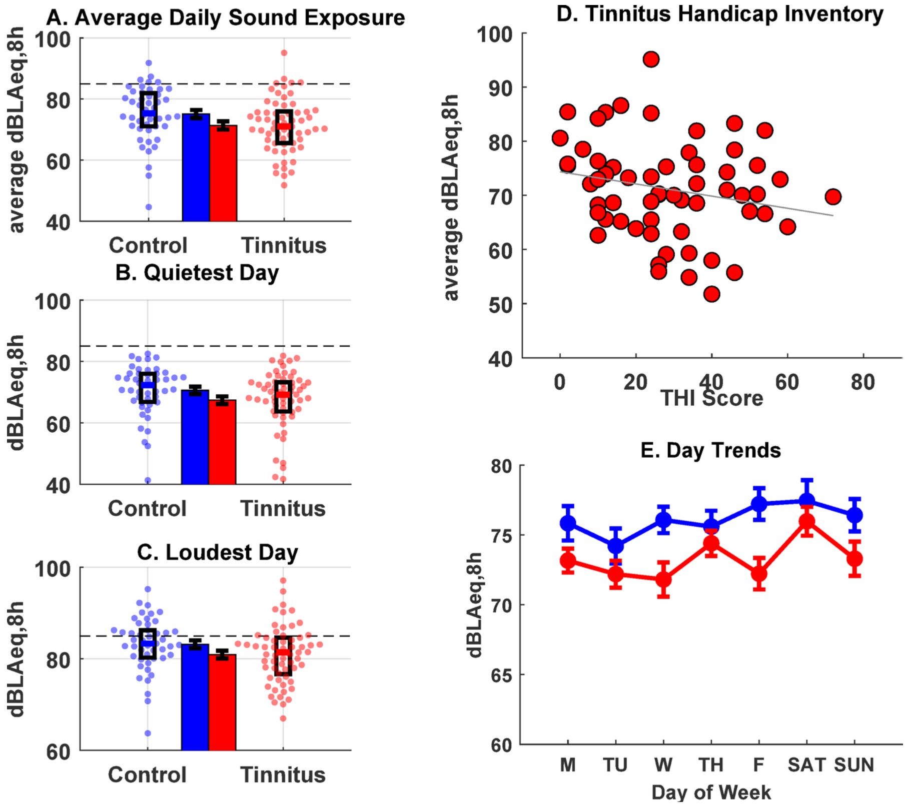

Fig. 2. The Tinnitus group had quieter daily environments. **(a)** The Tinnitus group (red) had lower mean daily average sound levels than the Control group (blue) when averaging across days of the week. The Tinnitus group also had lower sound levels for **(b)** the quietest and **(c)** loudest days of the week. For Panels a-c, a horizontal dashed line is plotted at 85 dBA to denote the National Institute for Occupational Safety and Health (NIOSH) recommended exposure limit (REL) of 85 dBA for 8 h. In each panel, bar graphs show the group mean, with error bars indicating one standard error of the mean. Bar graphs are flanked by the individual data plots arranged in a beeswarm plot[36] with a box showing the median and interquartile range for each group. **(d)** Among participants with tinnitus, greater tinnitus handicap was associated with lower daily sound levels (rho = -0.31, p = 0.02). **(e)** Daily sound levels for each day of the week were generally lower for the Tinnitus (red) compared to the Control (blue) groups.

	Group	N	Mean	SD	SE	p-value
Average Daily Sound Exposure (LAeq,8h)	Control	47	75.08	9.12	1.33	*p = 0.01*
	Tinnitus	61	71.35	8.86	1.14	
Quietest day (LAeq,8h)	Control	47	70.6	8.29	1.21	*p = 0.03*
	Tinnitus	61	67.39	9.88	1.27	
Loudest day (LAeq,8 h)	Control	47	83.18	5.84	0.85	*p = 0.06*
	Tinnitus	61	80.93	6.23	0.8	
Number of days > NIOSH REL	Control	47	0.96	1.29	0.19	*p = 0.01*
	Tinnitus	61	0.39	0.74	0.09	

Table 1. Group statistics for summative measures of personal sound exposure. *NIOSH REL* refers to the recommended exposure limit of 85 dBA over 8 h set by the National Institute for Occupational Health (SD = standard deviation, SE = standard error).

p = 0.03, 95% CI = [-0.28 -0.02]; age β = -0.12, t = -0.81, p = 0.42, 95% CI = [-0.21 0.09; PTA standardized β = 0.22, t = 1.5, p = 0.14, 95% CI = [-0.06 0.41]; Gender unstandardized β = -0.58, t = -0.26, p = 0.79, 95% CI = [-5.10 3.92]).

F. Group differences in daily sound exposure: Day of the week

Our recent studies[14,15] suggest that daily sound exposure varies in a meaningful way across different days of the week, prompting us to analyze the data according to the day of the week (Monday-Sunday). A linear mixed effects model, using ID as a Random effect grouping factor, showed a significant main effect of Group ($F(2,181.31) = 2952.55$, $p < 0.001$) and main effect of Day ($F(6,631.61) = 2.51$, $p = 0.02$), but no interaction between Day and Group ($F(6,631.61) = 1.11$, $p = 0.35$). The model fit statistics were 5517.87 and 5591.82 for the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC), respectively). While daily sound levels fluctuated across the week, the group differences were not day dependent, and the dominant trend was for the Tinnitus group to have lower daily sounds. That said on a qualitative basis, the day difference between groups was reduced on Tuesday, Thursday, and Saturday. For both groups, Tuesday and Thursday were the most common days for the dosimeter protocol to start and stop.

G. Quietest and loudest days

Tinnitus group had quieter loud days (Table 1, Fig. 2B and C). For each participant, we found the "quietest" and "loudest" day by calculating the minimum and maximum LAeq,8h during the week for each participant, using only days where a full 24-h recording was made. The "loudest" day was "quieter" for the Tinnitus group compared to the Control group ($U(106) = 1796$, $p = 0.03$, rank biserial correlation (rbb) = 0.25, rbb 95% CI = 0.04–0.45). The Tinnitus group also had fewer days that exceeded the NIOSH recommended daily exposure limit compared to the Control group $U(106) = 1786$, $p = 0.01$, rbb = 0.25, rbb 95% CI = 0.04–0.45). For the "quietest" day, the Tinnitus group had a lower LAeq,8h compared to the "quietest" day for the Control group, although the p-value is marginally non-significant. ($U(106) = 1736$, $p = 0.06$, rbb = 0.21, rbb 95% CI = 0.01–0.41).

Consistent with having quieter environments across the week, the Tinnitus group had fewer points ≥ 85 dBA than the Control group ($U(106) = 1798.50$, $p = 0.02$, rbb = 0.26, rbb 95% CI = [0.04 45]). On average, the Tinnitus group spent 138.32 min (2.3 h) in noisy environments during the week compared to 249.90 min (4.2 h) for the Control group. The ranges, however, were similar for the two groups (0–813.75, 0–858.75 min for the Tinnitus and Control groups, respectively).

H. Activity data

Tinnitus group spent less time engaged in noisy activities (Fig. 3).

To better understand the noise patterns of the two groups, we analyzed the journals collected during the week of noise dosimetry focusing first on noisy periods. This analysis included only the participants for whom journal data were available. From the journals, we coded noisy periods (≥ 85 dBA) during the week into different activity categories. Figure 3 (left panel) shows the total hours that each group in aggregate spent in noisy environments, color coded by the activity type. As a group, the Tinnitus group spent less time in noisy environments, with the greatest differences seen for Job, Home, and Social activities. These activity categories are plotted in yellow, dark blue, and red, respectively in Fig. 3. As a group, the Tinnitus group spent a total of 5.88 h in noisy job environments, 26.50 total hours in noisy home environments, and 42.13 total hours in noisy social environments, compared to 20.94, 51.43, and 52.37 total noisy hours for the Control group for these categories, respectively. Note that these summative tallies do not take into consideration that the Tinnitus group is larger (N = 56 activity logs) compared to the control group (N = 46).

On average, the Tinnitus group spent 0.10 h in noisy job environments, 0.47 h in noisy home environments, and 0.75 h in noisy Social activities, compared to 0.45, 1.10, and 1.11 for hours for Job, Social, and Home, respectively, for the Control group. Of these noisy categories, only the Home environment was statistically

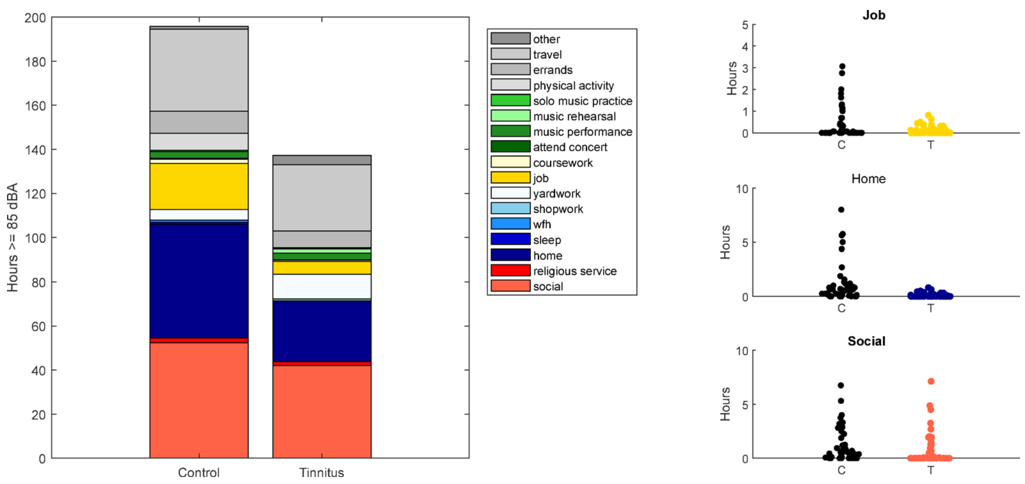

Fig. 3. (Left) The Tinnitus group spent less total time (in hours) in noisy environments (> 85 dBA). Time is categorized according to activity and summed across each group. Note that these summative tallies do not account for the Tinnitus group being larger (N = 56 activity logs) compared to the Control group (N = 46). (Right) Swarm plots for the Job, Home, and Social environments illustrate the data range and distribution for the Control (C, black) and Tinnitus (T) groups. For the Tinnitus group, the data are color coded, using the activity color codes in the left panel.

	Group	N	Mean (hours)	SD	SE	U	p-value	Rank-Biserial Correlation	SE Rank-Biserial Correlation
Job	Control	47	0.44	0.75	0.11	1057.5	*p* = 0.06	− 0.2	0.11
	Tinnitus	56	0.11	0.18	0.02				
Home	Control	47	1.09	1.77	0.26	1001	*p* = 0.03	− 0.24	0.11
	Tinnitus	56	0.47	0.79	0.11				
Social	Control	47	1.11	1.57	0.23	1052.5	*p* = 0.07	− 0.2	0.11
	Tinnitus	56	0.75	1.4	0.19				

Table 2. Group comparisons for noisy (>= 85 dBA) periods for Job, Home, and Social environments (SD = standard deviation, SE = standard error, U = Mann-Whitney U).

	Job		Home		Social	
	Control	Tinnitus	Control	Tinnitus	Control	Tinnitus
Valid	47	56	47	56	47	56
Missing	0	5	0	5	0	5
Median (hours)	29.25	23.72	51.19	53.81	6.25	4.16
Mean (hours)	28.88	20.91	57.66	55.19	8.52	7.57
Std. Deviation	27.84	16.82	33.79	22.42	7.3	9.53
Minimum	0	0	0	5.5	0	0
Maximum	159.44	61.5	197.25	101.69	30.18	39.75
Mann–Whitney	*U = 1491, p = 0.25*		*U = 1264, p = 0.74*		*U = 1539, p = 0.41*	
Rank biserial correlation (rbb)	*0.13*		*-0.039*		*0.17*	
Rbb 95% CI	*[-0.09 0.34]*		*[-0.26 0.18]*		*[-0.05 0.38]*	

Table 3. Group comparisons for total overall time in Job, Home, and Social environments (regardless of sound level).

different between groups (see Table 2 for statistics). Swarm plots show the data distribution of the noisy hours for these three activity categories in the right-hand panels of Fig. 3. For the Social category, the range is similar between the two groups, but there are more Tinnitus group participants with 0 h of noisy social time.

Although the Tinnitus group spent less time in noisy Job, Home, and Social environments, this is not an artifact of the Tinnitus group spending less time overall in these environments. Across the board, the groups spent the *same* amount of time in these environments (regardless of sound level). See Table 3 for statistics. Note, however, that for all three categories, the range is large for both groups. One of the Control group participants had "zero" Hours. This is because they worked from home and these work from home hours were counted in the "Job" tally. For this participant, any time when they were at home and awake, they reported they were working. For the Job category, four of the Control group participants did not log any hours, compared to 12 of the Tinnitus group participants. For the Social category, five of the Control group participants did not log any Social hours, compared to 11 of the Tinnitus group participants.

I. Time series patterns via FDA

Next, we examined the time series data using FDA. Figure 4 shows the results from pointwise comparisons with either raw or smoothed (i.e., denoised) time series data for the two groups. Short black segments on the x-axis indicate time points where the Wilcoxon test shows significant differences (p-value, < 0.1) between the Control and Tinnitus groups. The highlighted yellow segments indicate time points that remain significant after correcting for multiple comparisons[30]. Before applying this correction, the significant differences in the raw data appear scattered and irregular. In contrast, even before the correction, the smoothed data exhibited more coherent patterns of significant differences, with time intervals concentrated around midday and evening each day. After applying the correction, the smoothed data revealed a higher number of significant group differences compared to the raw data, highlighted by the yellow segments. These differences are especially notable Monday noon, Wednesday evening, Friday evening, and Sunday noon and evening. Although the difference on Saturday is also apparent from the two fitted mean curves, it was not significant, potentially due to large variations among the participants. The results from the raw and smoothed data are consistent, but the smoothing process enhances the clarity of the patterns and distinctions between the groups. For conciseness, all subsequent findings in this section are specifically derived from analyses utilizing smoothed data.

Figure 5 presents the 95% simultaneous confidence band for the smoothed data. While the estimated mean functions for the Control and Tinnitus groups displayed clear differences, the confidence bands overlapped across time. To reveal the times of day with maximal group differences, we also present the simultaneous confidence band of the group difference in the bottom panel of Fig. 5. The findings closely align with the pointwise comparison results presented in Fig. 4, especially group differences that arise on Monday, Friday, and Sunday. Additionally, a further significant difference appears on Tuesday evenings. The simultaneous confidence

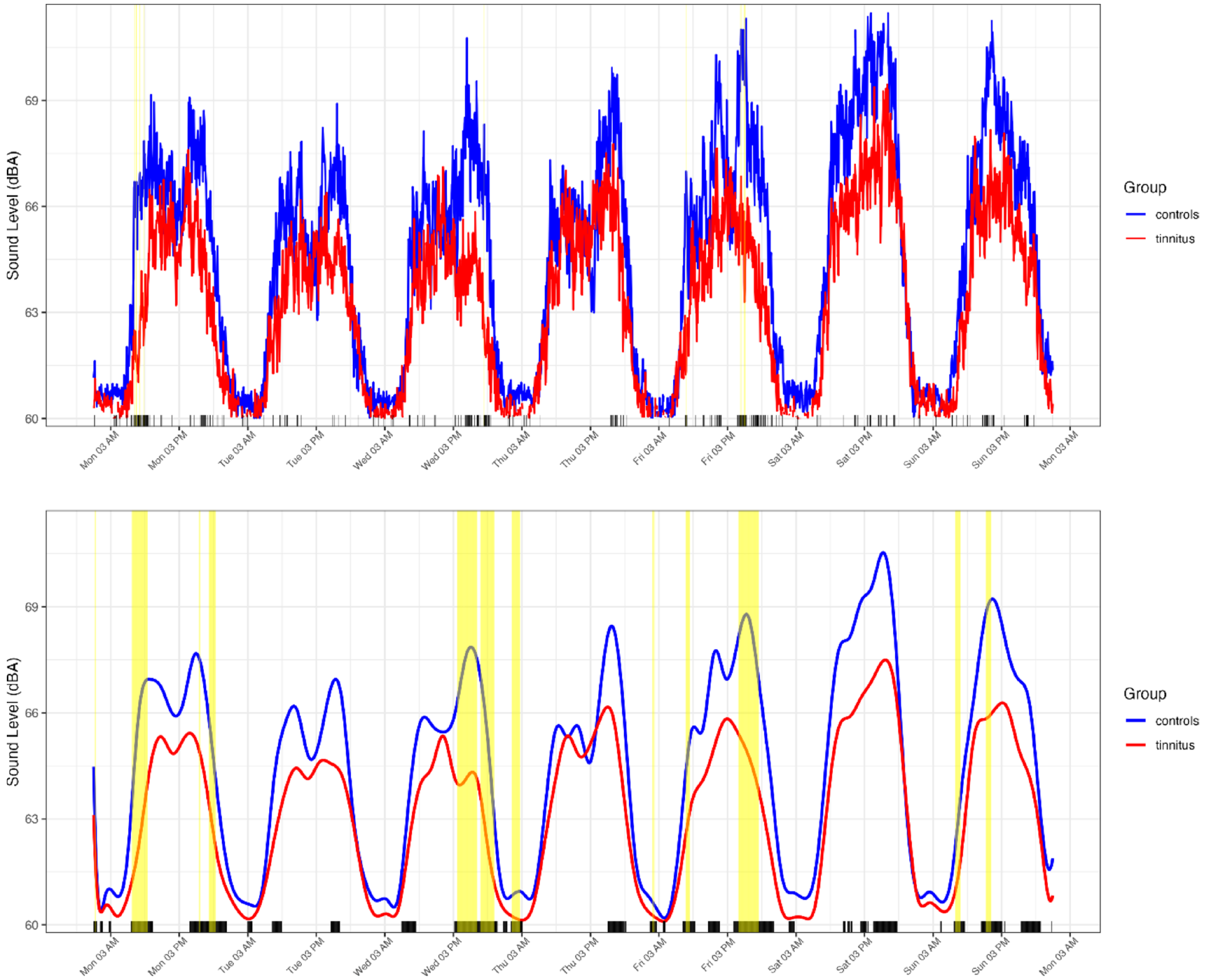

Fig. 4. Time series data for the Control (blue) and Tinnitus (red) groups Pointwise Wilcoxon tests for the raw data (top, A) and smoothed data (bottom, B). Black segments indicate significant differences from the Wilcoxon test, while the yellow segments denote significant differences after correcting for multiple comparisons. [Refer to Methods sections B and C under "Functional Data Analysis" for a description of how the data were smoothed"].

band comparison method verifies the temporal locations of differences between the Control and Tinnitus groups identified by the pointwise comparison.

As a supplement to FDA, Fig. 6. shows the proportion of time each group spent on average, in Job, Home, Social or Other activities during midday (12–2 pm) and evening (6–8 pm) hours. During the midday hours, the Control group was more likely to be working compared to the Tinnitus group ($p < 0.001$, Mann–Whitney U test for all days). By contrast, the Tinnitus group was more likely to be engaged in other activities, especially during the weekdays ($p < 0.001$, Mann–Whitney U Test). In the graph, Other refers to activities not captured by the Job, Home, and Social categories. During the evening hours, the groups were similar with respect to how they occupied their time. Correcting for multiple comparisons, none of the comparisons were different.

Discussion

Summary of findings

We studied the auditory environments of people with and without self-reported tinnitus, using a personal noise dosimeter that participants wore for one week during all waking activities. Our analysis, using both conventional summative metrics and novel time-series approaches to analyze dosimeter data, converged in showing that the Tinnitus group had quieter environments than the Control group. This finding, which persisted even when controlling for group differences in gender, age, and hearing thresholds, is striking given the large extent to which the literature links tinnitus to noise exposure.

In addition to having quieter environments, the Tinnitus group had on average, poorer hearing thresholds than the Control group, consistent with an etiology of noise-induced hearing loss (NIHL). Within the Tinnitus group, we also found that the higher the self-reported tinnitus handicap, as measured by the Tinnitus Handicap

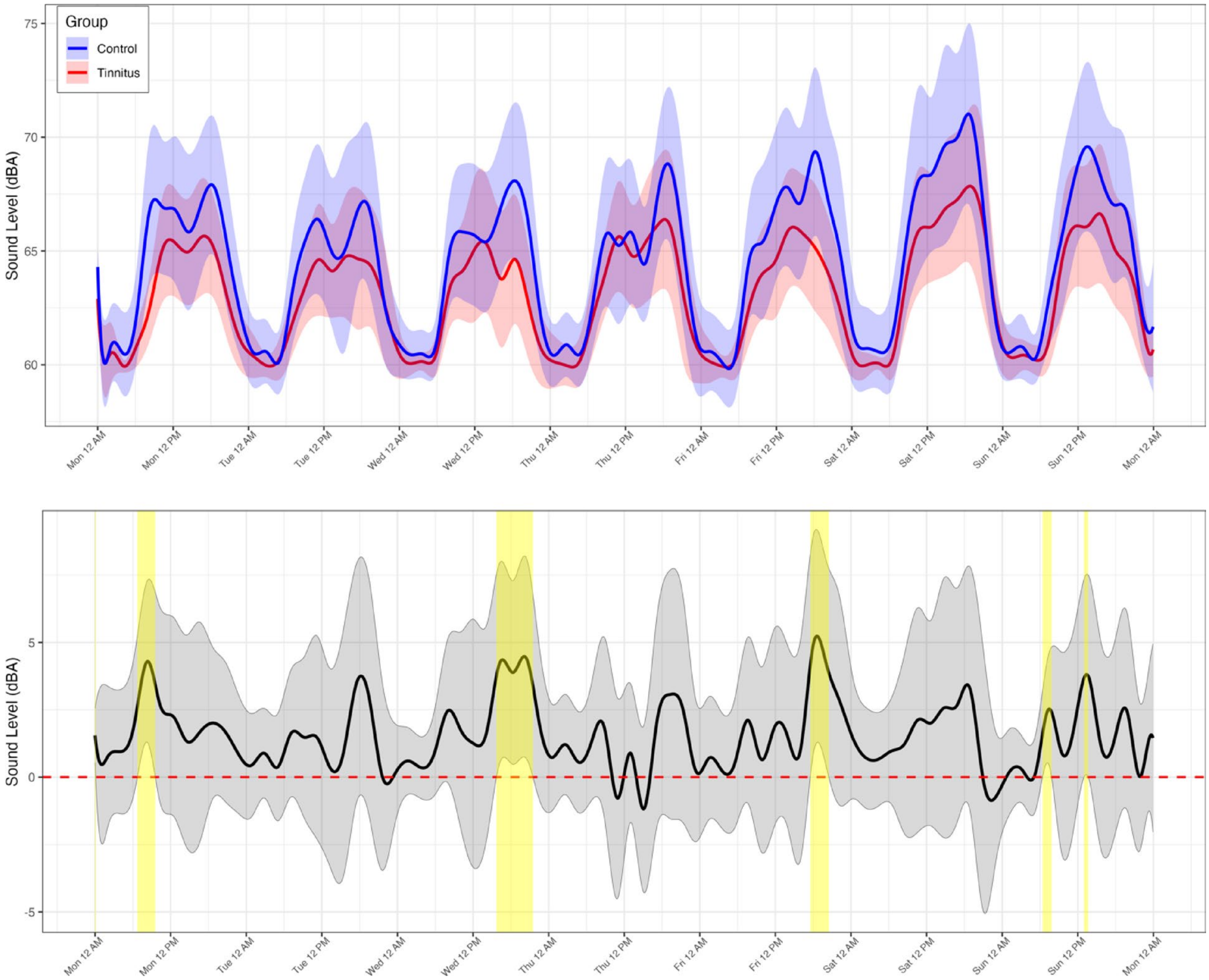

Fig. 5. (Top) 95% Simultaneous confidence bands (shading) for the smoothed (denoised) fitted curves for the Control (blue) and Tinnitus (red) groups. (Bottom) Difference (black lines) between the Control and Tinnitus smoothed fitted curves, with shading denoting the 95% confidence interval of the difference. Yellow segments denote significant differences. [Refer to the Methods for a description of Simultaneous confidence bands].

Inventory (THI), the lower the daily personal sound exposure, suggesting that lifestyle differences may scale as a function of tinnitus burden.

If tinnitus were a consequence of NIHL, it seems that the noisy activities that contributed to the hearing loss have since ceased or were too infrequent to be detected by one week of dosimetry. For both groups, average daily sound levels fell below 85 dB LAeq,8h, indicating that neither group was at high risk of noise-induced hearing loss based on the week of dosimetry data. Indeed the averages were well below the NIOSH recommended exposure limit (REL) of 85 dB LAeq,8h: the mean (and median) daily sound level for the Control group was ~ 75 dB LAeq,8h compared to ~ 71 dB LAeq,8h for the Tinnitus group. While a small number of participants did exceed the NIOSH recommended daily noise exposure limit, the number of participants above this limit was similar across the two groups. But, when we tallied the total time participants spent in noisy environments (≥ 85 dBA) during the week, we found that the Tinnitus group spent less time in noisy environments, with the most prominent group differences noted for social, home, and job-related environments. Critically, this difference was not due to the Tinnitus group spending less time overall in these environments.

We found that the differences in average sound exposure between the Tinnitus and Control groups were generally consistent across days (Fig. 2E) with the time series analysis (FDA) showing that differences were intensified at certain times of the day (midday and evenings) (Fig. 4 and 5). Group differences in sound levels were particularly apparent for Monday midday, Wednesday evenings, Friday evenings, and Sunday midday (12–2 pm) and early evenings (6–8 pm). These findings suggest that group differences are predictable and regularized. Group differences could reflect contrasts in lifestyle relating to when, how, and where an individual chose to spend their time, and the level of control they have over their surroundings. While the two groups did not differ overall in terms of how much time they worked across the week, the Tinnitus group was less likely to be working in the early afternoon (Fig. 6), suggesting that work schedules could influence differences in personal sound exposure during midday hours. For the early evening hours (6–8 pm), the groups did not differ in the

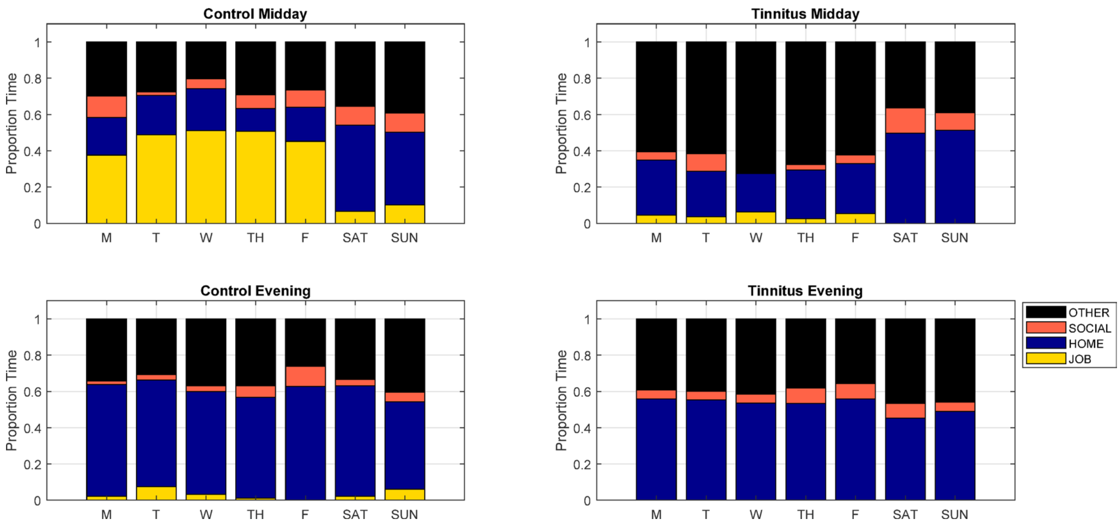

Fig. 6. Proportion of time spent in Work (yellow), Home (blue), Social (red) and Other environments (black) for midday (12–2 pm, top) and evening hours (6–8 pm, bottom) for the Control (right) and Tinnitus groups (left). In this graph, Other refers to activities not captured by the Work, Home or Social Labels.

proportion of time they spent engaged in work, social, or other activities. , suggesting Differences in personal sound exposure during the early evening hours may potentially not be due to broad differences in how the groups apportion their time, but in the specific types of activities they did at home, while socializing, or during the other activities they participated in.

Interpretations

One possible interpretation of our results is that people are isolating themselves because of their tinnitus, leading them to lead quieter lives and have quieter environments. Higher tinnitus handicap being associated with quieter environments in this dataset supports this interpretation. Confounding this interpretation, is that hearing loss has also been linked to social isolation[37–39]. However, within this dataset, the association between hearing thresholds and average daily sound levels was not significant and group differences in average daily sound exposures held when accounting for the effects of age, hearing, and gender. Thus, we contend that tinnitus, not hearing loss, age, or gender, is the dominant factor underlying the group differences in environmental sound level observed here.

To support the conclusion that people with tinnitus lead quieter lives, we compared our results to a large-scale (N = 286) study of typical noise levels in daily life in Michigan . This study, published a decade ago[24], used same personal noise dosimeter model as the current study. They reported daily median sound levels 3–4 dB higher than the median levels observed for our Control group. Differences between studies could be due to a variety of factors, including geographic variations, the influence of the COVID-19 pandemic on lifestyle, and also increased use of personal listening devices over the last decade. By comparison, in a study of 100 adults in Germany using a different noise dosimeter, the mean personal sound exposure level was 75.1 dB LAeq during daytime hours[40]. Although there were methodological differences between studies, the mean value is ostensibly close to what we observed for the Control group. Comparisons to these other datasets reinforce the conclusion that the Tinnitus group does not have a typical pattern of daily sound levels.

Limitations

Although there are clear advantages to using personal noise dosimeters over self-report, the methodology has inherent limitations. The chief limitation is that the devices do not detect sounds delivered directly to the ear via headphones or other personal listening devices, including hearing aids. Therefore, while our results suggest that people with tinnitus have quieter lives, this conclusion is specific to environmental data—it pertains to a person's surroundings and not the sounds they elect to listen to through a personal listening device. Data on hearing aid use in the Tinnitus dataset was not collected. Although some participants noted when they wore headphones in the journals, we also cannot specifically account for whether the Tinnitus group used headphones to mask their tinnitus. People with tinnitus often use masking noise to drown out their tinnitus. Indeed, noise masking is a feature of many modern hearing aids and is an attractive feature to people with tinnitus[41–43]. The absence of hearing aid and headphone data is a major constraint on our interpretation that people with tinnitus lead quieter lives. The conclusion that tinnitus is the result of noise exposure and that noise exposure patterns have changed since tinnitus onset is also speculative, as lifetime noise exposure data is not available for this dataset.

Another limitation is that the personal dosimeters used in this study record environmental sound levels even when not actively worn. To overcome this limitation, participants were instructed to wear the device during all waking hours. While we made concerted effort to encourage compliance and vet the quality of the data, we can only infer, and not confirm, when the device was worn.

The dosimeters used in this study are designed to measure personal exposure to sound levels that are risky to hearing health. As such, the device measurement settings are biased toward higher-intensity sounds, introducing gaps in the measurement log for low-intensity sounds that fall below the device threshold. An analogy can be drawn to measuring the dimensions of an iceberg, where only the highest part is visible above water and the shape and size below the water can only be inferred. In brief, the dosimeter is configured to calculate the total energy within a 3.75-min window, using fine temporal measurements during the window. Measurements that fall below the threshold (< 70 dBA) in the 3.75-min window are treated as zero in calculating the total energy. For example, if a sound source fluctuated between 69 and 71 dBA, the value stored by the dosimeter would be greater than 0, as the points below 70 dBA would be treated as zeros, but the values above 70 dBA would be treated as their nominal value when calculating the total energy. However, if the source was a constant 69 dBA, the dosimeter would not be sensitive to it, because it falls below the threshold of 70 dBA, and the value would be coded as zero, introducing a measurement gap in the dosimeter datal log. In data sample, the zeroed data were concentrated around midnight each day (Supplemental Fig. S4) and likely coincide with times when the person was in bed and the device was nearby but not directly attached to the participant. The actual sound levels during these times are unknown, creating a statistical complication, which we addressed in the functional data analysis (FDA) by preprocessing the data to replace values below the 70 dBA threshold (zeros in the log) with value of 60 dBA.

For the functional data analysis, we used B-spline curves to compare group-level differences over time. The fitted curves contained 84 knots, with each knot representing a 2-h interval. Eighty-four knots were found to produce better fit statistics than other tested values (21, 42, 168, 336 knots), using smaller and larger temporal intervals. An assumption and potential limitation of this approach is that the knots are equally spaced. That is, we assume that a person's day is meaningfully divided into 2-h intervals. Given that schedules are often highly regularized and structured to start at the top of the hour, dividing the week into hours is intuitive. Using a two rather than one-hour bin may have allowed us to capture differences between groups, while also accounting for individual differences when people wake, start and stop work, and go to sleep.

In addition to limitations imposed by the dosimeter and our analysis pipeline, the characteristics of the tinnitus group also influence interpretations. We found that 8.3% of the variance in personal sound exposure could be explained by THI. While statistically significant, this is modest in practical terms and could be due to having a limited THI range with most of the tinnitus sample falling in the mild or lower range. Only three participants had severe handicap and none had catastrophic handicap. The weak association between THI and personal sound exposure may be a consequence of this sampling bias. The weak relationship may also reflect limitations of the THI in evaluating the severity of the THI. Other surveys, like the Tinnitus Functional Inventory (TFI) with purportedly greater sensitivity[44] may have produced a stronger association. University newsletters and University clinical registries may also have introduced bias toward more health-conscious or tinnitus-aware individuals. This self-selection bias, together with the THI sampling bias, may limit the generalizability of our findings, underscoring the importance of replication in other demographics.

A limitation of the Tinnitus Handicap Inventory, and other tools like it, is that it captures a person's psychological and emotional response to tinnitus but has limited utility in capturing perceptual variability of tinnitus within affected individuals[45] or assessing audiological status. Two people could have the same tinnitus loudness and in theory the same audiological status, but because of psychological and psychiatric differences, experience different levels of handicap and distress from tinnitus. Psychiatric conditions, such as anxiety and depression, are known to correlate with tinnitus severity[11,46], and could influence both self-reported handicap and behavioral avoidance patterns. History of psychiatric disorders was not gathered as part of this study. Future studies should seek to differentiate psychological and audiological contributors to tinnitus handicap by including validated screening tools (e.g., PHQ-9[47], GAD-7[48], BDAI[49], BDI[50]).

In addition to noise, other lifestyle factors can contribute to the severity of tinnitus that we did not directly measure here. Dietary factors such as caffeine, alcohol, and salt intake have been shown to influence tinnitus severity in a subset of tinnitus patients[51]. In tinnitus patients, reduction of caffeine intake in a subset who consumed low to moderate amounts of coffee yielded a favorable outcome in tinnitus severity[52]. Short sleep duration, late chronotypes, and sleeplessness all correlate with the severity of tinnitus[53]. People with tinnitus also may recognize the impact of dietary, sleep, and noise factors on their tinnitus and moderate their daily exposure to keep tinnitus in the tolerable range[54,55]. While some participants diligently coded their sleep hours in the journals, others did not and left overnight time blank. Due to this variability, total sleep hours for the week were not analyzed.

The logistical realities of collecting a large dataset necessitated data be collected at two test sites, with most of the Tinnitus dataset being collected at one site. To limit variability between sites, the audiometric testing environments were standardized, the same model of personal noise dosimeters was used, and one of the testers was common across sites. While the dosimeter data collection protocol was identical across sites, the journaling format was different (paper vs. electronic) and this procedural variation could have introduced some uncontrolled variability in the activities reported and affect journal compliance. Although the total hours spent in home, work, and social environments were not statistically different on the group level, the journal data did suggest differences in work schedules (Fig. 6). It also indicated differences in employment status, with proportionally more of the Tinnitus group not working. Generally speaking, the participants who did not work during the week were either of retirement age or college student age. But we are cautious about drawing strong conclusions about work status from the journals alone. While our use of broad activity categories provides a general overview of the week, it limits the depth and nuance of the analysis.

Finally, we also cannot fully rule out differences in test sites. We note that the Control data was collected as part of larger study on auditory system aging that included surveys and metrics, such as occupation data and hearing aid use, not collected at the other test site where a shortened test protocol was used to facilitate recruitment of the Tinnitus group. We acknowledge this as a potential limitation to address in future work. Potential statistical methods to address test site differences include functional mixed-effects models, which adjust the effects of "site" within a functional regression framework and permits a global variance-component test of its influence. Future work should also focus on matching groups more closely with respect to age and hearing loss, with a greater number of control participants with elevated hearing thresholds.

Implications and Hypotheses for future research

The causes and consequences of having a quieter environment are worth considering. Being in quieter environments often makes tinnitus more noticeable and, in turn, more troubling to the person[56]. We speculate that the causal relationship may also be bidirectional, such that the cause may also be an effect. That is, greater handicap may lead to spending more time in quieter environments, which in turn may escalate tinnitus-related symptoms. We also note that the daily environments of the Tinnitus group were quieter than the Control group, but not whisper quiet. This may suggest a goldilocks effect where people with tinnitus prefer sound volumes that are neither too high nor too low. This preference level may reflect a listener's "mixing point," the level where an external sound and tinnitus begin to blend, and the tinnitus becomes less noticeable but is not totally masked[57]. Testing this possibility could yield insight into environmental conditions needed to appropriately manage tinnitus handicap and the underlying audiological condition.

If it is the case that people with tinnitus have quieter lives, what might trigger this lifestyle difference? One hypothesis is that people with tinnitus may be more aware of the risks of noise exposure and limit noisy activities to protect their hearing and reduce the impact of noise on tinnitus severity[54]. Depending on their socioeconomic and sociopolitical circumstances, people may be able to select housing, occupations, and social activities that match their cultural[58,59] and personal sensory performances (sound, temperature, lighting)[60–62]. Others may not have this luxury, or at least not for the entirety of the day. We interpret the results of the FDA, and the fact that differences are most pronounced around noon and in the evenings, as potentially suggesting that the group differences are maximal during times when people are likely to have more choice over their environment. This is speculative, as we did not solicit information about how much agency participants had in their environment.

Sound avoidance could also be a consequence of hyperacusis[54]. Tinnitus and hyperacusis are highly co-morbid and may even have common biological roots; both are theorized to arise from a dysregulation of central auditory system mechanisms following damage to the inner ear[63,64]. The damage caused by noise exposure reduces peripheral input to the central auditory system. Depending on the nature and extent of this damage, it may go undetected on routine hearing screenings. While the mechanisms are still under investigation, a prevailing theory is that tinnitus and hyperacusis arise as part of a compensatory process to correct this loss of input[63,65], with both being the byproduct of central gain mechanism overamplifying sound. Even if the level of biological amplification is not sufficient to produce hyperacusis, excessive amplification could lead to low intensity sounds perceived as louder to people with tinnitus, which could, in turn, influence their personal sound exposure patterns. The causal influence of central gain on auditory behaviors is an under-investigated topic. Previous work found an association between low tolerance for background noise and decreased time spent in environments with background noise in young adults with normal hearing[66]. It stands to reason that similar principles could operate for those with tinnitus. However, we did not specifically ask people with tinnitus whether they experienced hyperacusis or other forms of sound intolerances, and we also did not measure central gain or psychoacoustic measurements of loudness. As such, the connection between our data, hyperacusis, perception, and behaviors is only notional but it forms the basis of future work.

Clinical implications

Current clinical recommendations regarding the management of tinnitus in adults are centered around stress reduction strategies and avoidance of stimulants that exacerbate tinnitus intensity and related anxiety. In clinical settings, tinnitus management also includes technology, including the use of external tinnitus masking systems or combination amplification and masking devices. However, clinical masking systems are not individualized to the patient beyond the selection of type of masking stimulus and relative masker intensity. A deeper understanding of the sound exposure patterns of people with tinnitus may improve clinical management of the condition. Specifically, a better understanding of sound exposure patterns in people with tinnitus may aid in the development of clinical masking paradigms that are tailored to the individual, allowing the masker to be effective in reducing tinnitus-related stress but without exacerbating the tinnitus percept in the absence of the masker. Furthermore, clinicians' counseling on specific environmental modification strategies may be improved with a better understanding of sound exposure patterns in individuals with tinnitus.

The methodology we employed in this study has potential clinical applications beyond tinnitus. Greater understanding of the auditory environment and preferential listening conditions of disordered populations, such as those with tinnitus and with sensorineural hearing loss, will help advance the dynamic soundscape processing algorithms used in modern hearing aid and cochlear implant technology to improve outcomes. Beyond disordered populations, understanding sound exposure patterns in adults may help elucidate existing risks of noise exposure beyond the auditory system, including cardiovascular health, mental and emotional health, and cognition.

Conclusion

We found that people with tinnitus have lower daily sound levels compared to a Control group. Differences between groups may be explained by greater awareness of the dangers of noise exposure in the tinnitus group, influence of noise on the severity of tinnitus or potentially decreased tolerance of sound (hyperacusis) due to a compensatory increase in central gain arising from tinnitus-related changes in auditory physiology.

Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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References

1. Jarach, C. M. et al. Global prevalence and incidence of Tinnitus: A systematic review and meta-analysis. *JAMA Neurol* **79**, 888 (2022).
2. Schmidt, J. H., Paarup, H. M. & Bælum, J. Tinnitus severity is related to the sound exposure of symphony orchestra musicians independently of hearing impairment. *Ear Hear* **40**, 88–97 (2019).
3. Shehabi, A. M., Prendergast, G., Guest, H. & Plack, C. J. Noise exposure in palestinian workers without a diagnosis of hearing impairment: relations to speech-perception-in-noise difficulties, Tinnitus, and hyperacusis. *J. Speech Lang. Hear. Res.* **66**, 1085–1109 (2023).
4. Williams, W. & Carter, L. Tinnitus and leisure noise. *Int. J. Audiol.* **56**, 219–225 (2017).
5. Jafari, Z. et al. Tinnitus, sound intolerance, and mental health: the role of long-term occupational noise exposure. *Eur. Arch. Otorhinolaryngol.* **279**, 5161–5170 (2022).
6. Guest, H., Munro, K. J., Prendergast, G., Howe, S. & Plack, C. J. Tinnitus with a normal audiogram: Relation to noise exposure but no evidence for cochlear synaptopathy. *Hear. Res.* **344**, 265–274 (2017).
7. Moore, D. R., Zobay, O., Mackinnon, R. C., Whitmer, W. M. & Akeroyd, M. A. Lifetime leisure music exposure associated with increased frequency of tinnitus. *Hear. Res.* **347**, 18–27 (2017).
8. Valderrama, J. T. et al. Effects of lifetime noise exposure on the middle-age human auditory brainstem response, tinnitus and speech-in-noise intelligibility. *Hear. Res.* **365**, 36–48 (2018).
9. Ralli, M. et al. Work-related noise exposure in a cohort of patients with chronic Tinnitus: Analysis of demographic and audiological characteristics. *Int. J. Environ. Res. Public Health* **14**, 1035 (2017).
10. Turner, J., Larsen, D., Hughes, L., Moechars, D. & Shore, S. Time course of tinnitus development following noise exposure in mice. *J. Neurosci. Res.* **90**, 1480–1488 (2012).
11. McCormack, A. et al. Investigating the association between tinnitus severity and symptoms of depression and anxiety, while controlling for neuroticism, in a large middle-aged UK population. *Int. J. Audiol.* **54**, 599–604 (2015).
12. Guest, H. et al. The noise exposure structured interview (NESI): An instrument for the comprehensive estimation of lifetime noise exposure. *Trends Hearing* **22**, 2331216518803213 (2018).
13. Newman, C. W., Jacobson, G. P. & Spitzer, J. B. Development of the Tinnitus Handicap Inventory. *Arch. Otolaryngol. Head Neck Surg.* **122**, 143–148 (1996).
14. Tufts, J. B. & Skoe, E. Examining the noisy life of the college musician: weeklong noise dosimetry of music and non-music activities. *Int. J. Audiol.* **57**, S20–S27 (2018).
15. Jorgensen, E., Tufts, J. B. & Skoe, E. Examining sound levels across different timescales measured from body worn dosimeters. *Journal of the Acoustical Society of America Special Issue: Advances in Soundscape: Emerging Trends and Challenges in Research and Practice.* (in press).
16. Schecklmann, M., Landgrebe, M. & Langguth, B. Phenotypic Characteristics of Hyperacusis in Tinnitus. *PLoS ONE* **9**, e86944 (2014).
17. Chen, J. X., Whitton, J. P., Parthasarathy, A., Hancock, K. E. & Polley, D. B. Fluctuations in subjective Tinnitus ratings over time: Implications for clinical research. *Otol. Neurotol.* **41**, e1167–e1173 (2020).
18. Wang, M. *et al.* Subjective tinnitus patients with normal pure-tone hearing still suffer more informational masking in the noisy environment. *Front. Neurosci.* **16**, (2022).
19. Martines, F., Bentivegna, D., Martines, E., Sciacca, V. & Martinciglio, G. Characteristics of tinnitus with or without hearing loss: Clinical observations in Sicilian tinnitus patients. *Auris Nasus Larynx* **37**, 685–693 (2010).
20. Flodgren, E. & Kylin, B. Sex differences in hearing in relation to noise exposure. *Acta Otolaryngol.* **52**, 358–366 (1960).
21. Eng, A. et al. Gender differences in occupational exposure patterns. *Occup. Environ. Med.* **68**, 888–894 (2011).
22. Parker, A., Parham, K. & Skoe, E. Noise exposure levels predict blood levels of the inner ear protein prestin. *Sci. Rep.* **12**, 1154 (2022).
23. Siervogel, R. M., Roche, A. F., Johnson, D. L. & Fairman, T. Longitudinal study of hearing in children II: Cross-sectional studies of noise exposure as measured by dosimetry. *J. Acoust. Soc. Am.* **71**, 372–377 (1982).
24. Flamme, G. A. et al. Typical noise exposure in daily life. *Int. J. Audiol.* **51**, S3–S11 (2012).
25. Neitzel, R., Seixas, N. S., Camp, J. & Yost, M. An assessment of occupational noise exposures in four construction trades. *Am. Ind. Hyg. Assoc. J.* **60**, 807–817 (1999).
26. Qian, C. L., Behar, A. & Wong, W. Noise exposure of musicians of a ballet orchestra. *Noise Health* **13**, 59 (2011).
27. Fernández, M. D., Quintana, S., Chavarría, N. & Ballesteros, J. A. Noise exposure of workers of the construction sector. *Appl. Acoust.* **70**, 753–760 (2009).
28. Exposure, O. N. Revised criteria 1998. *National Institute for Occupational Safety and Health, http://www. cdc. gov/niosh/98–126. html* (1998).
29. Introduction. in *Functional Data Analysis* (eds. Ramsay, J. O. & Silverman, B. W.) 1–18 (Springer, New York, NY, 2005). https://doi.org/10.1007/0-387-22751-2_1.
30. Benjamini, Y. & Hochberg, Y. Controlling the false discovery rate: A practical and powerful approach to multiple testing. *J. Roy. Stat. Soc.: Ser. B (Methodol.)* **57**, 289–300 (1995).
31. Degras, D. A. Simultaneous confidence bands for nonparametric regression with functional data. *Stat. Sin.* **21**, 1735–1765 (2011).
32. Moritz, S. & Bartz-Beielstein, T. imputeTS: time series missing value imputation in R. *R J.* **9**, 207 (2017).
33. Hastie, T. J. Generalized Additive Models. in *Statistical Models in S* (Routledge, 1992).
34. Friedman, J. H., Hastie, T. & Tibshirani, R. Regularization paths for generalized linear models via coordinate descent. *J. Stat. Softw.* **33**, 1–22 (2010).
35. Hee Park Choi. fregion: Simultaneous Confidence Regions... - Google Scholar. https://scholar.google.com/scholar?hl=en&as_sdt=0%2C7&q=Hee+Park+Choi.+fregion%3A+Simultaneous+Confidence+Regions+for+Functional+Parameters.+R+package+version+1.0.0.+2021.+url%3A+https%3A%2F%2Fgithub.com%2Fhpchoi%2Ffregion&btnG=.
36. Stevenson, I. Beeswarm. (2019).
37. Shukla, A. et al. Hearing loss, loneliness, and social isolation: A systematic review. *Otolaryngol. Head Neck Surg.* **162**, 622–633 (2020).
38. Mick, P., Kawachi, I. & Lin, F. R. The association between hearing loss and social isolation in older adults. *Otolaryngol. Head Neck Surg.* **150**, 378–384 (2014).
39. Keesom, S. M. & Hurley, L. M. Silence, solitude, and serotonin: neural mechanisms linking hearing loss and social isolation. *Brain Sci.* **10**, 367 (2020).

40. Kraus, U. et al. Individual daytime noise exposure during routine activities and heart rate variability in adults: a repeated measures study. *Environ. Health Perspect.* **121**, 607–612 (2013).
41. Jacquemin, L., Gilles, A. & Shekhawat, G. S. Hearing more to hear less: a scoping review of hearing aids for tinnitus relief. *Int. J. Audiol.* **61**, 887–895 (2022).
42. Henry, J. A., Frederick, M., Sell, S., Griest, S. & Abrams, H. Validation of a novel combination hearing aid and Tinnitus therapy device. *Ear Hear.* **36**, 42 (2015).
43. Hoare, D. J., Searchfield, G. D., Refaie, A. E. & Henry, J. A. Sound therapy for tinnitus management: Practicable options. *J. Am. Acad. Audiol.* **25**, 62–75 (2020).
44. Meikle, M. B. et al. The tinnitus functional index: development of a new clinical measure for chronic Intrusive Tinnitus. *Ear Hearing* **33**, 153 (2012).
45. Langguth, B., de Ridder, D., Schlee, W. & Kleinjung, T. Tinnitus: Clinical insights in its pathophysiology-a perspective. *J. Assoc. Res. Otolaryngol.* **25**, 249–258 (2024).
46. Bhatt, I. S., Wilson, N., Dias, R. & Torkamani, A. A genome-wide association study of tinnitus reveals shared genetic links to neuropsychiatric disorders. *Sci. Rep.* **12**, 22511 (2022).
47. Kroenke, K., Spitzer, R. L. & Williams, J. B. W. The PHQ-9. *J. Gen. Intern. Med.* **16**, 606–613 (2001).
48. Spitzer, R. L., Kroenke, K., Williams, J. B. W. & Löwe, B. A brief measure for assessing generalized anxiety disorder: The GAD-7. *Arch. Intern. Med.* **166**, 1092–1097 (2006).
49. Beck, A. T., Epstein, N., Brown, G. & Steer, R. Beck anxiety inventory. *Journal of consulting and clinical psychology* (1993).
50. Beck, A. T., Steer, R. A. & Brown, G. K. Beck depression inventory. (1996).
51. Marcrum, S. C. et al. The influence of diet on tinnitus severity: Results of a large-scale Online Survey. *Nutrients* **14**, 5356 (2022).
52. Aljuaid, S. M. et al. Does caffeine intake increase the incidence of tinnitus? A systematic review. *Int. Arch. Otorhinolaryngol.* **25**, e628–e632 (2021).
53. Peng, J. et al. The relationship between sleep traits and tinnitus in UK Biobank: A Population-Based Cohort Study. *Ear Hear.* **44**, 53 (2023).
54. Sanchez, T. G. et al. Tinnitus is associated with reduced sound level tolerance in adolescents with normal audiograms and otoacoustic emissions. *Sci Rep* **6**, 27109 (2016).
55. Beukes, E. W. et al. Situationally influenced tinnitus coping strategies: a mixed methods approach. *Disabil. Rehabil.* **40**, 2884–2894 (2018).
56. Pan, T., Tyler, R. S., Ji, H., Coelho, C. & Gogel, S. A. Differences among patients that make their tinnitus worse or better. *Am. J. Audiol.* **24**, 469–476 (2015).
57. Tyler, R. S., Noble, W., Coelho, C. B. & Ji, H. Tinnitus retraining therapy: Mixing point and total masking are equally effective. *Ear Hear.* **33**, 588 (2012).
58. Ramírez-Esparza, N., Jiang, S., García-Sierra, A., Skoe, E. & Benítez-Barrera, C. R. Effects of cultural dynamics on everyday acoustic environmentsa). *J Acoust. Soc. Am.* **156**, 1942–1951 (2024).
59. Benítez-Barrera, C. R., Ramirez-Esparza, N., García-Sierra, A. & Skoe, E. Cultural differences in auditory ecology. *JASA Express Letters* **3**, 083601 (2023).
60. Jencks, C., Perman, L. & Rainwater, L. What is a good job? A new measure of labor-market success. *Am. J. Sociol.* **93**, 1322–1357 (1988).
61. Fang, X. et al. Soundscape perceptions and preferences for different groups of users in urban recreational forest parks. *Forests* **12**, 468 (2021).
62. Heerwagen, J. H., Heubach, J. G., Montgomery, J. & Weimer, W. C. Environmental design, work, and well being: Managing occupational stress through changes in the workplace environment. *AAOHN J.* **43**, 458–468 (1995).
63. Auerbach, B. D., Rodrigues, P. V. & Salvi, R. J. Central Gain Control in Tinnitus and Hyperacusis. *Front. Neurol.* **5**, (2014).
64. Vasilkov, V. et al. Evidence of cochlear neural degeneration in normal-hearing subjects with tinnitus. *Sci Rep* **13**, 19870 (2023).
65. Johannesen, P. T. & Lopez-Poveda, E. A. Age-related central gain compensation for reduced auditory nerve output for people with normal audiograms, with and without tinnitus. *iScience* **24**, (2021).
66. Franklin, C. A., White, L. J., Franklin, T. C. & Smith-Olinde, L. The relationship between the acceptance of noise and acoustic environments in young adults with normal hearing: A pilot study. *J. Am. Acad. Audiol.* **25**, 584–591 (2014).

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Author contributions
ES, KP, and DS designed the work; RC, JD, AK, DW, and PA contributed to data acquisition; ES, YZ, KC, and OH contributed to data analysis. ES, KP, RC, JD, AK, YZ, KC, and OH contributed to data interpretation. ES prepared Figs. 1 and 2. YZ prepared Figs. 3 and 4, as well as all supplemental figures. ES drafted the introduction and discussion. RC and AP contributed to writing the methods section. YZ, KC, and OH drafted sections of the manuscript relating to the functional data analysis. All authors reviewed the manuscript.

Declarations

Competing interests
The authors declare no competing interests.

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