Low-Sound-Level Auditory Processing in Noise-Exposed Adults

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Abstract

Early signs of noise-induced hearing damage are difficult to identify, as they are often confounded by factors such as age, audiometric thresholds, or even music experience. Much previous research has focused on deficits observed at high intensity levels. In contrast, the present study was designed to test the hypothesis that noise exposure causes a degradation in low-sound-level auditory processing in humans, as a consequence of dysfunction of the inner hair cell pathway. Frequency difference limens (FDLs) and amplitude modulation depth discrimination (MDD) were measured for five center frequencies (0.75, 1, 3, 4 and 6 kHz) at 15 and 25 dB sensation level (SL), as a function of noise exposure, age, audiometric hearing loss, and music experience. Forty participants, aged 33-75 years, with normal hearing up to 1 kHz and mild-to-moderate hearing loss above 2 kHz, were tested. Participants had varying degrees of self-reported noise exposure, and varied in music experience. FDL worsened as a function of age. Participants with music experience outperformed the non-experienced in both the FDL and MDD tasks. MDD thresholds were significantly better for high-noise-exposed, than for low-noise-exposed, participants at 25 dB SL, particularly at 6 kHz. No effects of age or hearing loss were observed in the MDD. It is possible that the association between MDD thresholds and noise exposure was not causal, but instead was mediated by other factors that were not measured in the study. The association is consistent, qualitatively, with a hypothesized loss of compression due to outer hair cell dysfunction.

1 Introduction

The body of literature related to cochlear synaptopathy (Kujawa and Liberman, 2009), also sometimes described as “hidden hearing loss” (Schaette and McAlpine, 2011), has increased rapidly over recent years (for review see Bramhall et al. 2019; Le Prell, 2019; Liberman & Kujawa, 2017; Plack et al. 2016). Experimental animal studies have shown that the synapses between inner hair cells (IHCs) and auditory nerve fibers can be damaged permanently as a consequence of either noise exposure or aging, without substantial effects on absolute threshold sensitivity (Liberman & Kujawa, 2017; Sergeyenko et al., 2013). Low-spontaneous-rate (SR) fibers may be preferentially affected (Furman et al. 2013; Kobel et al. 2017). Since the low-SR fibers typically have high thresholds and high saturation levels, they are thought to be responsible for coding supra-threshold sounds. Using both psychophysical and electrophysiological measures, noise-induced cochlear synaptopathy has been investigated indirectly in human participants with clinically normal audiograms, with some studies finding evidence for synaptopathy but others not (Bharadwaj et al. 2015; Bramhall et al. 2017, 2019; Couth et al. 2020; Grinn et al. 2017; Grose et al. 2017, 2019; Guest et al. 2017; Liberman et al. 2016; Marmel et al., 2020; Prendergast et al. 2017a, 2017b).

However, the early effects of noise damage may extend beyond synaptopathy for low-SR fibers. For the noise-induced cochlear synaptopathy, beside the loss of low-SR fibers, computational models suggest that a substantial loss of high-SR fibers is also required to obtain a large perceptual effect (Encina-Llamas et al., 2019; Marmel et al., 2015; Verhulst et al., 2018). Valero et al. (2017) showed that permanent threshold shifts in macaques after noise exposures up to 146 dB SPL were due to loss of both low- and high-SR fibers. Cochlear synaptopathy is commonly understood as primarily affecting low-spontaneous rate fibers, which have high thresholds (Furman et al. 2013). As a consequence of this, the perceptual impact is predicted to be observable at high intensity levels. Evidence for noise-induced low-SR synaptopathy is weak, but modelling suggests a need to explore also the contribution of damage to high-SR fibers (Encina-Llamas et al., 2019; Marmel et al., 2015; Verhulst et al., 2018). Few studies have explored the relation between noise exposure and auditory processing related to loss of high-SR fibers (requiring testing at low sensation levels, SLs), which may reflect a different type of sub-clinical hearing damage from that observed with low-SR fibers. Testing at low SLs allows investigation of localized regions of the cochlea, due to less spread of excitation, and therefore stimulation of a more limited number of IHCs.

Stone et al. (2008) assessed the listeners' ability to discriminate narrowband sounds with different envelope statistics as a function of low SLs in both a noise-exposed group and a control group. The sounds were noise bursts with either Gaussian amplitude or “low-noise” statistics (LNN; Pumplin, 1985) centered on 2, 3, or 4 kHz. The LNN was the target sound, which possessed the same power spectrum, but lower envelope fluctuations than the Gaussian-statistic noise. Rock musicians and frequent nightclub attendees formed the noise-exposed group (with noisy activities regularly exceeding 100 dBA). Compared to the control group, they had similar absolute thresholds between 2 and 4 kHz (the typical spectral region for noise-induced hearing damage, Smoorenburg, 1992) but were, on average, younger (22 vs. 29 years). Performance was measured as the duration of a signal burst (in ms) required in order to discriminate between the two noises, with longer times indicating worse performance. As the presentation level decreased to 12 dB SL, the performance of the noise-exposed group worsened, showing poorer fidelity of envelope coding. The results were interpreted as subtle IHC damage due to the long-term noise exposure. However, at least three out of 10 control subjects showed performance similar to that of the noise-exposed group at some frequencies.

The use of personal music players (PMPs), such as MP3 players or smartphones, is one particular ubiquitous cause of noise exposure (Le Prell et al. 2013; Sulaiman et al. 2014; Kumar et al. 2017). Some effects of PMP exposure were investigated by Vinay & Moore (2010) in 14 male participants using two psychophysical tasks: frequency difference limens (FDLs) at 20 dB SL, and amplitude modulation detection (AMD) at 10 and 20 dB SL. Eight of the participants were habitual PMP users while the remaining six were not. The experimental group was again, on average, younger than the control group (27.6 vs. 33.6 years). In the frequency range from 3 to 8 kHz, the experimental group had lower absolute audiometric thresholds (3-5 dB) and higher (worse) thresholds in the frequency discrimination task. Interestingly, the reverse was true for the AMD task, as the experimental group showed lower (better) AMD thresholds at 4 and 6 kHz relative to the control group. The authors suggested that this reflected mild outer hair cell (OHC) dysfunction producing loudness recruitment and potential magnification of amplitude modulation (AM) fluctuations (Moore et al. 1996).

The contribution of possible IHC and OHC dysfunction due to noise exposure and/or aging, and its effect on AMD, was further evaluated by Stone & Moore (2014). The cross-sectional study involved young (18-24 years) and older (26-35 years) participant groups, and each group was subdivided into low- and high-noise exposure subgroups with 16 participants in each subgroup. The AMD task was measured for carrier frequencies of 3, 4 and 6 kHz and at 10, 25 and 40 dB SL, using a modulation frequency of 25 Hz. Although there were some differences in pure-tone hearing thresholds among the subgroups, all participants had thresholds in the range of normal to mild. As the authors pointed out, the results for the AMD task at 10 dB SL were “somewhat paradoxical” because the high noise-exposure groups had higher (worse) AMD thresholds than the low-noise groups, but the older group, which had worse absolute thresholds and greater noise exposure, showed better AMD thresholds than the young group. Since the pattern of results cannot be ascribed only to a loss of either IHC or OHC function, they were explained as a balance between IHC and OHC dysfunction that may depend on different combinations of intensity, duration and regularity of noise exposure.

The above-mentioned studies employing low SLs attempted to detect early signs of noise-induced hearing damage. The diverging results may be due to one or some of the following reasons: First, poor quantification of noise exposure. In the present study we used the retrospective self-report interview developed in our laboratory, the "noise exposure structured interview" (NESI; Guest et al. 2018), which was effective in tinnitus classification (Guest et al. 2017) and has been shown to correlate with a measure of noise-induced cochlear synaptopathy

(Shehorn et al., 2020). Second, in studies with a small number of participants, the psychophysical tasks may have lacked sensitivity because the between-subject variability was large (Hedge et al. 2018; Heinrich & Knight, 2020). Third, previous work mostly focused on young adults with normal audiograms, neglecting the possible effects of age on hearing damage; measures of deficits accrued through prolonged noise exposure may be required (see also Carcagno & Plack, 2020; Prendergast et al. 2019; Valderrama et al. 2018). Here we tested a cohort of adults aged 33 to 75 years with mean pure-tone hearing thresholds in the range of normal to mild loss. The selection criteria were intended to disentangle the effects of age, hearing threshold and noise exposure on IHC and OHC dysfunction. Participants with normal hearing should have mainly IHC damage due to noise exposure (Bramhall et al., 2017), whereas participants with mild hearing loss may have damage to both IHCs and OHCs (Johannesen et al., 2014). Fourth, despite the fact that music experience may improve performance on psychoacoustic tasks (Yeend et al., 2017), confounding the effects of noise exposure (see also Couth et al., 2020), it was not accounted for in previous low-SL studies. Indeed, the majority of noise-exposed participants in Stone et al. (2008) were also musicians. Here we included participants with a range of music experience, including expert musicians. The current study therefore aimed to control better for these possible confounds.

This study was in the framework of a larger study (Stone et al. submitted) that aimed to evaluate the Threshold Equalizing Noise (TEN) test (Moore et al. 2004) as a possible early clinical indicator of damage to cochlear structures other than OHCs. The hypothesis was that noise-induced cochlear damage would affect high-SR fibers; hence the perceptual consequences would be measurable at low SLs. In adults with hearing level ranging from normal to mild, we predicted impaired frequency discrimination and AM depth discrimination (MDD) at low SLs in those with high noise exposure compared to those with low noise exposure. Although some authors have suggested that the effects may be too small to measure perceptually (e.g., Oxenham, 2016), previous work has provided evidence for a relation between noise exposure and performance on FDLs and AMD thresholds (Vinay & Moore, 2010; Stone & Moore, 2014), suggesting that behavioral measures may be sensitive to high-SR dysfunction.

2 Methods

2.1 Participants

Forty participants (20 females) between the ages of 33 and 75 years (mean 58.7 years) were selected from a larger pool of participants (N=112) recruited for an experiment to be reported elsewhere (Stone et al. submitted). The selection criteria for the sub-group were that they had, in the test ear, normal pure-tone hearing thresholds up to 1 kHz (i.e., average of 0.5, 0.75 and 1 kHz ≤ 20 dB HL) and a mild-to-moderate threshold between 3 and 6 kHz (i.e., average of 3, 4 and 6 kHz > 20 dB HL). Participants with asymmetrical hearing loss, whether sensorineural or conductive in origin, were tested in their better ear only, and efforts were made to exclude conductive losses with average air-bone gap at 0.5, 1 and 2 kHz of greater than 10 dB.

The study was approved by the National Research Ethics Service (NRES)

Committee North West - Greater Manchester Central (IRAS number 184199; REC number 16/NW/0260) and all participants gave informed consent.

2.2 Pure tone audiometry

Air-conduction and Bone-conduction audiometry were performed for each individual ear in accordance with British Society of Audiology's recommended procedure (British Society of Audiology, 2018). Air-conduction audiometric thresholds (Fig. 1) were measured at 11 frequencies between 125 Hz and 8000 Hz (i.e., octave frequencies from 125 Hz to 8000 Hz, and the half-octaves of 750, 1500, 3000 and 6000 Hz) using a Madsen Astera2 and TDH-39 supra-aural headphones. Bone-conduction audiometric thresholds were measured at 500, 1000, 2000, and 4000 Hz using a Radioear B71 bone vibrator.

2.3 Noise exposure

Lifetime noise exposure was estimated using the NESI (Guest et al. 2018). During this interview, participants identified noisy activities (such as recreational, occupational or educational, and firearm impulse exposures) to which they had been exposed, the duration of exposure to each activity (number of hours per day, days per week, weeks per year, and years), and hearing protection use in these activities (if any). The sound levels of these activities were estimated by the participants based on the vocal effort required to hold a conversation. For instance, if a participant thought that conversation required shouting at a listener 4 feet (1.2 m) away, then the level was recorded as 99 dBA.

2.4 Music Experience

The NESI was also used to construct a proxy measure of a participants' music experience. In particular, the total number of hours of playing a music instrument and/or singing (e.g., in front of an audience) was taken as the metric of music experience. The metric cannot discriminate participants with formal and informal (e.g., self-taught) music training, or those who either played, or used to play, at the time of the research, and the regularity of instrument playing. However, this metric was used previously (Prendergast et al., 2017b) and approximates the “Index of Music Instrument Playing” of the Music Use Questionnaire (Chin & Rickard, 2012).

2.5 Psychophysical tasks

2.5.1 General procedure

All testing was performed in a double-walled sound-attenuating booth in two separate sessions. Monaural stimuli were generated (24-bit resolution, 44.1 kHz sampling rate) using the AFC (alternative forced choice) software (Ewert, 2013) in MATLAB (R2015b, 8.6.267246, 64-bit), and presented via a Focusrite Scarlett 2i2 USB sound-card and Etymotic Research ER4s insert earphones. Psychophysical measures of absolute threshold (ABS), taken by the software, were followed by measures of FDLs and AM depth discrimination (MDD). The experiments were performed at five center frequencies (0.75, 1, 3, 4 and 6 kHz), at both 15 and 25 dB SL relative to the ABS. The rationale for the choice of frequencies was that performance at 0.75 and 1 kHz should be less affected by noise exposure than would performance at the three higher frequencies (Lutman et al. 2016), therefore controlling better for between-participant variability. The two SLs were chosen because previous studies (Stone & Moore, 2014; Vinay & Moore, 2010) had shown a significant difference in performance across low SLs.

The testing order was pseudo-randomized both by frequency, and by SL. All participants were trained in each task until their performance appeared to be stable (e.g., a low standard deviation). Practice runs were performed at a center frequency of 1.5 kHz because this was not used in the experimental tasks. The training generally took 1-5 minutes per task. For the data collection, at least two runs were obtained for each frequency and SL. If the standard deviation of the measured variable across reversals was greater than 3 dB, or if the difference in threshold between runs exceeded 5 dB, an additional run was obtained. The final thresholds were based on the average over runs. Visual feedback was provided indicating correctness of the response. In order to limit the possible variation of the intended presentation level within any frequency, the participants were instructed not to move or touch the insert earphones until all the measures for that frequency were taken. The participants were offered a rest break once all of the measures for a single frequency were collected.

2.5.2 Absolute Threshold

For each test frequency, ABS was measured for pure-tone signals in quiet using a three-alternative forced-choice method, with a two-down, one-up, adaptive tracking procedure. One random interval contained a pure tone whereas the others had no sound. The step size was initially 6 dB until the first reversal, decreased to 4 dB until the next reversal, and then was kept at 2 dB for six reversals. The threshold was estimated as the mean level of the last six reversals. The signals lasted 300 ms, including 10 ms ramps, with a 400 ms inter-stimulus interval.

2.5.3 Frequency Difference Limens

A two-alternative forced-choice paradigm, with a two-down one-up adaptive tracking procedure, was used. One interval contained four identical tone bursts (AAAA), while the other interval contained two alternated (target) bursts with a Δf ratio change in frequency between them (A'B'A'B'). The FDL was measured with the alternated bursts having symmetric shifts (on a log-frequency scale) around the test frequency. Tone burst duration was 400 ms including 20 ms ramps; the within-interval gap between each tone was 90 ms and, across-intervals, 400 ms. In order to reduce the availability of loudness cues, the level between individual bursts was randomly roved by ±3 dB, quantized in 1-dB steps. The frequency ratio was calculated as:

$$\Delta f = \left(1 + 10^{(0.1 * \Delta f_n)}\right)$$

where Δf_n was varied in dB. The step size was 10 dB until the first reversal, decreased to 5 dB until the next reversal, and was then 2 dB thereafter for six reversals. The participant's task was to indicate the interval containing the bursts alternating in frequency. The value of Δf was decreased following two correct responses in a row or increased following one incorrect response. The mean Δf was calculated as the geometric mean of the last six reversals.

2.5.4 Amplitude Modulation Depth Discrimination

A two-alternative forced-choice paradigm was used to measure the threshold for discriminating modulation depth. One interval contained the standard (target) AM tone with a modulation depth (m_s) fixed at 50% (i.e., -6 dB), while the other interval contained the comparison AM tone with a modulation depth (m_c)

initially set at 10% (i.e., -20 dB, a very shallow modulation). The depth in the comparison interval was always less than the standard depth. The tones had a modulation rate of 15 Hz, were 340 ms in duration, including 20 ms ramps, and the two intervals separated by a 90 ms gap. The use of an AM-rate of 15 Hz resulted in a narrow-bandwidth signal that fell within the passbands of the auditory filters. A ±3-dB level roving, again with a uniform distribution in 1-dB steps, was applied on each tone to limit overall loudness cues due to differences in modulation depth (Stellmack et al., 2006). The rove range was limited to ±3 dB because of the low presentation levels (15 and 25 dB SL) used in both tasks, and because, in the case of the MDD task, the reference modulation range was ±5 dB. The range chosen ensured that all signals did not drop below audibility, and that the range of signal levels requiring coding did not majorly overlap between the two nominal testing levels.

The task was to indicate the interval having the greater modulation depth. Following two correct responses in a row, the modulation depth m_c was increased, while following one incorrect response it was decreased. The modulation depth was varied arithmetically on a logarithmic scale. The initial step size was 4 dB (i.e., 5.8%) until the first reversal, decreased to 2 dB (i.e., 2.6%) until the next reversal, and was then 1 dB (i.e., 1.2%) thereafter for six reversals. There are several measures for expressing the MDD threshold reported in the literature; here we used the difference in modulation depth between the standard and the comparison (similar to Stellmack et al., 2006), both expressed as a peak-to-valley ratio (Moore et al., 1996):

$$\Delta m = 20log_{10}\left(\frac{1+m_s}{1-m_s}\right) - 20log_{10}\left(\frac{1+m_c}{1-m_c}\right)$$

2.6 Data analysis

The Spearman's correlation coefficient was calculated for the NESI score on Age because noise exposure and aging are strong and competitive factors as both can produce the loss of IHCs and OHCs. Previous studies were based on group analyses to investigate low SL hearing deficits (Stone et al. 2008; Stone & Moore, 2014; Vinay & Moore, 2010). So as to be able to compare our results with the literature, a similar approach was used via mixed-effects models (Baayen et al. 2008; Winter, 2013). Only participants with low and high noise exposure were included in the modelling. The separation may increase the likelihood of observing the effects of noise exposure as a difference between groups if there are floor or ceiling effects (see Prendergast et al., 2017a, 2017b). In order to account for individual differences across participants, the entire cohort was used when calculating the Spearman's correlation coefficient for ranked data (rho).

Mixed models were calculated separately for the FDLs and MDD thresholds. In the models, the thresholds were entered as the dependent variable. *Age* (as a scaled continuous variable), (test) *Frequency, SL*, *Hearing Status* group, *Noise Exposure* group, and *Music Experience* groups were evaluated as fixed effects. Random-effects and then fixed-effects were chosen via the backwards selection approach, i.e., a complex and large model was simplified based on step-wise deletion of model terms with high p-values (Baayen et al. 2008; Kuznetsova et al. 2015). The models were assessed using the Akaike Information Criterion

(Burnham & Anderson, 2002), and the marginal and conditional R^2. The marginal R^2 is the proportion of the variance in the response variable (i.e., thresholds) explained by the fixed effects, while the conditional R^2 is the proportion of the variance explained by the entire model, including both the fixed and the random effects (Johnson, 2014; Nakagawa et al. 2017; Nakagawa & Schielzeth, 2013).

Correlation analyses were performed separately for FDL and MDD thresholds for each combination of frequency and SL. The relation between psychophysical thresholds, NESI and Age was investigated using Spearman's correlation. The relation between psychophysical threshold and NESI was also controlled separately for each of music experience, Age and ABS via partial Spearman correlation. All statistical analyses were performed in R (version 3.6.3, R Core Team, 2020). The mixed models were fitted and evaluated using the packages *lme4* (Bates et al. 2015), *lmerTest* (Kuznetsova et al. 2017) and *performance* (Lüdecke et al. 2020). *Post hoc* pairwise comparisons were conducted via the estimated marginal means using *emmeans* (Lenth, 2020) with Kenward-Roger approximation for degrees of freedom and Bonferroni correction for multiple comparisons. Data were visualized within *ggplot2* (Wickham, 2009) using *Raincloud* (Allen et al. 2019).

3 Results

3.1 Hearing Status, Noise Exposure and Music Experience groups

Participants were divided in groups according to their AC hearing thresholds, NESI score and music experience. Since all participants had normal, or near-normal, hearing thresholds up to 1 kHz, and hearing loss at high frequency, combined low (0.5, 0.75 and 1 kHz) and high (3, 4 and 6 kHz) frequency descriptors were used (Fig. 2, panel a). Participants were classified either as Normal/Mild (27 participants, 12 females) with average of ≤20 dB HL at low frequency and between 20 and 40 dB HL at high frequency, or Normal/Moderate (13 participants, eight females) with an average of ≤20 dB HL at low frequency and an average of >40 dB HL at high frequency. There was no significant difference between the groups in age [t(38) = -1.688, p = 0.1], NESI score [t(38) = 0.527, p = 0.601] or music experience [W(38) = 126, p = 0.126].

The cumulative units of noise exposure (NESI score), *log10* transformed so as to obtain an approximately Gaussian distribution, was used to categorize participants into Low, Medium or High Noise-exposure groups (40-20-40% of distribution, respectively, Fig. 2, panel b). The Low and High Noise-exposure groups used in the mixed-effects modelling had median NESI scores of 1.046 (range: 0.232-1.510) and 2.233 (range: 1.851-3.203), respectively. However, the High Noise-exposure group was significantly younger than the Low Noise-exposure group [t(30) = 3.083, p = 0.004] with median ages of 53 and 64 years, respectively. There was no significant difference between the noise exposure groups in their average PTA [t(30) = 0.619, p = 0.541], or in their music experience [W(30) = 101.5, p = 0.295].

Twenty-one participants (10 females) had no music experience, while 19 (nine females) had either some experience or were expert musicians (Fig. 2, panel c). Groups of listeners with and without music experience did not differ in their age [t(38) = -0.254, *p* = 0.801] with median ages of 61 and 59 years, respectively; nor in their PTA [t(38) = 1.071, *p* = 0.291], with median values of 22 and 20 dB HL, respectively; nor in their NESI score [t(38) = 1.343, *p* = 0.187] with median values of 1.690 and 1.778, expressed as *log10(NESI)*, respectively.

3.2 Noise exposure

Estimated lifetime noise exposure ranged from to 0.232 to 3.203 in *log10* NESI units. Our maximum is larger than previously reported (e.g., Prendergast et al., 2017b, 2019). This was due to one participant with extensive orchestral experience. The other participants' data were within the range of previously reported data. There was no difference in the NESI score between females and males [t(38) = -1.282, *p* = 0.207], with medians (and ranges) of 1.552 (0.232-3.203) and 1.770 (0.677-2.690), respectively. There was a negative relation between lifetime noise exposure and age (Fig. 3, Spearman's correlation coefficient r = -0.437, *p* = 0.005).

3.3 Psychophysical tasks

The results for the psychophysical tasks are shown in Fig. 4 separated by Noise-exposure groups, and in the Supplementary Material, Fig. S1 separated by Hearing Status group, and Fig. S2 separated by the Music Experience group. Each figure shows ABS, FDLs and MDD, at 15 and 25 dB SL, as separate panels with a raincloud plot per group. Raincloud plots show mean and standard error (SE) of the thresholds as error-bars, participants' individual data (with some horizontal jitter for clarity) as dots, and probability densities as a 'half violin' plot. The color code is the same as used in Fig. 2 and is included in each ABS panel. Table. 1 shows Spearman correlations between the Noise-exposure scores and the thresholds for each task.

3.3.1 Frequency Difference Limens

The FDLs were fitted with a mixed model (marginal $R^2 = 0.45$, conditional $R^2 = 0.76$) having Frequency, Age (scaled), and Music Experience group as fixed effects (without the interaction terms); and including by-participant random intercepts and by-participant random slopes for Frequency (assuming homoskedasticity). FDLs increased (i.e., performance got worse) as a function of Age (see Fig. S3). The FDLs were significantly worse at 4 and 6 kHz when compared to the lower frequencies. Participants without music experience had worse performance [$\Delta f = -0.02$ *log10*(%)] relative to the participants with music experience [$\Delta f = -0.19$ *log10*(%); $t(28.8) = 3.954$, $p < 0.001$].

3.3.2 Amplitude Modulation Depth Discrimination

The specifications of the mixed model (marginal $R^2 = 0.23$, conditional $R^2 = 0.47$) for the MDD thresholds had SL, Noise groups and their interaction, and Music groups as fixed effects; participants were treated as random intercepts. It is important to highlight that there was no interaction between Noise Exposure and Music Experience groupings as the effect of noise exposure was not mediated by the effect of music experience. Overall, performance was better (lower thresholds) at 25 dB SL (median $\Delta m = 2.13$ dB) compared to at 15 dB SL ($\Delta m = 2.44$ dB). The High Noise Exposure showed significantly lower MDD thresholds than the Low-Noise Exposure group at 25 dB SL [$\Delta m = 1.74$ vs. 2.65 dB; $t(40.4) = -3.36$, $p = 0.002$] but not at 15 dB SL. Furthermore, MDD threshold was better for participants with some music experience ($\Delta m = 1.91$

dB) than for those without [Δm = 2.63 dB; t(29.1) = -3.66, $p = 0.001$]. There was no effect of Hearing Status group: Normal/Mild hearing participants had median Δm = 2.33 dB whereas participants in the Normal/Moderate hearing group had median Δm = 2.13 dB.

At 25 dB SL, a negative correlation existed between NESI score and MDD threshold at 0.75, 3, 4, 6 kHz (Table 1). The effect at 6 kHz was the most robust (r = -0.591, $p < 0.001$) and remained significant even after controlling for Age, Music Experience, and ABS; and correcting for multiple comparisons (α = 0.05/100, Bonferroni).

3.3.3 Exploratory analysis

Fig. 5 shows the results for the MDD task at 25 dB SL averaged over frequency in terms of the interaction between the Noise Exposure (i.e., Low vs High) and Music Experience (i.e., With vs Without) groups. The differences in the thresholds among these four subgroups were evaluated. The thresholds were highest (worst) in the participants with low lifetime noise exposure and without music experience (median Δm = 3.11 dB). The difference between these and those of the participants with music experience and high lifetime noise exposure (Δm = 1.63 dB) were significant after controlling for six comparisons [W = 0, $p < 0.001$].

4 Discussion

FDL and MDD tasks were used to test the hypothesis that noise exposure is associated with sub-clinical hearing deficits manifesting at a low SL in adults with normal hearing to mild hearing loss. The results do not support the primary hypothesis. In particular, participants with higher noise exposure had better MDD performance at 25 dB SL. In addition, FDLs did not vary with noise exposure but improved strongly with music experience and worsened with age.

4.1 Frequency Difference Limens

The FDLs were dependent on the test frequency and participants' music experience. FDLs increased (worsened) as a function of increasing frequency, irrespective of Noise Exposure or Hearing Status groups. The dependence of FDLs on frequency is well known in the literature. Using data from several studies, Micheyl et al. (2012) showed that the log-transformed FDL (as in this study) is well described by a power function of frequency with an exponent of 0.8.

Participants with music experience outperformed other participants. The effects of music experience on the FDLs are consistent with previous studies (Kishon-Rabin et al. 2001; Micheyl et al. 2006; Prendergast et al. 2017b). FDLs got worse as function of age as previously reported (e.g., Moore & Peters, 1992). Interestingly, we did not observe any effects of Hearing Status group on the FDLs. Similar observations were reported in a study of complex-tone F0 discrimination. Bianchi et al. (2019) observed similar performance between participants (≥ 55 years old) with and without hearing loss, but improved performance in musicians relative to non-musicians.

The possible confound due to the music experience and the lack of significant effects or correlation related to lifetime noise exposure in the present study, may suggest that the FDL is not a sensitive marker for noise-damage assessment.

Vinay & Moore (2010) reported an association between the use of PMPs and poor FDLs for frequencies centered between 3 and 8 kHz. However, since they did not record participants' music experience, it is not clear whether music experience could have been a determining factor in their study.

4.2 Amplitude Modulation Depth Discrimination

In general, a MDD threshold is measured as a function of the AM depth of a standard modulation m_s by varying the modulation depth of a comparison m_c (Ewert & Dau, 2004; Wakefield & Viemeister, 1990). Expressed as $[10log_{10}(m_c^2 - m_s^2)]$, The discrimination thresholds in these studies were around -10 dB, with m_s near to -6 dB (as in the current study). Our grand mean MDD threshold was Δm = 2.6 dB or, expressed in similar fashion to Ewert & Dau (2004) and Wakefield & Viemeister (1990), -9.4 dB.

To the authors' knowledge, MDD thresholds have never previously been measured in studies related to noise-induced hearing loss. Instead, AMD thresholds have been measured more extensively than MDD thresholds. Since the modulation depth m_s = 0 dB in the AMD task, the latter can be seen as a special case of MDD. Therefore, the results of our MDD thresholds can be interpreted alongside to those of AMD thresholds.

There was no effect of carrier frequency on MDD thresholds (similar to Lee, 1994), but performance improved at 25 dB SL compared to 15 dB SL. Better thresholds at higher SLs are consistent with other AMD results (e.g., Stone & Moore, 2014). In agreement with the FDLs, MDD thresholds were better for listeners with music experience compared to those without. Importantly, there was no interaction between music experience and noise exposure; therefore, the two effects can be discussed separately.

We found significantly better MDD thresholds for the High than for the Low Noise-Exposure group, but only at 25 dB SL. This was also observed in the correlational analyses of the NESI score on the MDD thresholds, particularly at 6 kHz. These results do not support our hypothesis since they were in the opposite direction to that predicted. However, similar AMD results were reported by Vinay & Moore, (2010) and an, albeit not significant trend, by Prendergast et al. (2017b). Damage to OHCs is associated with a loss of cochlear compression, which leads to abnormally rapid growth in loudness with level (i.e., loudness recruitment) enhancing the perceived magnitude of envelope fluctuations (Moore et al. 1996; Robles & Ruggero, 2001). This explanation is not entirely convincing in the case of the present results, because of the lack of a frequency effect on the MDD thresholds: participants had similar MDD thresholds at low frequency, with hearing in the normal range, and at high frequency with mild or moderate hearing loss, hence presumably with some OHC loss. Indeed, the rate of growth of loudness at low levels (near threshold) is similar in normal and impaired ears (Moore & Glasberg, 2004; Plack & Skeels, 2007). Furthermore, in tasks performed at 4 kHz and at 30 dB SL, participants with moderate hearing loss (between 40 and 60 dB HL at 4 kHz) showed better AMD but worse MDD thresholds than normal-hearing participants (Schlittenlacher & Moore, 2016). The poor MDD in participants with hearing loss has been associated with a saturation of fluctuation strength (Fastl, 1983). However, this was observed only up to a modulation rate of 4 Hz (Fastl, 1983), well below that of the 15 Hz used here. Recently, Wiinberg et al. (2019) measured AMD and MDD thresholds at 1 kHz at suprathreshold levels, both in adults with normal hearing, and also those with mild to moderately severe sensorineural hearing loss. The latter had a similar AMD but worse MDD thresholds than normal-hearing participants. The MDD results were interpreted through the stochastic undersampling principle (Lopez-Poveda & Barrios, 2013, but see also Marmel et al. 2015) as reduced fidelity in envelope encoding due to a loss of IHCs. In contrast to the participants recruited by Schlittenlacher & Moore (2016) and Wiinberg et al. (2019), we measured MDD in participants with normal hearing thresholds up to 1 kHz, and mild-to-moderate hearing loss above 2 kHz.

Stone & Moore (2014) found that normal-hearing participants frequently exposed to high-noise events (> 100 dBA SPL) had poorer AMD at 10 dB SL compared to low noise-exposed control participants. On the other hand, older participants showed better AMD at 10 dB SL than did their younger participants. The different time scale of noise exposure of the participants may lead to a combination of IHC and OHC dysfunction. In the current study, since the MDD threshold varied with noise exposure, in particular at 25 dB SL and 6 kHz, irrespective of age and hearing threshold, the MDD threshold may be associated only with OHC dysfunction.

Conclusions

In summary, no effect of noise exposure on FDLs was observed but they were affected primarily by participants' music experience and age. MDD thresholds improved with both music experience and noise exposure, with High Noise-

Exposed participants having lower thresholds. The results do not provide evidence for a deficit related to IHC dysfunction; hence we hypothesize that they could be related to OHC dysfunction. However, further research is required to determine if hair cell pathway dysfunction underlies lower MDD thresholds, and, if so, if there are differences in the relative contributions of IHC and OHC dysfunction.

Acknowledgments

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Figures Legends

Figure 1: Test-ear mean pure tone thresholds (black) and test-ear pure tone thresholds for each of the 40 participants (gray) in the Normal/Mild haring group (left panel) and Normal/Moderate hearing group (right panel).

Figure 2: Distributions of average pure tone hearing thresholds at 0.5, 0.75, 1, 3, 4 and 6 kHz (panel a), noise exposure structured interview (NESI) score (panel b), and music experience (panel c).

Figure 3: Noise exposure scores as a function of age for the 40 participants.

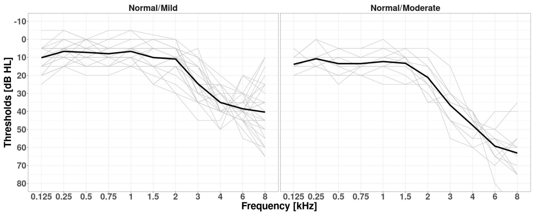
Figure 4: Mean data with SEs, individual data, and probability densities of ABS, FDL and MDD thresholds for the Low and High Noise-exposure groups.

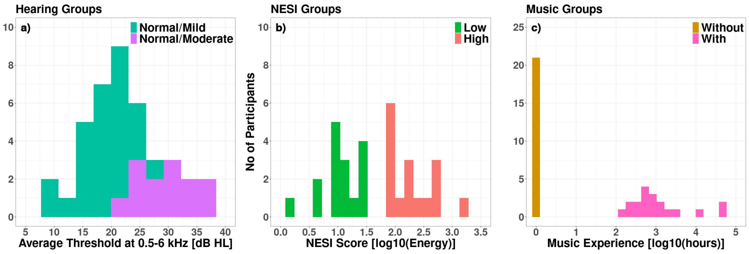
Figure 5: Interaction between Noise Exposure (Low vs High) and Music Experience (Without vs With) groups in the MDD task at 25 SL dB averaged over frequency.

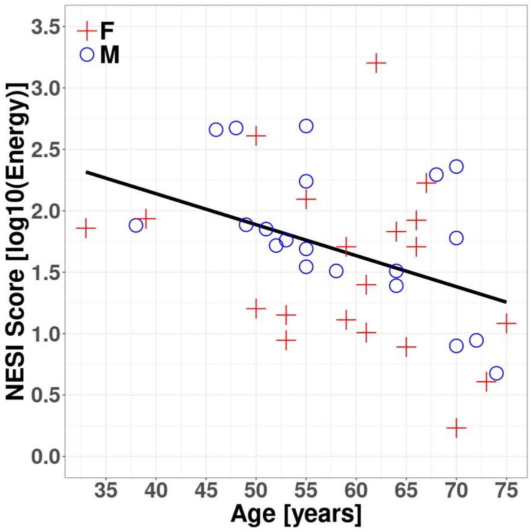
Figure S1: Mean with SE, individual data and probability densities of ABS, FDL and MDD thresholds for the Hearing groups.

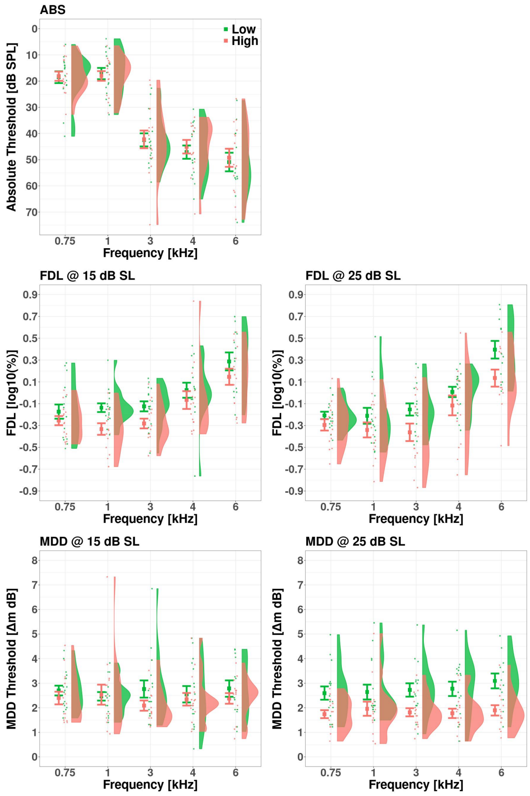
Figure S2: Mean with SE, individual data and probability densities of ABS, FDL and MDD thresholds for the Music groups.

Figure S3: FDLs as a function of age at 0.75 kHz ($r = 0.123$, $p = 0.284$), 1 kHz ($r = 0.227$, $p = 0.045$), 3 kHz ($r = 0.260$, $p = 0.020$), 4 kHz ($r = 0.257$, $p = 0.023$) and 6 kHz ($r = 0.381$, $p = 0.001$) averaged over SL.


Normal/Mild
Normal/Moderate
Thresholds [dB HL]
-10
0
10
20
30
40
50
60
70
80
0.125
0.25
0.5
0.75
1
1.5
2
3
4
6
8
Frequency [kHz]


Hearing Groups
a)
Normal/Mild
Normal/Moderate
0
2
4
6
8
10
5
10
15
20
25
30
35
40
Average Threshold at 0.5-6 kHz [dB HL]
NESI Groups
b)
Low
High
No of Participants
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
NESI Score [log10(Energy)]
Music Groups
c)
Without
With
0
5
10
15
20
25
0
1
2
3
4
5
Music Experience [log10(hours)]


F
M
NESI Score [log10(Energy)]
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
35
40
45
50
55
60
65
70
75
Age [years]


ABS
Low
High
Absolute Threshold [dB SPL]
0
10
20
30
40
50
60
70
0.75
1
3
4
6
Frequency [kHz]
FDL @ 15 dB SL
FDL @ 25 dB SL
FDL [log10(%)]
0.9
0.7
0.5
0.3
0.1
-0.1
-0.3
-0.5
-0.7
-0.9
MDD @ 15 dB SL
MDD @ 25 dB SL
MDD Threshold [Δm dB]
8
7
6
5
4
3
2
1
0

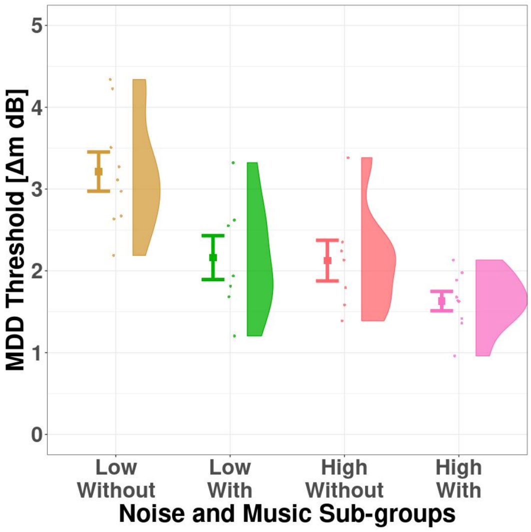
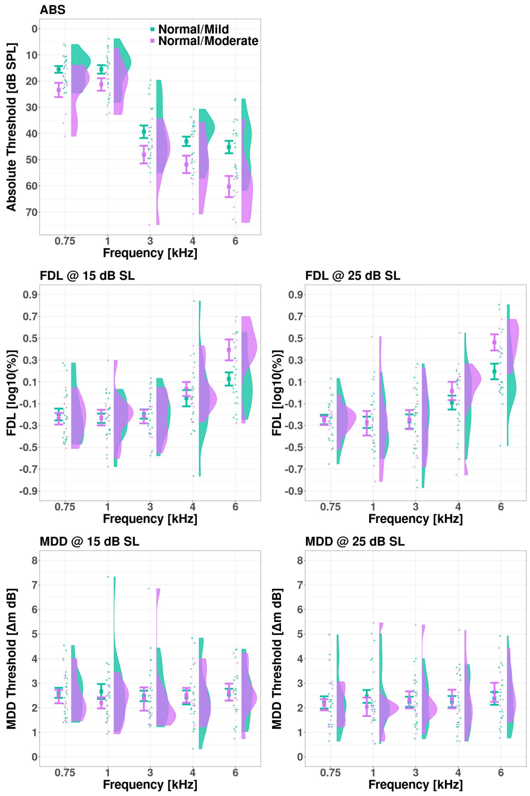
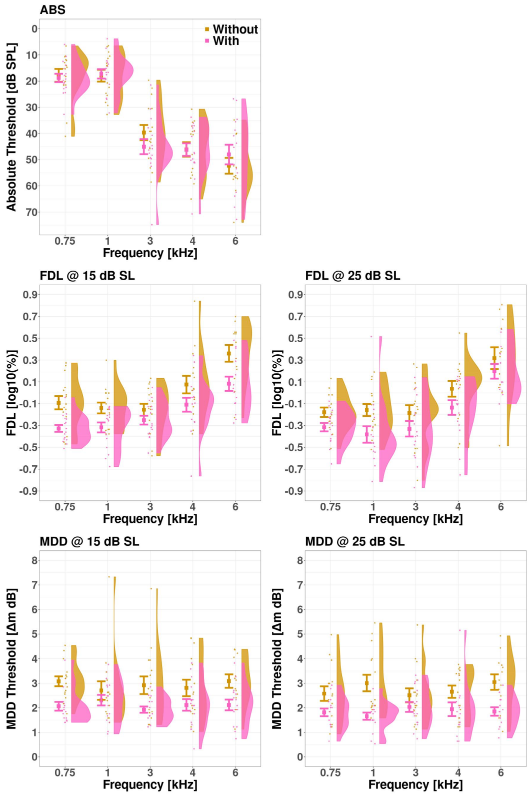
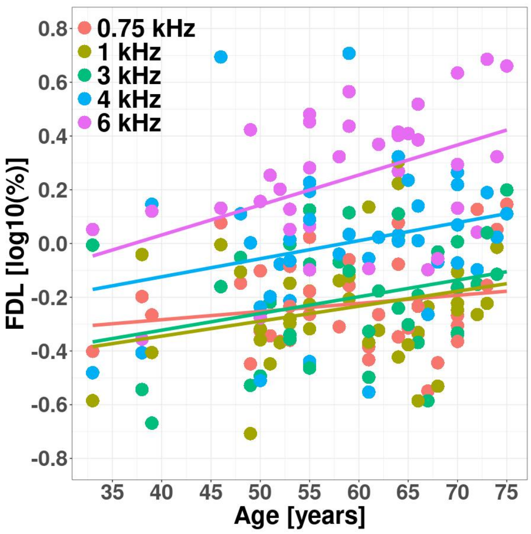

MDD Threshold [Δm dB]
0
1
2
3
4
5
Low Without
Low With
High Without
High With
Noise and Music Sub-groups

Table 1: Spearman's rho coefficients for the relation between psychophysical (ABS, MDD, and FDL) tasks and lifetime noise exposure (NESI); partial Spearman correlation between psychophysical tasks and lifetime noise exposure controlling separately for each of music experience, Age and ABS; and Age. Positive correlations indicate worse performance with increasing noise exposure or age. Negative correlations indicate better performance with increasing music experience or age. Key: * = p ≤ 0.05; ** = p ≤ 0.01; *** = p ≤ 0.001 (uncorrected).

Task	**Frequency [kHz]**				
	0.75	**1**	**3**	**4**	**6**
NESI					
FDL 15	-0.08	-0.34*	-0.36*	-0.27	-0.24
FDL 25	-0.22	-0.04	-0.26	-0.17	-0.41*
MDD 15	-0.20	0.01	-0.31	-0.13	-0.30
MDD 25	-0.42**	-0.31	-0.45**	-0.44**	-0.59***
NESI, controlling for Age					
FDL 15	-0.04	-0.28	-0.26	-0.21	-0.12
FDL 25	-0.17	0.09	-0.18	-0.04	-0.31
MDD 15	-0.16	-0.07	-0.23	-0.17	-0.2
MDD 25	-0.39*	-0.37*	-0.40*	-0.41**	-0.54**
NESI, controlling for Music					
FDL 15	0.09	-0.25	-0.29	-0.18	-0.12
FDL 25	-0.11	0.08	-0.19	-0.10	-0.37*
MDD 15	-0.04	0.08	-0.24	-0.06	-0.18
MDD 25	-0.33*	-0.14	-0.44**	-0.38*	-0.52**
NESI, controlling for ABS					
FDL 15	-0.07	-0.35*	-0.38*	-0.26	-0.23
FDL 25	-0.22	-0.04	-0.26	-0.16	-0.42*
MDD 15	-0.19	0.01	-0.31	-0.12	-0.29
MDD 25	-0.41*	-0.31	-0.45**	-0.44**	-0.59***
Age					
FDL 15	0.09	0.20	0.32*	0.19	0.34*
FDL 25	0.17	0.28	0.22	0.31	0.42*
MDD 15	0.13	-0.15	0.24	-0.04	0.33
MDD 25	0.15	-0.06	0.21	0.16	0.30


ABS
Normal/Mild
Normal/Moderate
Absolute Threshold [dB SPL]
0
10
20
30
40
50
60
70
0.75
1
3
4
6
Frequency [kHz]
FDL @ 15 dB SL
FDL @ 25 dB SL
FDL [log10(%)]
0.9
0.7
0.5
0.3
0.1
-0.1
-0.3
-0.5
-0.7
-0.9
MDD @ 15 dB SL
MDD @ 25 dB SL
MDD Threshold [Δm dB]
8
7
6
5
4
3
2
1
0


ABS
Without
With
Absolute Threshold [dB SPL]
0
10
20
30
40
50
60
70
0.75
1
3
4
6
Frequency [kHz]
FDL @ 15 dB SL
FDL [log10(%)]
0.9
0.7
0.5
0.3
0.1
-0.1
-0.3
-0.5
-0.7
-0.9
0.75
1
3
4
6
Frequency [kHz]
FDL @ 25 dB SL
FDL [log10(%)]
0.9
0.7
0.5
0.3
0.1
-0.1
-0.3
-0.5
-0.7
-0.9
0.75
1
3
4
6
Frequency [kHz]
MDD @ 15 dB SL
MDD Threshold [Δm dB]
8
7
6
5
4
3
2
1
0
0.75
1
3
4
6
Frequency [kHz]
MDD @ 25 dB SL
MDD Threshold [Δm dB]
8
7
6
5
4
3
2
1
0
0.75
1
3
4
6
Frequency [kHz]


0.75 kHz
1 kHz
3 kHz
4 kHz
6 kHz
FDL [log10(%)]
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
Age [years]
35
40
45
50
55
60
65
70
75