Disentangling the effects of hearing loss and age on amplitude modulation frequency selectivity

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Abstract

The processing and perception of amplitude modulations (AMs) in the auditory system reflect a frequency-selective process, often described as a modulation filterbank. Previous studies on perceptual AM masking reported similar results for older listeners with hearing impairment (HI) and young listeners with normal hearing (NH), suggesting no effects of age nor hearing loss on AM frequency selectivity. However, recent evidence has shown that age, independently of hearing loss, is detrimental to AM frequency selectivity. Hence, the present study aimed to disentangle the effects of hearing loss and age. A simultaneous AM masking paradigm was employed, utilizing a sinusoidal carrier at 2.8 kHz, narrow-band noise modulation maskers, and target modulation frequencies of 4, 16, 64, and 128 Hz. The results obtained from older (n=10, 63-77 years) and young HI listeners (n=3, 24-30 years) were

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compared to data from young and older NH listeners. Notably, the HI listeners generally exhibited lower (unmasked) AM detection thresholds and greater AM frequency selectivity compared to their NH counterparts of similar age. These findings suggest that age negatively affects AM frequency selectivity in both NH and HI listeners, while hearing loss improves AM detection and AM selectivity, likely due to the loss of peripheral compression.

I. INTRODUCTION

Most sounds encountered in everyday environments are complex signals that exhibit dynamic fluctuatations over time (Singh and Theunissen, 2003; Elliott and Theunissen, 2009). These fluctuations include variations in the temporal envelope, commonly referred to as amplitude modulations (AMs). The auditory system demonstrates a remarkable sensitivity to AMs, as evidenced by perceptual studies (e.g., Viemeister, 1979) and physiological investigations (see Joris *et al.*, 2004 for a comprehensive review). Similar to spectral masking effects in the audio-frequency domain, masking effects also occur in the AM frequency domain, resulting in reduced sensitivity to a target AM in the presence of a masking AM (Bacon and Grantham, 1989; Houtgast, 1989; Dau *et al.*, 1997a, 1997b; Ewert and Dau, 2000; Sek and Moore, 2003). Specifically, AM masking patterns provide evidence for a frequency-selective process, where the amount of AM masking decreases as the spectral distance between the masker and the target increases (Bacon and Grantham, 1989; Houtgast, 1989; Dau *et al.*, 1997a; Ewert and Dau, 2000; Ewert *et al.*, 2002; Sek and Moore, 2003; Moore *et al.*, 2009; Sek *et al.*, 2015; Füllgrabe *et al.*, 2021a, 2021b; Conroy *et al.*, 2023).

This frequency-selective characteristic of AM processing has been modelled using the concept of a modulation filterbank, which proposes that AM fluctuations are decomposed through an array of relatively broad bandpass modulation filters with a constant quality (Q) factor of approximately 1-2 (e.g., Dau *et al.*, 1997a, 1999; Ewert and Dau, 2000). Computational modelling studies have successfully applied the modulation filterbank concept to simulate data from various experimental paradigms, including simultaneous and non-simultaneous spectral and temporal signal detection and masking conditions (Dau *et al.*, 1997a, 1997b; Dau and Verhey, 1999; Verhey *et al.*, 1999; Ewert and Dau, 2000; Ewert *et al.*, 2002; Piechowiak *et al.*, 2007; Jepsen *et al.*, 2008; Jepsen and Dau, 2011; King *et al.*, 2019), sound texture perception (McDermott and Simoncelli, 2011; McDermott *et al.*, 2013; McWalter and Dau, 2015, 2017), auditory stream segregation (Elhilali *et al.*, 2009; Christiansen *et al.*, 2014), and speech

intelligibility (Jørgensen and Dau, 2011; Jørgensen et al., 2013; Relaño-Iborra et al., 2016, 2019; Zaar and Dau, 2017; Zaar et al., 2017; Steinmetzger et al., 2019; Zaar and Carney, 2022; for a review, see Relaño-Iborra and Dau, 2022). Furthermore, the modulation filterbank is conceptually consistent with the temporal dimension of a 'two-dimensional' spectro-temporal modulation filterbank, inspired by neural responses to spectro-temporally varying stimuli in the auditory cortex of ferrets (Kowalski *et al.*, 1996; Depireux *et al.*, 2001) and supported by data from perceptual learning and masking conditions (Sabin *et al.*, 2012; Oetjen and Verhey, 2015, 2017; Conroy *et al.*, 2022), as well as models of speech intelligibility (Elhilali *et al.*, 2003; Chi *et al.*, 2005; Zilany and Bruce, 2007; Chabot-Leclerc *et al.*, 2014). Overall, the versatility of the modulation filterbank model suggests that AM frequency selectivity is an essential auditory processing feature for quantitatively predicting perceptual data obtained with dynamically varying sounds.

Several studies have investigated the effects of age and hearing loss on AM perception, yielding mixed results. In terms of age effects, some studies showed a significant age-related deterioration in AM detection (He *et al.*, 2008; Füllgrabe *et al.*, 2015; Wallaert *et al.*, 2016), while other investigations did not find any effects on AM detection or AM depth discrimination (Schoof and Rosen, 2014; Paraouty *et al.*, 2016; Schlittenlacher and Moore, 2016; Paraouty and Lorenzi, 2017). Studies comparing listeners with normal hearing to listeners with hearing impairment (referred to hereafter as NH and HI listeners, respectively) have found either similar or lower (i.e., better) AM detection thresholds for the HI listeners (e.g., Moore *et al.*, 1992, 1996; Moore and Glasberg, 2001; Füllgrabe *et al.*, 2003; Sek *et al.*, 2015; Schlittenlacher and Moore, 2016; Wallaert *et al.*, 2017; Wiinberg *et al.*, 2019). The observed improvement in AM detection with hearing loss has been suggested to result from the loss of cochlear compression typically associated with sensorineural hearing loss (SNHL; Moore and Oxenham, 1998), which may lead to an increased internal representation of AM depth in HI listeners (Moore *et al.*, 1996; Jennings *et al.*, 2018). Additionally, the amplified neural coding of the envelope observed in mammals

and humans with SNHL (Kale and Heinz, 2010, 2012; Henry *et al.*, 2014; Zhong *et al.*, 2014; Millman *et al.*, 2017; Goossens *et al.*, 2018; Decruy *et al.*, 2020) may contribute, at least in part, to the effective increase in perceived AM depth with hearing loss. However, hearing loss has been shown to have a detrimental effect on supra-threshold AM depth discrimination (Schlittenlacher and Moore, 2016; Wiinberg *et al.*, 2019), suggesting that the increase in perceived AM depth may not necessarily be beneficial to AM depth discrimination.

Behavioral studies on AM frequency selectivity generally did not yield conclusive evidence of an effect of hearing loss (Takahashi and Bacon, 1992; Lorenzi *et al.*, 1997; Sek *et al.*, 2015). These studies focused on masked-threshold patterns (MTPs), which assess the detection threshold of an AM target in relation to the (center) frequency of a masker of fixed modulation depth. Takahashi and Bacon (1992) compared MTPs (using noise carriers and sinusoidal modulation targets and maskers) from ten young NH listeners and three groups of ten older listeners with mild hearing loss (classified as 'age-appropriate' normal hearing). While the older listeners faced more difficulties overall in completing the AM masking task, no simultaneous effect of age and hearing loss on AM frequency selectivity was found. Lorenzi *et al.* (1997) employed a similar approach with four young NH and three young HI listeners, observing comparable MTPs across both groups, despite a potential higher masking effect of modulation maskers located below the target modulation frequency in the HI listener group. Additionally, Sek *et al.* (2015), using sinusoidal carriers and sinusoidal modulation maskers, found no differences in AM masking patterns between six young NH and nine older HI listeners. These results suggested that neither age nor hearing loss affect AM frequency selectivity (Sek *et al.*, 2015).

However, recent results by Regev *et al.* (2023) showed a reduction in AM frequency selectivity associated with age when comparing young and older listeners with clinically normal hearing. These results are qualitatively consistent with the observations of reduced temporal selectivity inferred from auditory cortical functional magnetic resonance imaging (fMRI) responses by Erb *et al.* (2020). Regev

73 *et al.* (2023), using sinusoidal carriers and noise modulation maskers, compared MTPs from eleven
74 young NH listeners and ten older NH listeners. They found an age-related increase (i.e., deterioration)
75 in AM detection thresholds and a decrease in AM frequency selectivity, with estimated modulation
76 filter Q factors that were approximately halved in the older NH listeners compared to the young NH
77 listeners. Thus, the contrast between these recent findings and previous studies that did not identify a
78 simultaneous effect of age and hearing loss on AM frequency selectivity (Takahashi and Bacon, 1992;
79 Sek *et al.*, 2015) may suggest that hearing loss and age have antagonistic effects with regards to AM
80 frequency selectivity. In other words, hearing loss may 'counteract' the detrimental effects of ageing.
81 However, a direct comparison of MTPs between young NH listeners and similarly aged groups of
82 older NH and HI listeners tested using the same experimental approach has not yet been conducted.
83 The present study therefore aimed to independently evaluate the effects of hearing loss and age
84 on AM frequency selectivity by collecting data from HI listeners who were approximately age-matched
85 to the older NH listeners included in Regev *et al.* (2023), using the same experimental approach. Young
86 HI listeners were also included to explore whether a perceptual 'benefit' from hearing loss could be
87 observed in the absence of ageing effects. The study involved ten older and three young HI listeners,
88 ranging in age from 63 to 77 and 24 to 30 years, respectively. MTPs were collected using an AM
89 masking paradigm with sinusoidal carriers and bandpass Gaussian-noise modulation maskers (Ewert
90 *et al.*, 2002). Additionally, unmasked AM detection thresholds were obtained using sinusoidal carriers.
91 The data obtained from the older HI listeners were compared to those obtained from the older NH
92 listeners reported in Regev *et al.* (2023) to assess the effects of hearing loss on AM frequency selectivity.
93 Furthermore, the data from the older HI listeners were also compared to the young NH listener results
94 of Regev *et al.* (2023) to determine whether the lack of a simultaneous effect of age and hearing loss
95 observed in previous studies could be replicated (Takahashi and Bacon, 1992; Sek *et al.*, 2015). Despite
96 the limited number of young HI listeners , their data were included to provide insights into the effects

of hearing loss in the absence of ageing. To quantify the AM frequency selectivity reflected in the data at the listener group level, a simple approach applying linear fits separately to each skirt of the MTPs was employed.

II. METHODS

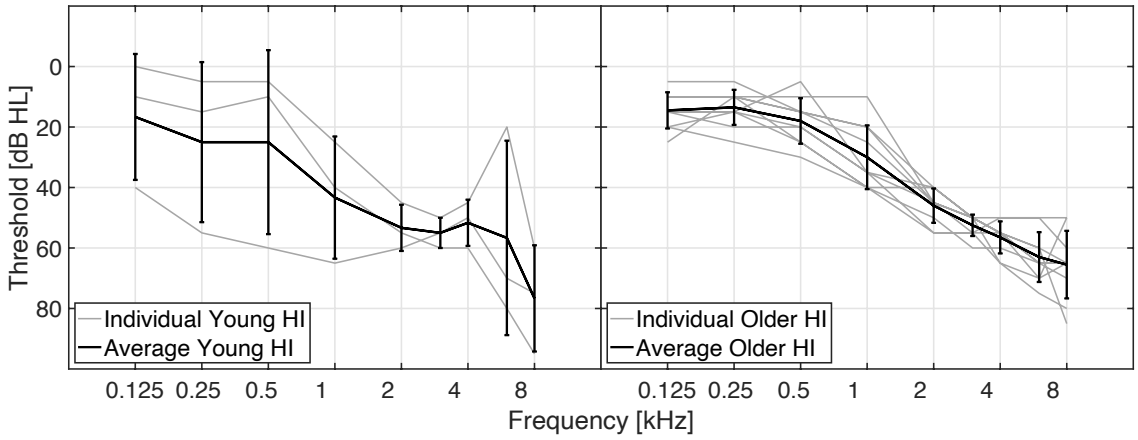
A. Listeners

Ten older HI listeners, aged 63-77 years (mean age = 70.4 years, 2 female) and three young HI listeners, aged 24-30 years (mean age = 26 years, all female) participated in the study. On average, the older HI listeners were 4.5 years older than the older NH listeners tested in Regev *et al.* (2023), while the young HI listeners were less than one year older than the young NH listeners. All listening experiments were conducted monaurally. The individual audiograms in the test ear are shown in Figure 1. The older HI listeners had a high-frequency sloping hearing loss, classified as an N2 or N3 standard audiogram (Bisgaard *et al.*, 2010).[1] The young HI listeners had more heterogeneous audiograms. For each listener, the test ear was selected as the one where the audiometric threshold at 3 kHz was within 50 to 60 dB HL. These limits were chosen to ensure that the listeners had a significant hearing loss around the AM carrier frequency (2.8 kHz) and, at the same time, that the stimuli's sound pressure level (SPL) would not exceed 85 dB to avoid discomfort. All listeners had a SNHL, as indicated by air-bone gaps ≤ 15 dB.[2] Working memory capacity was assessed with a reverse digit span test (RDS), implemented binaurally as described in Fuglsang *et al.* (2020) with an added linear gain according to the Cambridge formula (CamEq; Moore and Glasberg, 1998) using a maximum-gain limit of 30 dB at any frequency. The young and older HI listeners were found to have similar average RDS scores (0.56 and 0.53 on a normalized scale, respectively), which are also comparable to the average RDS scores

[1] The classification of the collected audiogram as one of the standard audiograms was performed using the lowest mean squared error between the standard audiograms and the audiometric thresholds at frequencies from 1 to 8 kHz.
[2] Except for one young HI listener who showed a gap of 20 dB at 4 kHz and one older HI listener who showed a gap of 20 dB 1 kHz.

118 reported for the young NH listeners in Regev *et al.* (2023) and slightly, but not significantly, higher
119 than for Regev *et al.*'s older NH cohort (0.59 and 0.42, respectively).

120 All participants gave written informed consent. Ethical approval for the study was provided by
121 the Science Ethics Committee of the Capital Region in Denmark (reference H-16036391). All
122 participants were financially compensated for their time.



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124 Figure 1: Individual and average audiograms in the test ear, for all participants. The left and right
125 panels show the audiograms for the young and older HI listeners, respectively. Individual audiograms
126 are shown in light gray, and group averages and standard deviations are shown in black.

127 **B. Procedure and apparatus**

128 The experimental conditions and parameters were the same as described in Regev *et al.* (2023),
129 with few modifications introduced to compensate for audibility loss. The stimulus presentation level
130 in all experiments was adjusted to be 30 dB sensation level (SL) for all HI listeners, based on their
131 hearing threshold at the carrier frequency, in an approach similar to that of Sek *et al.* (2015). This
132 resulted in presentation levels of 78-80 dB SPL for the young HI listeners and 73-85 dB SPL for the
133 older HI listeners (79 dB SPL on average for both groups).

134 The hearing threshold for the unmodulated pure-tone carrier at 2.8 kHz was measured adaptively.
135 The signal had a duration of 300 ms, including 50-ms raised-cosine ramps, and the intervals were

separated by 600 ms of silence. The step size was initially 8 dB, was then reduced to 4 dB after the first lower reversal, and was finally reduced to 2 dB after the second lower reversal. The threshold was defined as the average SPL of the target tone across the last six reversals. The threshold measurement was repeated at least three times, and the final threshold was computed as the average across all repetitions.

All listening tests were conducted in double-walled soundproof booths. All thresholds were measured using a 3-interval 3-alternative forced-choice (3I-3AFC) paradigm with a 1-up 2-down tracking procedure, measuring the 70.7%-correct point on the psychometric function (Levitt, 1971). The experiments were implemented using the AFC toolbox in MATLAB (Ewert, 2013). The stimuli were digitally generated in MATLAB (The Mathworks Inc., 2015; Natick, Massachusetts) with a sampling frequency of 48 kHz, converted to analog using an RME Fireface soundcard (Haimhausen, Germany), and played through Sennheiser HDA200 headphones (Wedemark, Germany). The output level was calibrated using a GRAS RA0039 ear simulator (Holte, Denmark) and the frequency response of the headphones was compensated using an inverse digital filter. The listeners received visual feedback during the tests ("correct"/"incorrect"). The order of testing was the same for both groups, as summarized in Appendix A.

C. Experimental conditions

1. Stimuli

The AM detection task and masked-threshold patterns (MTPs; Ewert and Dau, 2000) shared common aspects of the stimuli. In both conditions, the thresholds were measured for sinusoidal AM at target modulation frequencies of 4, 16, 64, and 128 Hz, imposed on a 2.8-kHz sinusoidal carrier. The carrier had a duration of 600 ms, including 50-ms raised-cosine onset and offset ramps. The target modulation (and masker modulation in the MTP task) had a duration of 500 ms, including 50-ms raised-cosine onset and offset ramps, and was temporally centered in the carrier. The target

160 modulation was imposed with a 0-degree starting phase. The stimulus intervals were separated by 500
161 ms of silence. The stimuli of all three intervals were calibrated to the desired presentation level to
162 ensure that no level cues were available. The tracking variable was the target's modulation depth,
163 expressed on a dB scale as $M = 20log_{10}(m)$, where m is the modulation depth on a linear scale. The
164 step size was initially 4 dB, was reduced to 2 dB after the first lower reversal, and was finally reduced
165 to 1 dB after the second lower reversal.

166 *a. AM detection thresholds*

167 For the AM detection task, the starting modulation depth of the target was -5 dB. The threshold
168 for any measurement run was defined as the average target modulation depth across the last six
169 reversals. The measurement at each target modulation frequency was repeated three times, and the
170 final threshold was defined as the average across repetitions. Additional measurements were included
171 if the standard error across repetitions exceeded 2 dB, until that limit was respected.[3] All listeners
172 completed two training runs (at the target modulation frequencies of 4 and 128 Hz). Figure 2 shows
173 an example of the stimulus envelope for the reference interval (i.e., the unmodulated carrier, in panel
174 A) and the target interval (i.e., the carrier modulated with the target modulation, in panel B) for a target
175 modulation frequency of 128 Hz.

176 *b. Masked-threshold patterns*

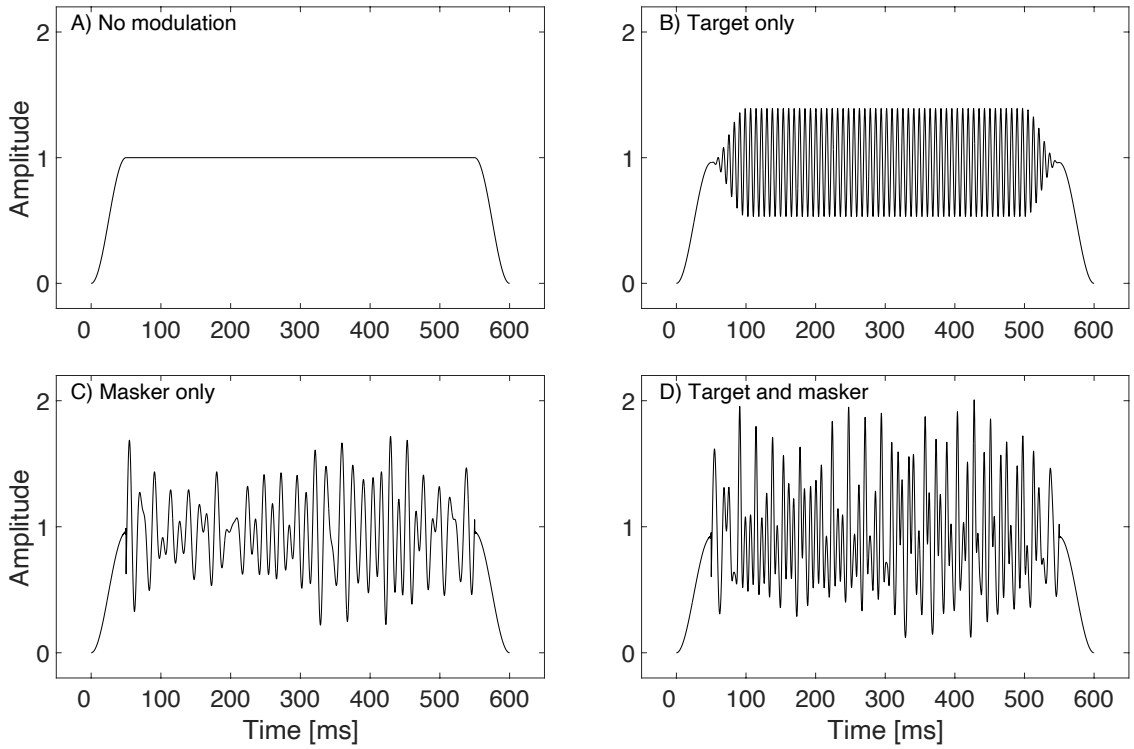
177 For the MTP task, the target and masker modulations were applied simultaneously on the carrier
178 using a multiplicative approach, as described in Regev *et al.* (2023). The masker modulation was a
179 narrow-band Gaussian noise with a fixed bandwidth corresponding to ½-octave when centered on
180 the target modulation frequency. For target modulation frequencies of 4 and 16 Hz, the masker
181 modulation was centered at frequencies ranging from -2 to +2 octaves relative to the target modulation

[3] Overall, 8 measurements were added across 2 of the young HI listeners and 1 measurement was added for a single older HI listener.

182 frequency, in steps of 2/3 octaves. In order to avoid cues from spectrally resolved modulation
183 sidebands, the highest masker-modulation center frequency was limited to 128 Hz, such that the
184 masker-modulation center frequencies only ranged from -2 to +2/3 and 0 octaves for the target
185 modulation frequencies of 64 and 128 Hz, respectively. Furthermore, for these target modulation
186 frequencies, a masked threshold was also measured for a masker modulation centered around 4 Hz,
187 corresponding to -4 and -5 octaves relative to the target modulation frequencies, respectively. For
188 these additional conditions, the lower cutoff frequency of the masker modulation was set to 1 Hz,
189 thus effectively reducing the masker's bandwidth. The resulting masker-modulation bandwidths and
190 center frequencies for all conditions are summarized in Appendix B. For each measurement run, a 2
191 s-long generation of the masker modulation was created. For each interval, a 500-ms segment,
192 randomly cut out of the long masker modulation, was then applied on the carrier. The root-mean
193 square (rms) modulation depth of the masker modulation was fixed to -10 dB.

194 The starting modulation depth of the target was 0 dB. The threshold for any measurement run
195 was defined as the average target modulation depth across the last eight reversals. The measurement
196 at each masker-modulation center frequency was repeated three times, and the final threshold was
197 defined as the average across repetitions. To avoid overmodulation, the maximum allowed modulation
198 depth was 0 dB. If the procedure required a modulation depth higher than 0 dB more than three times
199 over the course of a measurement run, the run was stopped and an extra measurement run was carried
200 out to replace it. If this happened more than 5 times for any condition, the threshold was considered
201 as unmeasurable. This was the case for a single older HI listener, where thresholds could not be
202 estimated at masker-modulation center frequencies of +2/3 and +4/3 octaves relative to the 4 Hz
203 target modulation frequency. This listener's masked thresholds at 4 Hz were therefore not included in
204 the statistical analyses, or in the figures below, such that the MTP analyses at 4 Hz included only nine
205 older HI listeners. Additional measurements were also included if the standard error across repetitions

206 exceeded 2 dB, until that limit was respected.[4] For each MTP, the listeners completed three training
207 run (at the masker-modulation center frequencies of -2, 0, and +2 octaves relative to the target
208 modulation frequency). Figure 2 shows an example of the stimulus envelope for the reference interval
209 (i.e., the carrier modulated with the masker modulation, in panel C) and the target interval (i.e., the
210 carrier modulated with both the target and masker modulations, in panel D), for a target modulation
211 frequency of 128 Hz and a masker-modulation center frequency of 64 Hz.
212



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214 Figure 2: Examples of the temporal envelopes of the stimuli used in the AM detection and MTP
215 experiments. Panel A: Reference interval in the AM detection task, represented by an unmodulated
216 sinusoidal carrier (2.8 kHz). Panel B: Target interval in the AM detection experiment, containing the

[4] Overall, a total of 2 measurements were added for a single young HI listener, and 7 measurements for 3 of the older HI listeners, due to aborted measurement runs. Furthermore, 5 measurements were added for 2 of the young HI listeners and 10 measurements for 4 of the older HI listeners, due to excessive standard errors. Masked thresholds could not be estimated for a single older HI listener, at masker modulation center frequencies of +2/3 and +4/3 octaves relative to the 4-Hz target modulation frequency.

same carrier as in Panel A modulated by a sinusoidal target modulation (128 Hz). Panel C: Reference interval in the MTP experiment, containing the same carrier as in Panel A modulated by a narrowband-noise masker modulation (between 43.6 and 88.2 Hz, centered at 64 Hz). Panel D: Target interval in the MTP experiment, with the same carrier as in Panel A modulated by the sinusoidal target modulation and the narrowband-noise masker modulation.

2. Estimates of AM frequency selectivity

Ewert *et al.* (2002) and Regev *et al.* (2023) used the envelope power spectrum model of masking (EPSM; Ewert and Dau, 2000) to quantify the AM frequency selectivity reflected in their MTPs, by finding the Q-factor of the best-fitting bandpass modulation filter representing the experimental data. However, high levels of asymmetry were observed in the MTPs in the present study (as described in detail below), which are not consistent with the EPSM's assumption of symmetry. Hence, a simplified approach was used here to quantify AM frequency selectivity. The best-fitting linear approximation (in terms of the least-squared error) was obtained separately for each skirt using the masked thresholds at the masker locations ranging from -2 to +2 octaves. Each linear fit was constrained to crossing the on-target masked threshold. The bandwidth of the asymmetrical modulation filter was then estimated by measuring the spectral distance between the 3-dB-down points on the fits obtained for each skirt when interpolating across masker locations ranging from -4 to +4 octaves. For the 128-Hz pattern, the high-frequency cutoff was estimated by assuming symmetry around the target modulation frequency. Finally, the metric quantifying AM frequency selectivity was obtained as an overall 'Q-factor' by computing the ratio of the filter's characteristic (modulation) frequency to the fitted bandwidth.

D. Statistical analysis

Analyses of variances (ANOVAs) of linear mixed-effects model fittings were used to assess the differences between the results for the older HI listeners obtained in the present study and the data for the NH listeners obtained in Regev *et al.* (2023). Each model and corresponding ANOVA were applied twice. First, to estimate the effects of hearing loss in isolation from age effects, the results for the older HI listeners were compared with the results for the older NH listeners. Second, using an analysis comparable to that employed in previous studies, the results for the older HI listeners were compared with the results obtained for the young NH listeners. For the analysis of the AM detection thresholds, the listeners were considered as a random effect and group classification and modulation frequency were considered as fixed effects. The MTPs were analyzed separately for each target modulation frequency. The listeners were considered as a random effect and group classification and masker-modulation center frequency were considered as fixed effects. Levene's test was used to assess the homoskedasticity of the residuals and Shapiro-Wilk's test was used to assess the normality of residual's distribution.[5] Post-hoc analyses were conducted using estimated marginal means and a Holm-Bonferroni correction criterion was applied for multiple comparisons. The level of statistical significance was set to 5% in all analyses. Due to the low number of young HI listeners (3), no statistical analysis was performed to compare their data to those of the other groups.

[5] Levene's test was not passed for one of the models applied, while Shapiro-Wilk's test was not passed for 3 of the other models. However, the deviations were minor, and the model predictions matched the average group data accurately. Hence, no transformations of the data were applied in order to keep all applied analyses consistent.

III. RESULTS

A. AM detection thresholds

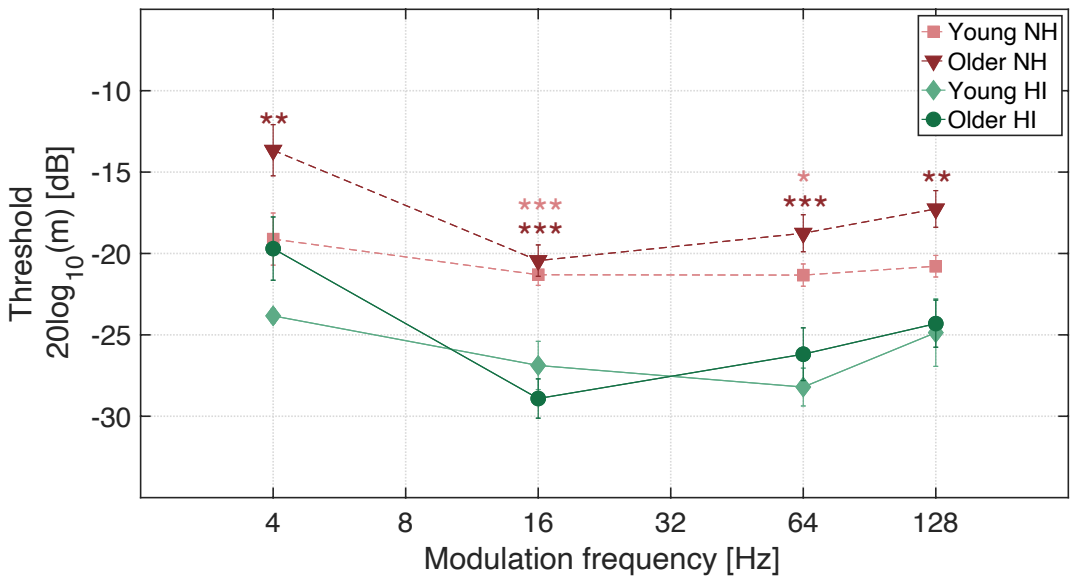

Figure 3 (Color online): Average AM detection thresholds for each listener group as a function of modulation frequency. The data for the young HI listeners are indicated by diamonds connected by solid lines. The data for the older HI listeners are shown as circles connected by solid lines. The results for the young and the older NH listeners (dashed lines; reproduced from Regev *et al.*, 2023) are shown as triangles and squares, respectively. Means and standard errors are shown. The stars indicate the level of statistical significance of the differences in thresholds between the older HI and older NH listeners (dark stars), and the older HI and young NH listeners (light stars; $*p < 0.05$, $**p < 0.01$, $***p < 0.001$).

Figure 3 shows the mean AM detection thresholds as a function of modulation frequency, for both the young HI (diamonds) and the older HI listeners (circles), as well the young NH (squares) and the older NH listeners (triangles) reproduced from Regev *et al.* (2023). Substantial levels of individual variability were observed in the data (see supplementary Figure 1). The statistical analysis comparing the thresholds for the older HI and the older NH listeners revealed a significant main effect of group

[$F_{1,18} = 21.21, p < 0.001$] and modulation frequency [$F_{3,54} = 22.84, p < 0.001$]. The post-hoc analysis revealed that the older HI listeners had significantly lower (i.e., better) AM detection thresholds than the older NH listeners at all modulation frequencies [effect size (M) $= -6.04$ dB, standard error (SE) $= 1.995$ dB; $M = -8.47$ dB, $SE = 1.995$ dB; $M = -7.43$ dB, $SE = 1.995$ dB; $M = -7.05$ dB, $SE = 1.995$ dB, for 4, 16, 64, and 128 Hz, respectively].

The statistical analysis comparing the thresholds for the older HI and the young NH listeners revealed a significant main effect of group [$F_{1,19} = 8.13, p = 0.01$] and modulation frequency [$F_{3,57} = 14.66, p < 0.001$], as well as a significant interaction between both factors [$F_{3,57} = 5.26, p = 0.003$]. The post-hoc analysis revealed that the older HI listeners had significantly lower AM detection thresholds than the young NH listeners at modulation frequencies of 16 Hz [$M = -7.6$ dB, $SE = 1.82$ dB] and 64 Hz [$M = -4.86$ dB, $SE = 1.82$ dB].

B. Masked-threshold patterns (MTPs)

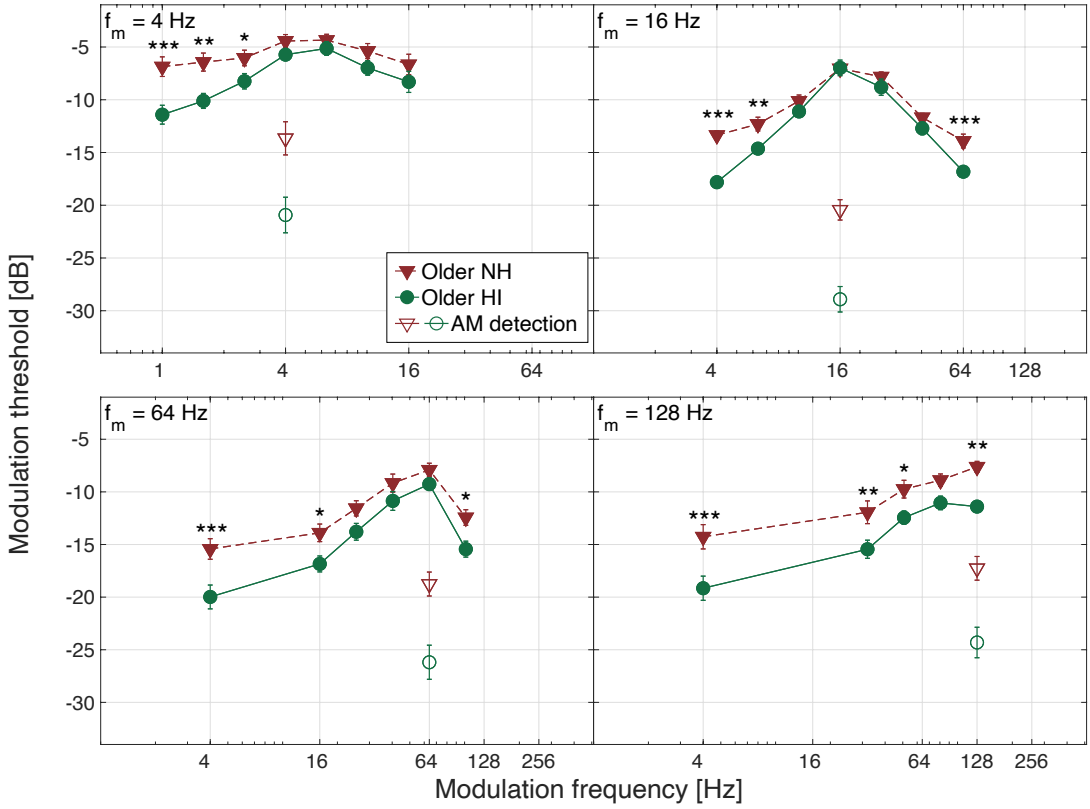

Figure 4 (Color online): Average MTPs (filled symbols) and AM detection thresholds (open symbols, replotted from Figure 3[6]) for the older HI and the older NH listeners. The data for the HI listeners are indicated by the circles connected by solid lines and the data for the NH listeners (reproduced from Regev *et al.*, 2023) are shown as triangles connected by dashed lines. Each panel represents the results for a specific target modulation frequency: 4 Hz (top left), 16 Hz (top right), 64 Hz (bottom left), and 128 Hz (bottom right). Note that the data from one of the older HI listeners was excluded from the 4-Hz panel for both the MTP and AM detection threshold. Means and standard errors are shown. Stars indicate the level of statistical significance of the differences between in masked thresholds between the two groups (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

[6] The AM detection threshold for a target modulation frequency of 4 Hz reflects the data for only 9 of the 10 older HI listeners.

Figure 4 shows the mean MTPs for the older HI (circles) and the older NH listeners (triangles; reproduced from Regev *et al.*, 2023). Each panel shows the MTPs for a specific target modulation frequency. The mean AM detection thresholds are also shown, indicated by the open symbols (replotted from Figure 3[6]). The statistical analysis comparing the older HI and the older NH listeners revealed a significant main effect of group at all target modulation frequencies [$F_{1,17} = 7.31, p = 0.015$; $F_{1,18} = 20.18, p < 0.001$; $F_{1,18} = 8.70, p = 0.009$; $F_{1,18} = 14.43, p = 0.001$, for 4, 16, 64, and 128 Hz, respectively]. A significant interaction between listener group and masker-modulation center frequency was found at the target modulation frequencies of 4 Hz [$F_{6,102} = 3.36, p = 0.005$] and 16 Hz [$F_{6,108} = 4.64, p < 0.001$], whereas the interaction approached, but did not reach, significance at the target modulation frequency of 64 Hz [$F_{5,90} = 2.01, p = 0.085$]. At the target modulation frequency of 4 Hz, the post-hoc analysis revealed that the older HI listeners had significantly lower (better) masked thresholds than the older NH listeners for the masker modulations centered at -2, -4/3, and -2/3 octaves relative to the target frequency. At 16 Hz, the post-hoc analysis revealed that the older HI listeners had significantly lower masked thresholds than the older NH listeners for the masker modulations centered at -2, -4/3, and +2 octaves relative to the target frequency. At 64 Hz, the post-hoc analysis revealed that the older HI listeners had significantly lower masked thresholds than the older NH listeners for the masker modulations centered at -4, -2, and +2/3 octaves relative to the target frequency. Finally, at 128 Hz, the post-hoc analysis revealed that the older HI listeners had significantly lower masked thresholds than the older NH listeners for the masker modulations centered at -5, -2, -4/3, and 0 octaves relative to the target frequency. The details of the post-hoc analyses can be found in Appendix B. Overall, a sharpening of the MTPs was found for the older HI listeners, as compared to the older NH listeners, at the target modulation frequencies of 4 Hz (on the low-frequency skirt), 16 Hz, and 64 Hz. Conversely, the high-frequency skirt of the 4-Hz MTP suggests a similar selectivity for the older HI and NH listeners. Finally, the MTP at 128

Hz reflects a general improvement (i.e., decrease) of the masked thresholds for the older HI listeners, but an overall broader pattern, compared to the older NH listeners. High levels of asymmetry were also observed in the older HI listener's MTPs, as quantified by the slopes of the obtained linear fits (see supplementary Figure 2). At the target modulation frequency of 4 Hz, this was reflected by a steeper slope of the low-frequency skirt (3 dB/octave) than the high-frequency skirt (1 dB/octave) and an off-target peak threshold (for the masker centered at +2/3 octaves relative to the target frequency). A similar observation was made at 16 Hz, with a steeper slope of the low-frequency skirt (5.6 dB/octave) than that that of the high-frequency skirt (4.6 dB/octave). At 64 Hz, the older HI listeners displayed a much shallower slope of the low-frequency skirt (3.6 dB/octave) compared to the high-frequency side (9.3 dB/octave), although the latter was computed based only on the average masked threshold at +2/3 octaves.

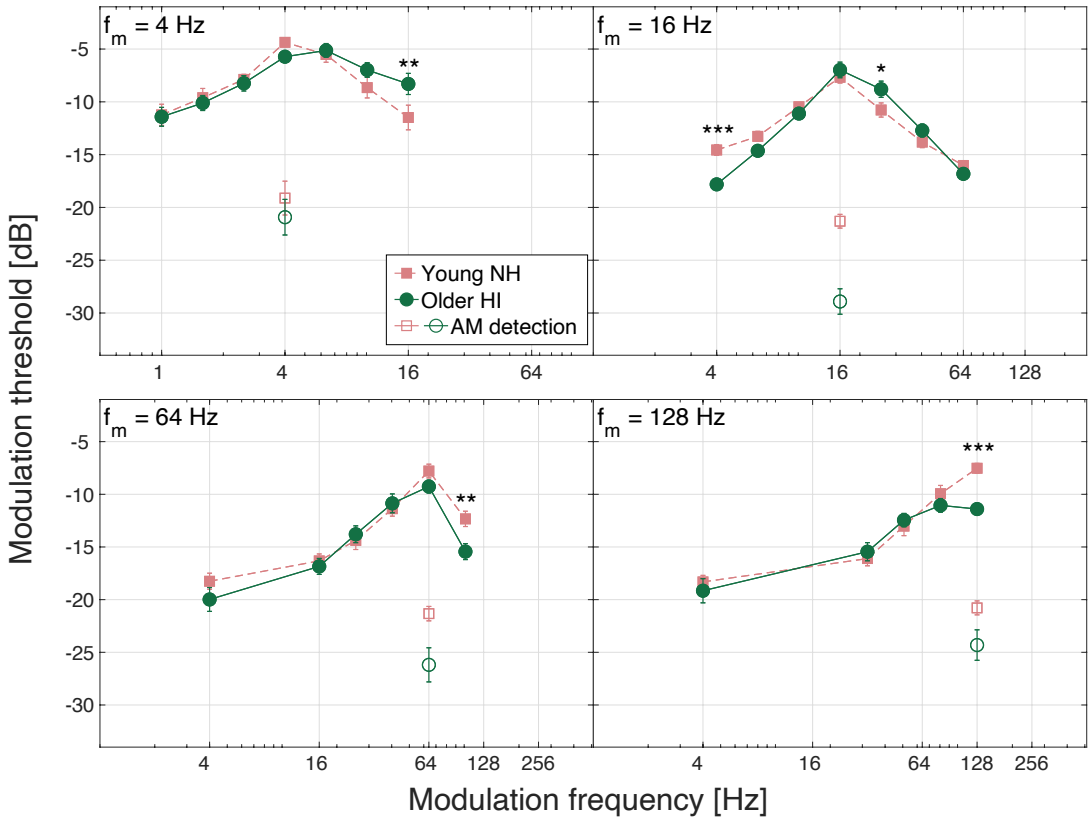

Figure 5 (Color online): Average MTPs (filled symbols) and AM detection thresholds (open symbols, replotted from Figure 3[6]) for the older HI and young NH listeners. The data for the older HI listeners are shown as circles connected by solid lines and the data for the young NH listeners (reproduced from Regev et al., 2023) are indicated by the squares connected by the dashed lines. Each panel represents the results for a specific target modulation frequency: 4 Hz (top left), 16 Hz (top right), 64 Hz (bottom left), and 128 Hz (bottom right). Note that the data from one of the older HI listeners was excluded from the 4-Hz panel for both the MTP and AM detection threshold. Means and standard errors are shown. Stars indicate the level of statistical significance of the differences in masked thresholds btween the two groups (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

Figure 5 shows the mean MTPs obtained from the older HI (circles) and the younger NH listeners (squares; reproduced from Regev *et al.*, 2023). Each panel shows the MTPs for a specific target modulation frequency. The mean AM detection thresholds are also shown and indicated by the open

symbols (replotted from Figure 3[6]). The statistical analysis comparing the older HI and the young NH listeners revealed no main effect of group for any of the target modulation frequencies. However, a significant interaction between listener group and masker-modulation center frequency was found at all target modulation frequencies [$F_{6,108} = 3.95, p = 0.001$; $F_{6,114} = 8.1, p < 0.001$; $F_{5,95} = 4.12, p = 0.002$; $F_{4,76} = 6.3, p < 0.001$, for 4, 16, 64, and 128 Hz, respectively]. At the target modulation frequency of 4 Hz, the post-hoc analysis revealed that the older HI listeners had significantly higher (worse) masked thresholds than the young NH listeners for the masker modulations centered at +2 octaves relative to the target. At 16 Hz, the post-hoc analysis revealed that the older HI listeners had significantly lower (i.e., better) masked thresholds for the masker modulations centered at -2 octaves relative to the target frequency, and significantly higher masked thresholds than the young NH listeners for masker modulations centered at +2/3 octaves above relative to the target frequency. At 64 Hz, the post-hoc analysis revealed that the older HI listeners had significantly lower masked thresholds than the young NH listeners for the masker modulations centered at +2/3 octaves relative to the target frequency. Finally, at 128 Hz, the post-hoc analysis revealed that the older HI listeners had significantly lower masked thresholds than the young NH listeners for the masker modulations centered at the target modulation frequency. The details of the post-hoc analyses can be found in Appendix B.

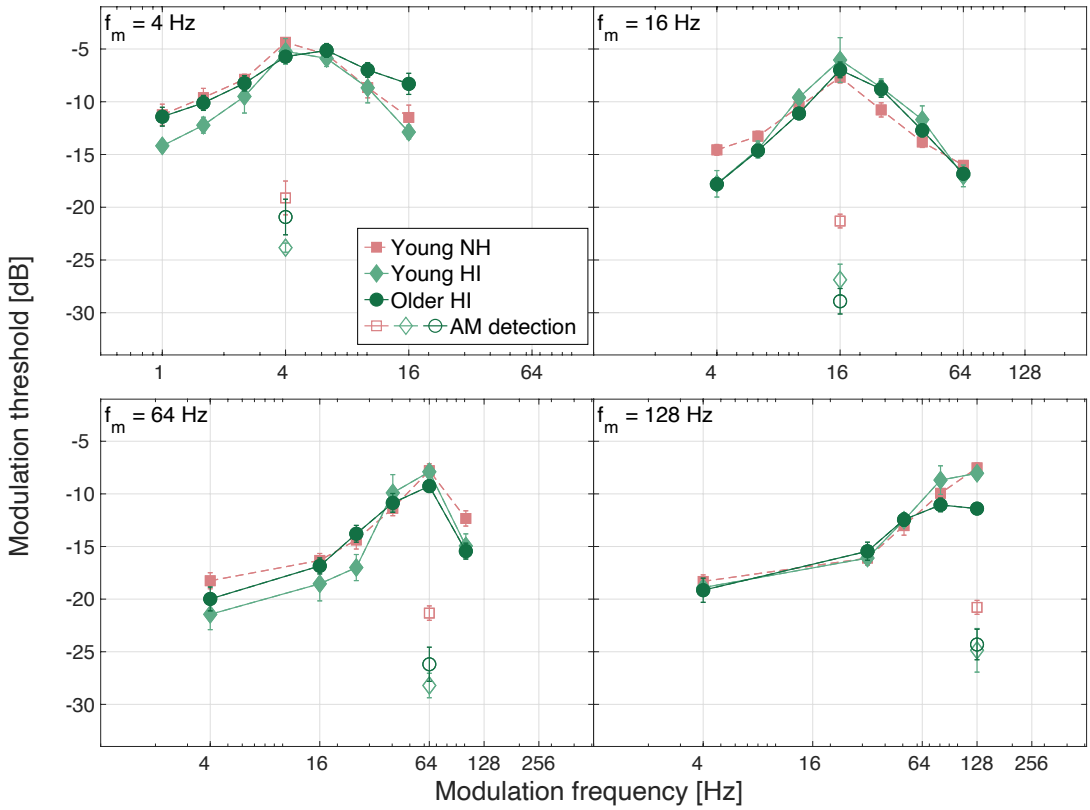

Figure 6 (Color online): Average MTPs (filled symbols) and AM detection thresholds (open symbols, replotted from Figure 3[6]). The data for the young and older HI listeners (solid lines) are indicated by the diamonds and circles, respectively. The data for the young NH listeners (reproduced from Regev *et al.*, 2023) are shown as dashed lines and squares. Each panel represents the results for a specific target modulation frequency: 4 Hz (top left), 16 Hz (top right), 64 Hz (bottom left), and 128 Hz (bottom right). Note that the data from one of the older HI listeners was excluded from the 4-Hz panel for both the MTP and AM detection threshold. Means and standard errors are shown.

Figure 6 shows the mean MTPs for both the young HI (diamonds) and the older HI listeners (circles) as well as the data from the young NH listeners (squares) as obtained in Regev *et al.* (2023). Each panel shows the MTPs for a specific target modulation frequency. The mean AM detection thresholds are also shown and indicated by the open symbols (replotted from Figure 3[6]).

Similar to the MTPs obtained from the older HI listeners, high levels of asymmetry were also observed in the MTPs of the young HI listeners. At the target modulation frequency of 4 Hz, this was reflected by a steeper slope of the low-frequency skirt (4.8 dB/octave) than the high-frequency skirt (3.3 dB/octave). A similar observation was made at 16 Hz, with a steeper slope of the low-frequency skirt (6 dB/octave) than that of the high-frequency skirt (5 dB/octave). At 64 Hz, the young HI listeners displayed a much shallower low-frequency skirt (5.6 dB/octave) compared to the high-frequency side (10.6 dB/octave), although the latter was computed based only on the average masked threshold at +2/3 octaves.

Table 1 summarizes the overall Q-factors (representing the ratio of the filter's characteristic frequency to its bandwidth estimated at the 3-dB-down point) fitted to the average data of each listener group and indicates the fits' mean square errors (MSEs, in dB) in parentheses. The table also shows the ratio of the fitted Q-factors for each group to the Q-factor fitted for the young NH listeners, thus providing a comparison to the baseline represented by the young NH listeners. A ratio higher than 1 indicates sharper tuning for the listener group in question as compared to the young NH listeners, and vice-versa. For the older NH listeners, the reduced Q-factor ratio reflects the age-related reduction of AM frequency selectivity already shown by Regev *et al.* (2023). In contrast, the results for the older HI listeners suggest a sharper tuning for this group as compared to the older NH listeners at the modulation frequencies of 4, 16, and 64 Hz, and reduced AM frequency selectivity at 128 Hz. Compared to the young NH listeners, the results for the older HI listeners show a similar, or slightly greater, AM frequency selectivity at the modulation frequencies of 16 and 64 Hz, and a broader tuning at 4 and 128 Hz. The young HI listeners' results suggest generally greater AM frequency selectivity compared to the older HI listeners, and even higher Q-factors (i.e., sharper tuning) than the young NH listeners at the modulation frequencies of 4, 16, and 64 Hz.

Table 1: Overall fitted Q-factors, defined as the ratio of the filter's characteristic frequency to its bandwidth estimated at the 3-dB-down point, and MSEs for the modulation filters fitted to the average group data using an asymmetric linear fitting approach. The table also shows the ratio of fitted Q-factors for each group to the Q-factor fitted for the young NH listeners (representing the baseline).

Target modulation frequency [Hz]	**Estimated "Q-factor"** ***(Overall MSE [dB])***				**Q/Q_{YNH}**		
	YNH	**ONH**	**YHI**	**OHI**	**ONH**	**YHI**	**OHI**
4	0.77 *(0.35)*	0.10 *(0.16)*	0.81 *(0.78)*	0.14 *(0.30)*	0.13	1.05	0.18
16	0.96 *(0.14)*	0.75 *(0.44)*	1.24 *(0.38)*	1.13 *(0.30)*	0.78	1.29	1.18
64	1.38 *(0.15)*	1.14 *(0.09)*	1.90 *(1.0)*	1.45 *(0.14)*	0.83	1.38	1.05
128	0.96 *(0.05)*	0.40 *(0.10)*	0.82 *(0.98)*	0.27 *(0.96)*	0.42	0.85	0.28

403 **IV. DISCUSSION**

404 **A. Summary of main findings**

405 This study aimed to investigate the potentially 'antagonistic' effects of hearing loss and age on AM
406 frequency selectivity. These opposing effects were suggested based on recent findings of an age-related
407 reduction in AM frequency selectivity (Regev et al., 2023), which appeared to contradict previous
408 conclusions that neither age nor hearing loss affect AM frequency selectivity (Takahashi and Bacon,
409 1992; Sek *et al.*, 2015). Behavioral MTPs and unmasked AM detection thresholds were collected from
410 three young and ten older HI listeners (24-30 and 63-77 years), and the results were compared to the
411 data obtained from young and older NH listeners in Regev *et al.* (2023). Both HI groups demonstrated
412 lower (i.e., better) AM detection thresholds compard to their similarly aged NH counterparts, and the
413 older HI listeners also exhibited lower detection thresholds than the young NH listeners for target
414 modulation frequencies above 4 Hz (Figure 3). Furthermore, for target modulation frequencies below
415 128 Hz, the older HI listeners generally showed greater AM frequency selectivity than the older NH
416 listeners (Figure 4). When compared to the young NH listeners, the older HI listeners displayed an
417 asymmetric broadening of the MTP at the target modulation frequency of 4 Hz (with a shallower high-
418 frequency skirt), but similar or even slightly sharper tuning at 16 and 64 Hz (Figure 5). At the target
419 modulation frequency of 128 Hz, the older HI listeners showed lower masked thresholds overall
420 compared to the older NH listeners (with an average offset of approximately 3.4 dB) and similar
421 masked thresholds to the young NH listeners for the off-target maskers, effectively indicating reduced
422 AM frequency selectivity compared to both NH groups. The data from the young HI listeners
423 suggested greater AM frequency selectivity compared to the older HI listeners, as well as generally
424 sharper tuning compared to the young NH listeners (Figure 6). Notably, both the young and older HI
425 listeners exhibited high levels of asymmetry in their MTPs, with generally steeper low-frequency skirts
426 compared to the high-frequency side. Finally, the best-fitting Q-factor obtained using a simple linear

427 fitting approach supported the previous observations and suggested that AM frequency selectivity in
428 HI listeners is similar to, or greater than, that in similarly aged NH listeners, except at the highest
429 target modulation rate of 128 Hz (Table 1).

430 **B. Antagonistic effects of hearing loss and age**

431 The results obtained from both the AM detection and MTP tasks suggest a general perceptual
432 benefit from hearing loss, in terms of an increased detectability of the target modulation and a
433 sharpening of the masked patterns. This benefit effectively counteracts the detrimental effects of age
434 on AM detection and AM frequency selectivity. The improvement of AM detection thresholds in HI
435 listeners compared to NH listeners is consistent with previous studies (e.g., Bacon and Gleitman, 1992;
436 Moore and Glasberg, 2001; Sek *et al.*, 2015; Schlittenlacher and Moore, 2016; Wallaert *et al.*, 2017;
437 Wiinberg *et al.*, 2019). It has been suggested that this improvement is due to an effectively increased
438 internal representation of the signal's AM depth resulting from the loss of compression commonly
439 associated with SNHL (Moore *et al.*, 1996; Jennings *et al.*, 2018). The trends observed in the data from
440 the young HI listeners support the notion that age is detrimental to AM detection whereas SNHL
441 provides a perceptual benefit. Conversely, previous AM masking studies comparing young NH and
442 older HI listeners at low target modulation frequencies (≤ 16 Hz) found no differences in MTPs
443 (Takahashi and Bacon, 1992; Sek *et al.*, 2015) and concluded that neither SNHL nor age affect AM
444 frequency selectivity. The present results are broadly consistent with the observation that MTPs are
445 similar for young NH and older HI listeners at low modulation frequencies, although an asymmetric
446 broadening of the 4-Hz MTP was found for the older HI listeners, with a shallower high-frequency
447 skirt. However, the collected data also showed that SNHL generally improves AM frequency
448 selectivity for listeners of similar age at target modulation frequencies below 128 Hz. In contrast, the
449 data obtained at 128 Hz consistently showed lower masked thresholds for the older HI listeners
450 compared to the older NH listeners, indicating a reduction in AM frequency selectivity. Additionally,

451 a slight broadening of the pattern at 128 Hz was observed for young HI listeners compared to the
452 young NH group.

453 The results of the present study reveal that young listeners generally perform better than older
454 listeners with the same hearing status, as already shown by Regev *et al.* (2023). Furthermore, although
455 a sharpening of the MTPs in HI listeners was not observed on each skirt of the patterns, HI listeners
456 generally outperformed similarly aged NH listeners in terms of AM detection thresholds and tuning
457 of the MTPs.

458 **C. Potential mechanism underlying the perceptual benefit of hearing loss**

459 The underlying auditory processes that account for the sharper MTPs observed in the older HI
460 listeners compared to older NH listeners may not be straightforward. It seems unlikely that SNHL
461 would improve AM frequency selectivity by 'restoring' the bandwidth of the hypothetical modulation
462 filters. Instead, the greater AM frequency selectivity observed here in the HI listeners may be an
463 'apparent' effect resulting from the reduced peripheral compression which is typically associated with
464 SNHL. One notable characteristic of the data obtained from the HI listeners is the strong asymmetry
465 of the MTPs, with a steeper slope on the low-frequency skirt compared to the high-frequency side.
466 This observation was also made by Regev *et al.* (2023) regarding their NH listener data, although the
467 effect was less prominent than in the present study. The asymmetry suggests that an additional cue
468 for the detection of the target may be available when the modulation maskers are centered below -
469 but not above - the target modulation frequency. The existence of such a cue was discussed in previous
470 studies by Bacon and Grantham (1989) and Strickland and Viemeister (1996), who observed negative
471 masking when an AM target was masked by low-frequency AM maskers relative to the target
472 modulation frequency. They argued that listeners may be able to detect the target modulation in the
473 temporal dips of the masker modulation, or 'listen in the dips', which is a detection cue analogous to
474 the release from masking provided by envelope fluctuations in spectral masking tasks (e.g., Buus,

475 1985). In the present study, the random dips occurring in the modulation masker would be longer
476 than (or close to) one cycle of the target for masker modulations with center frequencies below the
477 target, while this would not be the case for modulation maskers centered above the target.
478 Consequently, it is possible that these local temporal features in the stimulus aid the detection of the
479 target in the presence of low-frequency maskers. Furthermore, the data suggest that such a cue, if
480 present, may be more salient for HI listeners than for NH listeners. The loss of cochlear compression
481 in HI listeners might increase the target's AM depth glimpsed in the temporal valleys of the masker,
482 further enhancing the detectability of the target. This notion is also consistent with the findings of
483 Wallaert *et al.* (2017), which showed a greater improvement in AM detection thresholds for HI listeners
484 compared to NH listeners when increasing the numbers of cycles of the target modulation, suggesting
485 an enhanced temporal integration in the HI listeners. This may imply that HI listeners require fewer
486 cycles of the target modulation to detect its presence, potentially contributing to the improved
487 performance measured in the lower skirt of the MTPS.

488 If this detection mechanism indeed mediated the sharper MTPs in HI listeners, investigating AM
489 frequency selectivity using an AM forward-masking paradigm should eliminate the perceptual benefit
490 of SNHL. AM forward masking has been used as an alternative approach to investigate AM frequency
491 selectivity (Wojtczak and Viemeister, 2005; Moore *et al.*, 2009; Füllgrabe *et al.*, 2021a, 2021b) because
492 it avoids extraneous cues resulting from the interaction between target and masker modulations. While
493 it remains unclear whether AM simultaneous and AM forward-masking paradigms reveal the same
494 underlying AM frequency-selective process, a study comparing age-matched NH and HI listeners
495 using such a paradigm could provide valuable insights into the origins of the observed asymmetry.
496 However, such a study has not been conducted thus far. Additionally, computational auditory models
497 could be employed to assess the plausibility of 'listening in the dips' as a mechanism underlying the
498 present results.

499 The hypothesis that increased sensitivity to the temporal envelope, resulting from the loss of
500 cochlear compression, offers a perceptual advantage for HI listeners is also supported by the findings
501 of Bianchi *et al.* (2016). Their study demonstrated that pitch-discrimination performance for
502 unresolved complex tones was comparable between older HI and young NH listeners when the
503 stimulus envelope could be effectively amplified through reduced compression (i.e., when it was
504 maximally peaky). However, performance was worse for the older HI listeners in other cases. In
505 addition to, or partially connected with, the loss of cochlear compression, the better-than-normal AM
506 detection thresholds and AM frequency selectivity observed in the HI listeners may also be related to
507 the increased neural coding of the envelope which has been shown both in animal models and humans
508 (Kale and Heinz, 2010, 2012; Henry *et al.*, 2014; Zhong *et al.*, 2014; Millman *et al.*, 2017; Goossens *et*
509 *al.*, 2018; Decruy *et al.*, 2020). This increased internal representation of the envelope, while it may
510 reflect a listening advantage in simple AM detection and masking paradigms such as the ones
511 considered in the present study, has been suggested to ultimately be detrimental to speech intelligibility
512 in noise (Millman *et al.*, 2017; Goossens *et al.*, 2018; Decruy *et al.*, 2020). Hence, it could potentially
513 contribute to the difficulties often experienced by HI listeners in complex listening scenarios.

514 **D. Limitations of the study**

515 The presentation levels used in the present study were not directly comparable to those employed
516 by Regev *et al.* (2023) with NH listeners. Regev *et al.* used a fixed 65 dB SPL (corresponding to average
517 levels of 67 and 57 dB SL for the young and older NH listeners, respectively), while the present study
518 adjusted the level for the HI listeners to be at 30 dB SL (corresponding to 79 dB SPL on average),
519 following a similar approach to Sek *et al.* (2015). This methodological difference implies that the
520 presentation level was both lower in terms of SL (by 27-37 dB) and higher in terms of SPL (by 14 dB)
521 for the HI listeners compared to the NH listeners. Previous studies have highlighted the effect of the
522 interaction between presentation level and hearing status on AM detection thresholds, often finding

523 lower AM detection thresholds for HI listeners than for NH listeners at equal SL, but similar
524 thresholds at equal SPL (Bacon and Gleitman, 1992; Moore and Glasberg, 2001; Füllgrabe *et al.*, 2003;
525 Schlittenlacher and Moore, 2016; Wallaert *et al.*, 2017; Moore *et al.*, 2019), although some studies still
526 found differences at equal SPL (Sek *et al.*, 2015; Jennings *et al.*, 2018). Hence, it is possible that the
527 present results were influenced by the difference in presentation levels across the two listener groups.
528 However, the present finding that the HI listeners showed lower AM detection thresholds than the
529 NH listeners at both lower SLs and higher SPLs seems consistent with previous studies that reported
530 similar results (Füllgrabe *et al.*, 2003; Jennings *et al.*, 2018). Füllgrabe *et al.* (2003) observed an increased
531 difference in AM detection thresholds between NH and HI listeners when the experiment was
532 repeated with a fixed SL for all participants. Additionally, Wojtczak (2011) investigated the effects of
533 carrier level on AM frequency selectivity with NH listeners and found that a reduction in SL led to an
534 increase in AM detection thresholds and a broadening of the MTPs. Therefore, it is likely that
535 investigating NH and HI listeners at equal SL would have further increased the observed differences
536 between the two groups in the present study. However, it remains unclear whether lower AM
537 detection thresholds and sharper MTPs would still be found in the HI listeners compared to the NH
538 listeners if they were tested at equal SPL.

539 The small number of young HI listeners included in this study, along with the significant variability
540 in their audiograms (except for the frequency of interest), limited the conclusions that could be drawn
541 from their data. Despite the small group size, the results from the young HI listeners in this study may
542 offer some valuable insights. Indeed, the data obtained across the three young HI listeners were
543 consistent with the observations made based on the other listener groups. Specifically, young listeners
544 exhibited sharper tuning than older listeners with the same hearing status, and HI listeners generally
545 demonstrated sharper tuning compared to similarly aged NH listeners. Conducting further

546 investigations with a larger sample of young HI listeners may help validate the trends identified in the
547 present study.

548 Finally, the method used to quantify AM frequency selectivity in the present study was limited by
549 the pronounced asymmetry observed in the MTPs. Previous studies quantified the tuning of the
550 hypothetical modulation filters using the EPSM (Ewert and Dau, 2000; Ewert *et al.*, 2002; Regev *et al.*,
551 2023), which assumes symmetrical filters centered around the characteristic modulation frequency.
552 However, the present results do not support this assumption, indicating the need for revising the
553 EPSM to incoporate more flexible filter shapes. Similar conclusions were drawn by Regev *et al.* (2023),
554 who observed large variability in individual MTPs. Consequently, the Q-factor values reported in this
555 study for the young and older NH listeners differ from those reported by Regev *et al.* (2023) due to
556 the different approaches used to quantify AM frequency selectivity. However, the overall finding of
557 lower Q factors for the older NH listeners compared to the young NH listeners remains consistent
558 between the two investigations.

559 **V. CONCLUSION**

560 The present study investigated the effects of hearing loss on AM frequency selectivity by
561 employing a simultaneous AM masking task. Ten older and three young HI listeners were included in
562 the study, ranging in age from 63-77 and 24-30 years, respectively. These age ranges were
563 approximately matched to the young and older NH listeners tested in the study conducted by Regev
564 *et al.* (2023). The findings revealed that HI listeners exhibited lower AM detection thresholds and
565 generally sharper MTPs compared to the NH listeners, suggesting that hearing loss may counteract
566 the detrimental effects of age on AM frequency selectivity. The MTPs showed strong levels of
567 asymmetry, with generally steeper low-frequency skirts. A potential mechanism proposed to explain
568 these results was the detection of the target modulation in the dips of low-frequency masker
569 modulations, coupled with the effective increase in AM depth resulting from the loss of cochlear

compression. This suggests that the observed sharpening of the MTPs in HI listeners may be linked to the loss of cochlear compression rather than a 'restoration' of the bandwidth of underlying hypothetical modulation filters. Although differences in presentation levels between the HI and NH listeners may have influenced the threshold differences, the results of this study motivate further investigations into the effects of hearing loss on AM masking and AM frequency selectivity, as well as their interaction with age-related effects. Furthermore, in addition to the loss of cochlear compression, the lower AM detection thresholds and greater AM frequency selectivity observed in HI listeners may be associated with an increased neural coding of the envelope, which has been suggested to be detrimental to speech intelligibility in complex listening scenarios. Hence, future studies examining the effects of hearing loss on AM masking can offer valuabe insights into the underlying mechanisms that contribute to the perceptual benefits observed in HI listeners and their implications for complex auditory perception and speech intelligibility.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflict of interest to report.

Ethics Approval

All participants gave written informed consent and were financially compensated for their time. Ethical approval for the study was provided by the Science Ethics Committee of the Capital Region in Denmark (reference H-16036391).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon request.

605 **APPENDIX**

606 **A. Experimental protocol**

607 Table 2 summarizes the experimental protocol used for each HI listener (both young and older).
608 Modulation rate discrimination thresholds were also collected, in addition to experiments described
609 above, but the results were not considered in the present study.

610

611 Table 2: Experimental protocol implemented for all HI listeners, including the tests of modulation
612 rate discrimination (MRD), masked threshold pattern (MTP), hearing threshold at the carrier
613 frequency (HT), and reverse digit span (RDS).

Session	***Test***	***Order***
1	HT followed by MRD	Fixed within session
2-5	MTP 4 Hz	Random across sessions
	MTP 16 Hz	
	MTP 64 Hz	
	MTP 128 Hz followed by AM detection	
Any (2-5)	RDS	Randomly added to any session

614

615 **B. Parameters and post-hoc analyses for masked-threshold patterns**

616 Table 3 summarizes the post-hoc analysis results on the ANOVA comparing the MTPs for the
617 older HI and NH listeners (Figure 4).

618

619 Table 3: Summary of post-hoc analysis results on the MTPs comparing older HI and older NH
620 listeners, for each target modulation frequency. The effect sizes (M) and standard errors (SEs) are
621 reported for each pairwise comparison. The significant p-values are highlighted in bold.

Target frequency f_m [Hz]	***Effective masker-modulation bandwidth [Hz]***	***Masker-modulation center frequencies [Hz]***	***Masker-modulation position [octaves re target f_m]***	***M [dB]***	***SE [dB]***	***Corrected p-value***
4	1.4	1	-2	-4.6	1.1	**< 0.001**
		1.6	-4/3	-3.7		**0.001**
		2.5	-2/3	-2.2		**0.047**
		4	0	-1.3		0.237
		6.3	2/3	-0.8		0.472
		10.1	4/3	-1.6		0.147
		16	2	-1.7		0.134
16	5.6	4	-2	-4.5	0.8	**< 0.001**
		6.3	-4/3	-2.3		**0.003**
		10.1	-2/3	-1		0.196
		16	0	0.1		0.935

		25.4	2/3	-1		0.2
		40.3	4/3	-1		0.179
		64	2	-2.9		**< 0.001**
64	15.1	4	-4	-4.6	1.2	**< 0.001**
	22.3	16	-2	-3		**0.014**
		25.4	-4/3	-2.2		0.061
		40.3	-2/3	-1.7		0.152
		64	0	-1.4		0.249
		101.6	2/3	-3		**0.013**
128	27.2	4	-5	-4.9	1.2	**< 0.001**
	44.6	32	-2	-3.5		**0.005**
		50.8	-4/3	-2.7		**0.027**
		80.6	-2/3	-2.2		0.074
		128	0	-3.8		**0.003**

Table 4 summarizes the post-hoc analysis results on the ANOVA comparing the MTPs for the older HI and young NH listeners (Figure 5).

Table 4: Summary of post-hoc analysis results on the MTPs comparing older HI and young NH listeners, for each target modulation frequency. The effect sizes (M) and standard errors (SEs) are reported for each pairwise comparison. The significant p-values are highlighted in bold.

Target frequency f_m [Hz]	***Effective masker-modulation bandwidth [Hz]***	***Masker-modulation center frequencies [Hz]***	***Masker-modulation position [octaves re target f_m]***	***M [dB]***	***SE [dB]***	***Corrected p-value***
4	1.4	1	-2	-0.2	1.1	0.873
		1.6	-4/3	-0.5		0.662
		2.5	-2/3	-0.4		0.747
		4	0	-1.4		0.24
		6.3	2/3	0.4		0.736
		10.1	4/3	1.7		0.15
		16	2	3.2		**0.008**
16	5.6	4	-2	-3.3	0.8	**< 0.001**
		6.3	-4/3	-1.4		0.081
		10.1	-2/3	-0.6		0.405
		16	0	0.7		0.371
		25.4	2/3	2		**0.013**
		40.3	4/3	1.1		0.16
		64	2	-0.8		0.304
64	15.1	4	-4	-1.7	1.1	0.126

	22.3	16	-2	-0.5		0.637
		25.4	-4/3	0.6		0.597
		40.3	-2/3	0.5		0.648
		64	0	-1.5		0.191
		101.6	2/3	-3.1		**0.008**
128	27.2	4	-5	-0.8	1.1	0.434
	44.6	32	-2	0.7		0.542
		50.8	-4/3	0.6		0.594
		80.6	-2/3	-1.1		0.302
		128	0	-3.9		**< 0.001**

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