Impact of age versus hearing loss on amplitude modulation frequency selectivity and speech intelligibility

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Abstract

The perception of amplitude modulations (AMs), which is characterized by a frequency-selective process in the modulation domain, is considered critical for speech intelligibility. Previous studies have provided evidence of an age-related decline in AM frequency selectivity, as well as a notable sharpening of AM tuning associated with hearing loss, possibly due to a perceptual advantage resulting from peripheral compression loss. This study aimed to examine whether speech intelligibility in noisy environments would support the following ideas: i) age-related declines in AM tuning might lead to poorer speech intelligibility, and ii) sharper AM tuning associated with hearing loss would not result in improved speech intelligibility. Young (n=10, 22-28 years) and older listeners with normal hearing (n=9, 57–77 years) as well as older listeners with hearing impairment (n=9, 64-77 years) were included in the investigation. All participants had previously taken part in studies on AM frequency selectivity. Speech intelligibility was tested in various listening conditions, including stationary, fluctuating, and

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competing-speech maskers. Consistent with the hypothesis, the results revealed an age-related increase in speech reception thresholds, with an additional negative impact of hearing loss. These findings motivate further exploration of the relationship between AM frequency selectivity and speech intelligibility in noisy environments.

I. INTRODUCTION

Temporal envelope fluctuations (also referred to as "amplitude modulations" or AMs) are commonly used to describe sounds that exhibit dynamic variations over time (e.g., Singh and Theunissen, 2003; Elliott and Theunissen, 2009). The auditory system displays a remarkable sensitivity to AMs, as evidenced by physiological studies (see Joris *et al.*, 2004 for a review) and behavioral investigations of AM detection (e.g., Viemeister, 1979; Kohlrausch *et al.*, 2000). Analogous to masking effects in the audio-frequency domain, the detectability of target AMs is disrupted in the presence of separate masking AM components. AM masking has been extensively studied by behavioral investigations (e.g., Bacon and Grantham, 1989; Houtgast, 1989; Dau *et al.*, 1997; Verhey *et al.*, 2003) as well as through recent neurophysiological research (Viswanathan *et al.*, 2021). Behavioral studies of AM masking have provided evidence of a frequency-selective process in the modulation domain, often conceptualized as a series of bandpass modulation filters known as the modulation filterbank (e.g., Dau *et al.*, 1997, 1999; Ewert and Dau, 2000; Ewert *et al.*, 2002). Computational modelling studies have shown that this concept significantly contributes to quantitatively predicting experimental data from various psychoacoustic tasks (e.g., Dau *et al.*, 1997, 1999; Jepsen *et al.*, 2008; Jepsen and Dau, 2011; McDermott and Simoncelli, 2011; McWalter and Dau, 2017), underscoring the importance of AMs in auditory processing and perception.

Beyond their role in 'simple' listening tasks, AMs have been argued to be crucial for accurate speech intelligibility (Houtgast and Steeneken, 1985; Drullman *et al.*, 1994; Smith *et al.*, 2002; Elliott and Theunissen, 2009). The significance of AMs in speech was highlighted by vocoding studies, which demonstrated that intact envelope information conveyed through a few broad spectral bands was sufficient for precise speech recognition in quiet, even when spectral cues were greatly reduced (e.g., Shannon *et al.*, 1995; Dorman *et al.*, 1997; Xu *et al.*, 2005). Based on this, AM masking has been proposed as the primary mechanism underlying speech intelligibility in noise, whereby speech

reception thresholds (SRTs) - reflecting the signal-to-noise ratio required for 50% speech recognition - are proportional to the modulation-domain signal-to-noise ratio (SNR_{env}) between speech and the masker (e.g., Dubbelboer and Houtgast, 2008; Jørgensen and Dau, 2011). The central role of AM masking in speech intelligibility in noise was also emphasized by studies using maskers designed to contain AMs or to have maximally flat envelopes, which suggested that steady maskers, usually associated with energetic masking (EM) in the audio-frequency domain, effectively function as AM maskers due to their inherent envelope fluctuations (Stone *et al.*, 2012; Stone and Moore, 2014). Computational auditory modeling studies have successfully incorporated these concepts by employing the SNR_{env} (Jørgensen and Dau, 2011; Jørgensen *et al.*, 2013; Chabot-Leclerc *et al.*, 2014) or correlation-based measures (Relaño-Iborra *et al.*, 2016, 2019; Steinmetzger *et al.*, 2019) at the output of the modulation filterbank as decision metrics. Based on these modeling studies, the spectral decomposition of the stimulus envelope carried out by the modulation filterbank, i.e., AM frequency selectivity, has been suggested as an important factor for accurately predicting SRTs (see Relaño-Iborra and Dau, 2022, for a review of different speech intelligibility models using modulation filtering).

Regev *et al.* (2023a, 2023b) investigated the effects of age and hearing loss on the selectivity of hypothetical modulation filters using a perceptual AM masking task. Regev *et al.* (2023a) found a general reduction in AM frequency selectivity associated with age, resulting in broader masking patterns among older compared to young listeners with normal hearing (NH listeners). Conversely, Regev *et al.* (2023b) demonstrated a general sharpening of masking patterns among young and older listeners with hearing impairment (HI listeners) compared to similarly aged NH listeners. This finding suggested that sensorineural hearing loss was accompanied by a perceptual benefit that partially offset the detrimental effects of age, possibly due to the HI listeners' ability to exploit an increased internal representation of AM depth resulting from reduced peripheral compression when "listening in the dips" of the masker. Such alterations in the selectivity of the hypothetical modulation filters due to

age and hearing loss may affect speech intelligibility in noise by either increasing or reducing the amount of AM masking at the output of the modulation filters.

The effects of age and hearing loss on speech intelligibility have received significant attention in the literature. Hearing loss is known to cause a decline in speech intelligibility in both quiet and noisy environments (e.g., Glasberg and Moore, 1989; Humes and Christopherson, 1991; Frisina and Frisina, 1997; see Humes and Dubno, 2010 for a review). In addition to audibility loss, speech intelligibility challenges associated with hearing loss have been linked to various supra-threshold deficits, including reduced frequency selectivity, poorer temporal fine structure processing, reduced recovery from forward masking, poorer AM depth discrimination, and loudness recruitment (Glasberg and Moore, 1986, 1989; Oxenham and Moore, 1997; Moore and Oxenham, 1998; Moore, 2003; Lorenzi *et al.*, 2006; Strelcyk and Dau, 2009; Schlittenlacher and Moore, 2016). Aided speech intelligibility performance has also been shown to be strongly correlated with deficits in spectro-temporal modulation detection in HI listeners (e.g., Bernstein *et al.*, 2016; Zaar *et al.*, 2023). Recent neurophysiological studies have suggested that poorer speech intelligibility in HI listeners may be related to increased neural coding of the envelope (Millman *et al.*, 2017; Goossens *et al.*, 2018; Decruy *et al.*, 2020). This effect may be partly attributed to an increased internal representation of the AM depth resulting from the loss of cochlear compression commonly associated with sensorineural hearing loss (Moore *et al.*, 1996; Jennings *et al.*, 2018). In addition to the effects of hearing loss itself, age and reduced cognitive function have been found to contribute to the decline in speech intelligibility observed in older HI listeners (e.g., Dubno *et al.*, 1984; Humes and Christopherson, 1991; Frisina and Frisina, 1997; Humes, 2002, 2007; Humes *et al.*, 2006), suggesting that cognitive and age-related perception deficits may also play a role in speech intelligibility challenges.

To investigate these potential mechanisms, cross-sectional studies focusing on age-related effects have been conducted, often in listeners without or with mild hearing loss. While these studies have

consistently shown a detrimental effect of age on speech intelligibility in the presence of competing speech maskers (Rajan and Cainer, 2008; Helfer and Vargo, 2009; Schoof and Rosen, 2014; Füllgrabe *et al.*, 2015; Gordon-Salant and Cole, 2016; Goossens *et al.*, 2017; Decruy *et al.*, 2019; Sobon *et al.*, 2019), the effects of age in stationary and fluctuating noise have been less consistent. Some studies have found differences between young and older listeners (e.g., Goossens *et al.*, 2017; Decruy *et al.*, 2019; Sobon *et al.*, 2019), while others have not (Rajan and Cainer, 2008; Helfer and Vargo, 2009; Schoof and Rosen, 2014). Overall, the age-related increase in SRTs has been found to be more pronounced for speech maskers than for stationary or fluctuating noises (e.g., Goossens *et al.*, 2017; Decruy *et al.*, 2019; Sobon *et al.*, 2019). The observed age-related decline in speech intelligibility has been suggested to be mediated by deficits in temporal processing (e.g., Gordon-Salant *et al.*, 2006; Anderson *et al.*, 2012; Füllgrabe *et al.*, 2015; Goossens *et al.*, 2016; Decruy *et al.*, 2019), as well as by reduced cognitive abilities (Humes *et al.*, 2012; Füllgrabe *et al.*, 2015; Gordon-Salant and Cole, 2016).

Since AM frequency selectivity has been identified as a significant factor contributing to accurate speech intelligibility, it is reasonable to suggest that the age-related decline in AM selectivity reported by Regev *et al.* (2023a) may contribute to the aforementioned challenges in speech intelligibility. A reduction in AM tuning would likely result in increased AM masking, which could disrupt the intelligibility of the target speech. Additionally, the observed beneficial effects of hearing loss on AM frequency selectivity, as reported by Regev *et al.* (2023b), may also impact speech intelligibility in noisy environments. However, although the increased AM frequency selectivity found in older HI listeners compared to older NH listeners (Regev *et al.*, 2023a, 2023b) may suggest a decrease in AM masking with hearing loss, it is hypothesized that this would not directly translate into improved speech intelligibility. Indeed, the greater AM frequency selectivity in HI listeners is believed, as proposed by Regev *et al.* (2023b), to be linked to reduced cochlear compression, which is known to be connected to various supra-threshold deficits that impair speech intelligibility (e.g., Glasberg and Moore, 1989;

Oxenham and Moore, 1997; Moore and Oxenham, 1998; Moore, 2003). Furthermore, the assumption that a sharpening in AM tuning with hearing loss would not lead to an improvement in speech intelligibility is consistent with previous studies showing that HI listeners exhibit higher SRTs than age-matched NH listeners (Goossens *et al.*, 2017).

The present study explored whether the results of speech intelligibility tests align with the assumption that an age-related decline in AM frequency selectivity may negatively impact speech intelligibility, while a sharpening of AM tuning with hearing loss would not be beneficial for speech intelligibility. SRTs were collected for speech in noise, building upon the previous studies on AM frequency selectivity (Regev *et al.*, 2023a, 2023b), using a subset of the participants. Young NH, older NH, and older HI listeners were tested on sentence recognition in various maskers, including speech-shaped noise, fluctuating noise, and competing talkers. It was hypothesized that the older NH listeners would exhibit an age-related increase in SRTs, and that the older HI listeners would demonstrate a further increase in SRTs associated with their hearing loss.

II. METHODS

A. Listeners and previously published data

Ten young NH listeners, aged 22-28 years (mean age = 24.7 years, eight female), nine older NH listeners, aged 57–77 years (mean age = 66.9 years, six female), and nine older HI listeners, aged 64-77 years (mean age = 71.2 years, 2 female), participated in the study. All listeners were native Danish speakers. The experiment was conducted monaurally. Figure 1 shows the audiograms in the participants' test ears. Among the young NH listeners, all had audiometric pure-tone thresholds (PTTs) ≤ 20 dB HL at frequencies ranging from 125 Hz to 8 kHz. In the older NH listeners, all had PTTs ≤ 20 dB HL at frequencies ranging from 125 Hz to 4 kHz, PTTs ≤ 25 dB HL at 6 kHz, and

PTTs ≤ 45 dB HL at 8 kHz. The older HI listeners exhibited a high-frequency sloping hearing loss, classified as an N2 or N3 standard audiogram (Bisgaard *et al.*, 2010).[1] All HI listeners had a sensorineural hearing loss, with air-bone gaps ≤ 15 dB at 1, 2, 3, and 4 kHz.[2]

Prior to this study, all listeners took part in the AM frequency selectivity studies conducted by Regev *et al.* (2023a, 2023b). In those studies, masked-threshold patterns (MTPs) were used to assess the detection threshold of a target AM across different masker center frequencies, providing an indication of AM frequency selectivity. Figure 2 indicates an example of the MTPs for a 4-Hz target modulation frequency, while Table 1 presents the slopes obtained from linear fits applied to the group-level MTPs for target modulation frequencies ranging from 4 to 128 Hz, following the method described in Regev *et al.* (2023b). As reported by Regev *et al.* (2023a, 2023b), the MTPs and corresponding fitted slopes indicate a general decline in AM frequency selectivity with age, which is partially compensated by the presence of hearing loss, as reflected by the shallower slopes observed in the older NH listeners compared to the young NH and older HI listeners.[3]

Regev *et al.* (2023a, 2023b) also evaluated working-memory capacity using a reverse digit span (RDS) test, which was administered binaurally following the procedure described in Fuglsang *et al.* (2020). For the HI listeners, a linear gain was applied based on the Cambridge formula (CamEq; Moore and Glasberg, 1998), with a maximum gain of 30 dB at any frequency. The older NH listeners exhibited significantly lower average RDS scores (0.40 on a normalized scale) compared to the young NH and older HI listeners (0.60 and 0.52, respectively).[4]

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[1] The classification of the audiograms was performed using the lowest mean squared error between the standard audiograms and the collected audiometric thresholds at frequencies from 1 to 8 kHz.
[2] Except for one listener who showed a gap of 20 dB at 1 kHz.
[3] The similar fitted slopes obtained with the older NH and older HI listeners for a 128-Hz target modulation frequency reflect the overall lower masked thresholds obtained from the older HI listeners (see Regev et al., 2023b for further details).
[4] This was shown by the post-hoc analysis run on a linear model ANOVA using estimated marginal means. The older NH listeners had significantly lower RDS scores than the young NH and older HI listeners [M = 0.21, SE = 0.05 dB; M = 0.13, SE = 0.05 dB, respectively].

All participants provided written informed consent and were offered financial compensation for their participation. The study received ethical approval from the Science Ethics Committee of the Capital Region of Denmark (reference H-16036391).

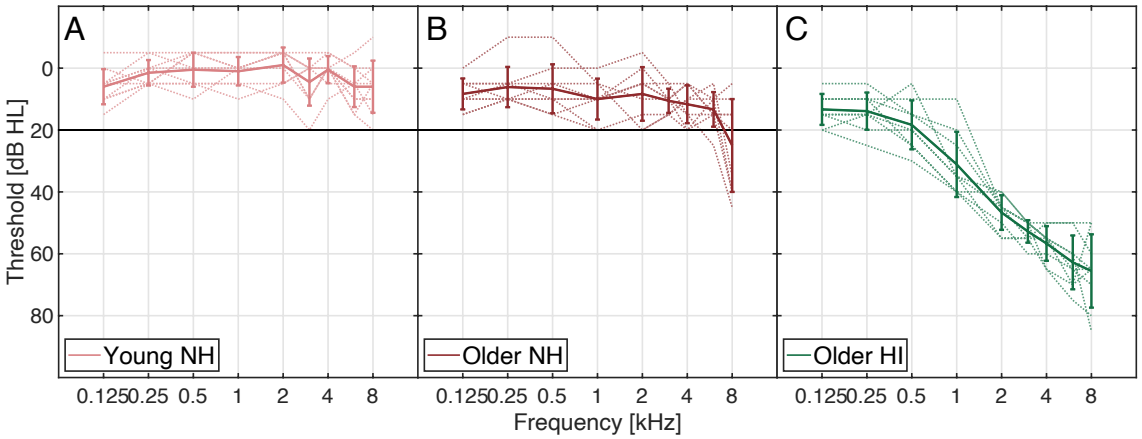

Figure 1: Individual and average audiograms of the test ear for each listener group. The light lines show the individual audiograms, while the dark lines represent the average and standard deviation across listeners. Panel A shows the audiograms for the young NH listeners, with the black horizontal line indicating the 20 dB HL normal-hearing criterion. Panel B displays the audiograms for the older NH listeners, also with the black horizontal line denoting the 20 dB HL normal-hearing criterion. Panel C presents the audiograms for the older HI listeners.

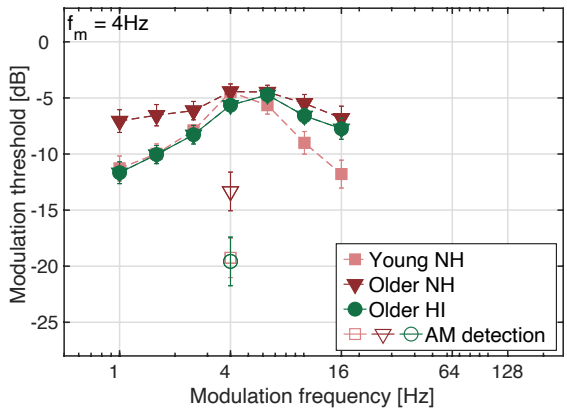

Figure 2: Average MTPs and AM detection thresholds for a 4-Hz target modulation frequency. The results for the young NH group are presented as dashed lines and squares, the older NH group as dashed lines and triangles, and the older HI group as continuous lines and circles. The bottom open symbols represent the average AM detection threshold for each group. The means and standard errors are shown. Data adapted from Regev *et al.* (2023a) and (2023b).

Table 1: Slopes obtained from the asymmetric linear fitting approach applied to the low- and high-frequency skirts of the group-level MTPs, following the method described in Regev *et al.* (2023b). The slopes are presented for the young NH (YNH), older NH (ONH), and older HI (OHI) groups at target modulation frequencies of 4, 16, 64, and 128 Hz. The slope values are reported in dB/octave.

Target modulation frequency [Hz]	**Fitted slope [dB/octave]**					
	Low-frequency skirt			***High-frequency skirt***		
	YNH	***ONH***	***OHI***	***YNH***	***ONH***	***OHI***
4	3.7	1.5	3.2	-3.4	-1.0	-0.8
16	3.8	3.3	6.0	-4.3	-3.2	-4.8
64	4.4	2.5	3.7	-6.2	-6.3	-9.1
128	4.2	1.7	1.7	-	-	-

B. Apparatus

The listening test was conducted in a single-walled soundproof booth. The experiment was conducted using MATLAB (The Mathworks Inc., 2015). The stimuli were digitally played using SoundMexPro (HörTech, Oldenburg, Germany), converted to analog using an RME Fireface soundcard (Haimhausen, Germany), and played monaurally 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 no feedback during the test.

C. Procedure and stimuli

Speech intelligibility in noise was assessed using the Danish Hearing in Noise Test (HINT; Nielsen and Dau, 2011). The HINT speech material consists of 10 test lists and 3 training lists, each containing 20 five-word sentences. The sentences were spoken by a male speaker with an estimated average fundamental frequency (F_0) of 123 Hz. The speech signals were combined with five different masking noises: i) a stationary speech-shaped noise (SSN); ii) a fluctuating ICRA-5 noise (Dreschler *et al.*, 2001) resembling a single male talker in terms of spectral and temporal characteristics; iii) a single male competing talker reading a news piece (F_0 = 118 Hz); iv) a single female competing talker reading a news piece (F_0 = 173 Hz); and v) a 'cocktail party' condition. The recordings of the competing talkers had previously been edited to reduce long pauses to 65 ms. The cocktail-party noise was generated by combining a relatively dry recording from a cafeteria with the recordings of the male and female competing talkers mentioned earlier. The levels of the competing talkers were each 3 dB higher than that of the cafeteria noise. Prior to mixing, each recording was convolved with an impulse response from the Aachen Impulse Response database (office setting with a dummy head at a 1m distance from the loudspeaker; Jeub et al., 2009) to introduce reverberation to the original recordings (T_{60} = 0.37 s). The spectra of all recordings (prior to mixing the cocktail-party noise) had been pre-processed to

187 match the long-term average spectrum of the HINT speech material as closely as possible. The long-
188 term average spectra and modulation spectra of the Danish HINT speech material and of all the
189 maskers are presented in Figure 3.

190 The SRT for each masking noise was determined by conducting two separate measurements using
191 different lists. The final SRT was obtained by averaging the SRTs obtained from the two
192 measurements. The order of masker presentation and the lists used for each masker were randomized
193 across the listeners. Both repetitions for each masker were always conducted consecutively.[5] The SRTs
194 were estimated at the 50%-correct point using an adaptive 1-up 1-down sentence-based scoring rule.
195 A response was considered correct if all five words of the sentence were repeated accurately. The step
196 size in SNR was set at 4 dB for the first four sentences and reduced to 2 dB afterwards. To refine the
197 tracking procedure, a special rule was implemented for the 5th sentence: The change in SNR was
198 computed as the average of the preceding four SNRs and the predicted following SNR, minus the
199 immediately preceding SNR. The first sentence was repeated until the listener could accurately repeat
200 the entire sentence. If the sentence had to be repeated more than four times, the run was terminated,
201 and the starting SNR was increased by 2 dB before starting again. The SRT of a run was calculated as
202 the average SNR across sentences 5 to 20 plus the SNR required for a fictitious 21st sentence,
203 determined by scoring the 20th sentence (Soli and Wong, 2008). The scoring of the repeated words
204 was performed by a trained native Danish speaker.

205 The speech was played at a fixed level of 60 dB SPL. The masking noise was looped over the
206 recording, played continuously, and adjusted in level to achieve the desired SNR. For the HI listeners,
207 linear amplification was added to both the speech and masking noise according to the Cambridge

[5] Due to a mistake in the audibility compensation, one of the older HI listeners was tested twice on the entire HINT corpus. However, more than 7 weeks separated the two testing sessions. Nielsen and Dau (2011) reported an average improvement in SRT of only 0.5 dB across two sessions separated by three weeks. Hence, the current case was likely not affected by memorization of the speech material.

formula (CamEq; Moore and Glasberg, 1998), with a maximum gain of 30 dB at any frequency. Each participant underwent training using all three training lists with the SSN. The starting SNR for each masker and each run was adjusted to be 6 dB lower than the expected SRTs. The expected SRTs were determined based on a pilot test conducted with young NH listeners and were defined relative to the SRT measured from the final training run. Therefore, the starting SNR was 6 dB lower than the SRT of the listener's last training list for the SSN, male competing talker, and cocktail party conditions; 9 dB lower for the ICRA noise; and 15 dB lower for the female competing talker condition.

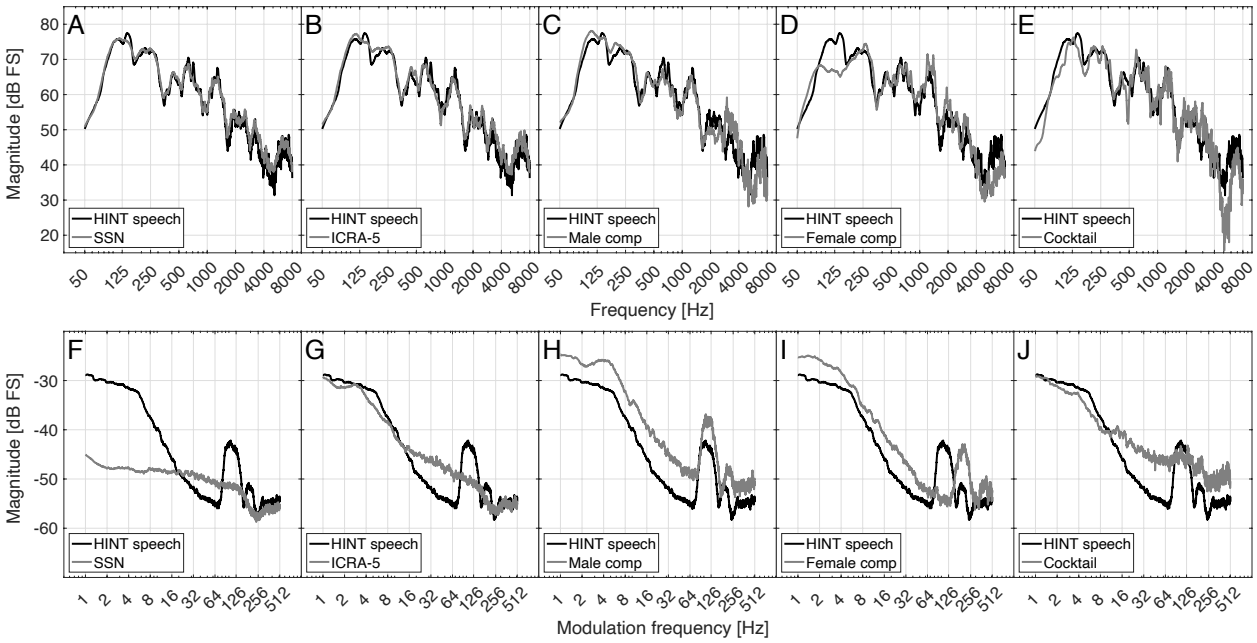

Figure 3: Long-term average spectra (top row) and modulation spectra (bottom row) of the speech material and maskers. Each panel shows the spectra for the HINT speech material (black line) and one of the maskers (gray line). Panels A and F: SSN; Panels B and G: ICRA-5; Panels C and H: Male competing talker; Panels D and I: Female competing talker; Panels E and J: Cocktail-party condition.

D. Statistical analysis

All statistical analyses were conducted using the SRTs averaged across both repetitions for each listener and masker. This was assumed to represent performance, given that the degree of variability

223 between the two SRT estimates across maskers (assessed by calculating the standard deviation across
224 the absolute differences in SRTs, $\sigma_{\Delta|SRT|}$) was considered sufficiently small for all listener groups.
225 Notably, although small, the variability across all maskers was highest for the young NH listeners
226 ($\sigma_{\Delta|SRT|}$ = 2.43 dB) compared to the older NH listeners ($\sigma_{\Delta|SRT|}$= 1.76 dB) and older HI listeners
227 ($\sigma_{\Delta|SRT|}$= 1.49 dB). Analyses of variances (ANOVAs) of linear mixed-effects model fittings were
228 performed to examine the differences between the listener groups. Two sets of analysis were
229 conducted: First, the older NH group was compared to the young NH listeners to isolate the effects
230 of age from hearing loss, and second, the older HI group was compared to the older NH listeners to
231 isolate the effects of hearing loss from age-related effects. In both analyses, the listeners were treated
232 as a random effect, while group classification and masker were considered as fixed effects.[6] Post-hoc
233 analyses were carried out using estimated marginal means, and a Holm-Bonferroni correction criterion
234 was applied to account for multiple comparisons. The significance level for all analyses was set at 5%.

[6] 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. Shapiro-Wilk's test was not passed for either model, likely due to the relatively small group sizes and to the presence of outliers in the older HI data. However, no other aspect of the data justified the removal of the outliers, and they were therefore kept in the dataset. Furthermore, the average fittings of the models to the experimental data were found to be accurate, and the models were hence considered as appropriate.

III. RESULTS

A. Speech intelligibility

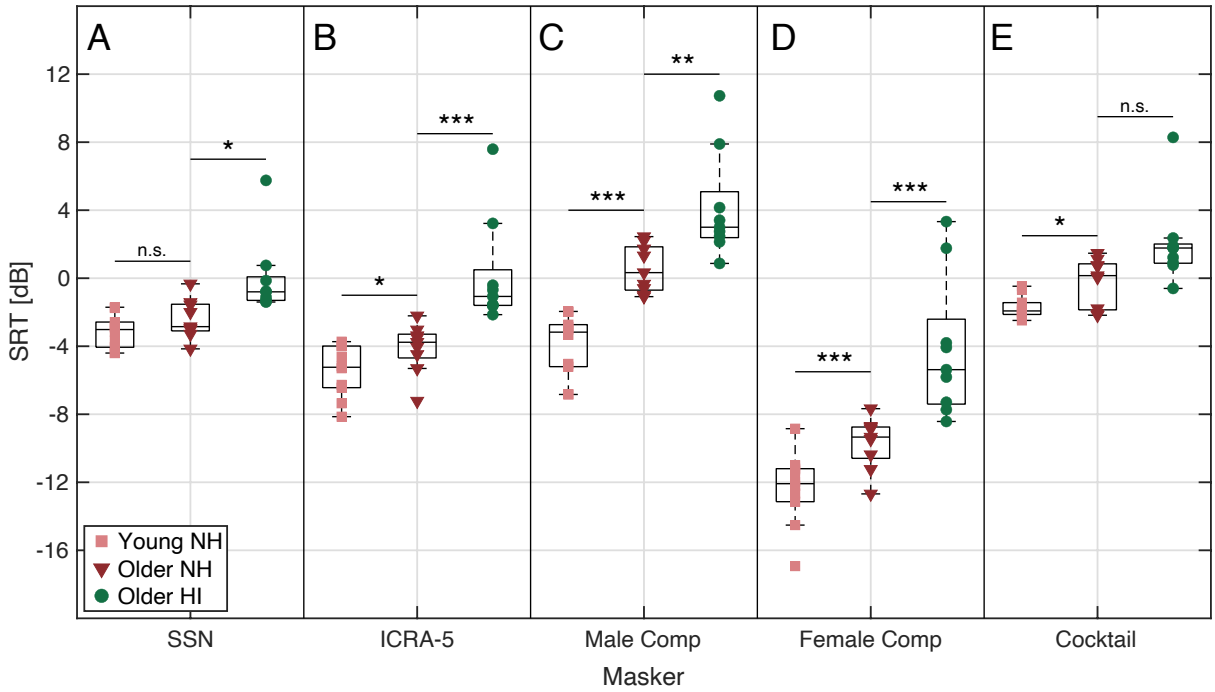

Figure 4: Boxplots displaying the SRTs for all listeners. Each panel corresponds to a specific masker: Panel A: Speech-shaped noise (SSN), Panel B: ICRA-5 fluctuating noise, Panel C: Single male competing talker (same sex), Panel D: Single female competing talker (different sex), Panel E: Cocktail-party noise. The SRTs for the young NH listeners are represented by squares, older NH by triangles, and older HI by circles. The stars indicate the level of statistical significance of the differences between the groups separated by the horizontal black lines (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$), while "n.s." denotes non-significant differences. Note that the young NH and older HI groups were not compared in the statistical analysis.

The SRTs for all listeners and groups are shown in Figure 4 for each masker. The young NH listeners are represented by squares, older NH listeners by triangles, and older HI listeners by circles.

The statistical analysis comparing young and older NH listeners, focusing on the effects of age, revealed significant main effects of masker [$F_{4,68}$ = 274.2, p < 0.001] and listener group [$F_{1,17}$ = 17.56, p < 0.001], as well as a significant interaction between both factors [$F_{4,68}$ = 9.284, p < 0.001]. In the analysis comparing older NH and older HI listeners, examining the effects of hearing loss, significant main effects of masker [$F_{4,64}$ = 141.6, p < 0.001] and listener group [$F_{1,16}$ = 12.86, p = 0.002], as well as a significant interaction between both factors [$F_{4,64}$ = 5.321, p < 0.001], were observed. Post-hoc analyses revealed that the older NH listeners had significantly higher SRTs than the young NH listeners for the ICRA-5 condition [Effect size (*M*) = 1.39 dB, standard error (*SE*) = 0.68 dB], male competing talker [*M* = 4.53 dB, *SE* = 0.68 dB], female competing talker [*M* = 2.70 dB, *SE* = 0.68 dB], and cocktail-party condition [*M* = 1.53 dB, *SE* = 0.68 dB]. Additionally, the older NH listeners had significantly lower SRTs than the older HI listeners for the SSN condition [*M* = 2.36 dB, *SE* = 1.14 dB], ICRA-5 condition [*M* = 4.30 dB, *SE* = 1.14 dB], male competing talker [*M* = 3.60 dB, *SE* = 1.14 dB], and female competing talker [*M* = 5.52 dB, *SE* = 1.14 dB]. The increase in SRT for the older HI listeners in the cocktail-party condition approached, but did not reach, significance [*M* = 2.24 dB, *SE* = 1.14 dB, p = 0.06]. Furthermore, the post-hoc analyses revealed that the female competing talker resulted in significantly lower SRTs than all other maskers for all listener groups. The male competing talker yielded significantly higher SRTs than all other maskers for the older NH and older HI listeners (except for the cocktail-party condition in the older NH group), while the cocktail-party condition yielded the highest SRTs for the young NH listeners. Finally, the ICRA-5 noise resulted in significantly lower SRTs than the SSN for the young and older NH listeners, but not for the older HI listeners. Additional details and results from all post-hoc analyses can be found in Appendix A.

IV. DISCUSSION

The aim of the present study was to investigate whether the findings from speech intelligibility tests would be consistent with the AM frequency selectivity data collected in previous studies by Regev *et al.* (2023a, 2023b). These previous investigations demonstrated an age-related decline in AM frequency selectivity and a sharpening of AM tuning with hearing loss (see Figure 2 and Table 1). A subset of the listener cohort measured by Regev *et al.* (2023a, 2023b) was considered here. It was expected that the age-related reduction in AM frequency selectivity would correspond to poorer speech intelligibility in older compared to young NH listeners. Conversely, the sharper AM tuning observed in older HI listeners was not anticipated to result in better speech intelligibility compared to the older NH listeners. The results revealed an overall decline in speech intelligibility with age, which was further exacerbated by the presence of hearing loss. These findings are consistent with previous studies that have shown a deterioration of speech intelligibility with age (e.g., Rajan and Cainer, 2008; Helfer and Vargo, 2009; Schoof and Rosen, 2014; Füllgrabe *et al.*, 2015; Gordon-Salant and Cole, 2016; Goossens *et al.*, 2017; Decruy *et al.*, 2019) and hearing loss (e.g., Glasberg and Moore, 1989; Humes and Christopherson, 1991; Frisina and Frisina, 1997; see Humes and Dubno, 2010 for a review).

The observed increase in SRTs with age aligns with the age-related reduction in AM frequency selectivity reported by Regev *et al.* (2023a). Broader modulation filters, indicative of reduced AM selectivity, may lead to increased AM masking, resulting in a decrease in the SNR_{env} at the output of these filters and potentially poorer speech intelligibility in noise. However, the lack of a significant age-related increase in SRT for the SSN condition is not consistent with this notion, contrary to expectations. Since the SSN contains intrinsic envelope fluctuations that act as a relatively broadband modulation masker (as argued by Stone *et al.*, 2012), one might have expected the broader AM tuning found in older NH listeners to lead to an increase in AM masking. However, the SRTs obtained with

296 the SSN likely reflect aspects of EM rather than AM masking. This is suggested by the extensive
297 overlap observed in the audio spectra of the SSN and HINT speech material (Figure 3, panel A),
298 compared to the highly positive SNR_{env} observed when comparing their modulation spectra at low
299 modulation frequencies (Figure 3, panel F), indicating that the SSN provided more EM than AM
300 masking. Conversely, the differences in modulation spectra between the target speech and masking
301 noise were much smaller for the other maskers, suggesting that AM masking (and thus potentially AM
302 frequency selectivity) may have played a more prominent role in those cases (Figure 3, panels G-J).
303 Notably, the older NH listeners exhibited a reduced release from masking when exposed to the
304 fluctuating ICRA-5 noise compared to the young NH listeners, consistent with previous studies
305 (Dubno *et al.*, 2002, 2003; Grose *et al.*, 2009; Goossens *et al.*, 2017). In addition to potentially being the
306 result of an age-related increase in forward masking (e.g., Gifford *et al.*, 2007), the reduced release from
307 masking observed in the older NH listeners may also be attributed to increased AM masking due to
308 the loss of AM frequency selectivity, which may have limited the benefit derived from the slow
309 temporal fluctuations in the ICRA-5 condition.

310 Regarding the effects of hearing loss, the higher SRTs observed in the older HI listeners compared
311 to the older NH group are consistent with the expectation that the increase in AM frequency selectivity
312 observed in HI listeners (as reported in Regev *et al.*, 2023b) would *not* lead to improved speech
313 intelligibility. Regev *et al.* (2023b) argued that the greater AM frequency selectivity with hearing loss
314 was an "apparent" effect, resulting from improved detection of the AM target during temporal dips
315 in the masker due to the loss of cochlear compression. Since the loss of compression is also associated
316 with other supra-threshold deficits, such as loudness recruitment, poorer recovery from forward
317 masking, and reduced frequency selectivity (Glasberg and Moore, 1986, 1989; Oxenham and Moore,
318 1997; Moore and Oxenham, 1998), it is evident that the process potentially underlying the improved
319 AM frequency selectivity is also linked to the mechanisms underlying poorer speech intelligibility in

320 HI listeners. However, while poorer speech intelligibility was expected in the HI listeners,
321 disentangling the potential impact of the effective sharpening in AM tuning with hearing loss on
322 speech intelligibility is not straightforward. It remains unclear whether a) the sharper AM tuning with
323 hearing loss improves SRTs but is outweighed by co-occurring supra-threshold deficits typically
324 associated with hearing loss, or b) the process underlying the sharpening of AM tuning with hearing
325 loss itself ultimately impairs speech intelligibility.

326 The present findings indicate that declines in speech intelligibility with age and hearing loss are
327 most prominent in contexts that involve high cognitive demand and informational masking (IM), such
328 as in the presence of competing-talker maskers. IM encompasses various factors that complicate the
329 separation of the target and masker speech signals, such as stream segregation (Brungart et al., 2001;
330 Darwin et al., 2003; Schneider et al., 2007; Kidd et al., 2016; see Kidd et al., 2008 for a review). In the
331 groups considered here, the older NH listeners exhibited significantly lower RDS scores compared to
332 the young NH listeners. Such reduced cognitive abilities have been suggested to mediate the age-
333 related increase of SRTs under conditions of IM (Rajan and Cainer, 2008; Gordon-Salant and Cole,
334 2016; Goossens *et al.*, 2017). Therefore, the poorer speech intelligibility observed in the older NH
335 listeners in the present study may be partly attributed to a reduction in working-memory capacity.
336 However, the older NH listeners were also found to have higher SRTs than the young NH listeners
337 in the ICRA-5 condition, which does not involve IM or high cognitive demand. This finding is broadly
338 consistent with studies that reported no significant correlation between reduced cognitive abilities and
339 increased SRTs in older listeners (e.g., Schoof and Rosen, 2014), suggesting that other factors may
340 also contribute to the age-related decline in speech intelligibility. These factors may be associated with
341 age-related temporal processing deficits, as suggested by perceptual (Pichora-Fuller and Souza, 2003;
342 Pichora-Fuller and MacDonald, 2008; Helfer and Vargo, 2009; Füllgrabe et al., 2015; see Fitzgibbons
343 and Gordon-Salant, 2010 for a review) and neurophysiological research (e.g., Anderson et al., 2012;

344 Decruy et al., 2019; Parthasarathy et al., 2019b; Roque et al., 2019; for reviews see Parthasarathy et al.,
345 2019a and Anderson and Karawani, 2020). The hypothesis that the age-related reduction in AM
346 frequency selectivity (as reported by Regev *et al.*, 2023a) may contribute to increased SRTs aligns with
347 the notion that temporal processing deficits underlie the challenges in speech intelligibility associated
348 with age. In the case of hearing loss, the differences in SRTs between older NH and older HI listeners
349 were also largest for the fluctuating and competing-talker maskers. This observation is consistent with
350 the reduced release from masking commonly found in HI listeners (e.g., Bacon *et al.*, 1998; Bernstein
351 and Grant, 2009; Strelcyk and Dau, 2009; Goossens *et al.*, 2017), as well as with the suggestion that
352 the effects of hearing loss on speech intelligibility are most pronounced in cognitively demanding
353 settings (e.g., Schneider *et al.*, 2010; Goossens *et al.*, 2017). Although the older HI listeners showed
354 higher RDS scores than their older NH counterparts, they did exhibit a marginally reduced working-
355 memory capacity compared to the young NH listeners. Hence, the large effect of hearing loss in
356 conditions involving IM may be partly connected to the age-related cognitive decline discussed earlier.
357 Conversely, the older HI listeners were also found to have higher SRTs than their older NH
358 counterparts in the SSN and ICRA-5 conditions, which are commonly assumed not to involve high
359 cognitive demand. Overall, while reduced cognitive ability in older listeners may have partly mediated
360 the observed effects of age and hearing loss on speech intelligibility, the results also indicate that supra-
361 threshold deficits influenced the SRTs, likely related to reduced cochlear compression and temporal
362 envelope processing deficits.

363 Although the data from the present study revealed significant group-level results that support a
364 relationship between AM tuning and speech intelligibility in noise with age, as well as the absence of
365 a benefit in speech intelligibility from the sharper AM tuning with hearing loss, it is important to
366 consider several co-occurring factors that may have influenced the results. Even though all the older
367 NH listeners exhibited clinically normal hearing up to 4 kHz, their audiometric thresholds were on

368 average 8 dB higher than those of the young NH listeners between 125 Hz and 8 kHz, with the greatest
369 differences occurring at 8 kHz. Although these differences in audiometric thresholds are small,
370 previous studies have suggested that they can have a considerable effect on speech intelligibility
371 (Dubno and Ahlstrom, 1997; Dubno *et al.*, 2000). Moreover, the older NH listeners included in the
372 present study may have experienced reduced audibility at extended high frequencies (> 8 kHz), which
373 have also been suggested to play a role in speech intelligibility (e.g., Hunter *et al.*, 2020; Polspoel *et al.*,
374 2022). These aspects may have contributed to the observed age-related increase in SRTs. Concerning
375 the experimental approach, since the tests provided listeners with cues beyond the temporal envelope,
376 factors such as IM, EM, and stream segregation likely interacted with age- and hearing loss-related
377 perception deficits. Therefore, establishing an unambiguous connection between SRTs and AM
378 frequency selectivity based solely on the present data is not possible.
379

380 **V. SUMMARY AND CONCLUSION**

381 Speech intelligibility in noise was examined in three groups: young listeners with normal hearing,
382 aged 22-28 years, older listeners with normal hearing, aged 57-77 years, and older listeners with hearing
383 impairment, aged 64 – 77 years. All participants had previously taken part in AM masking studies
384 investigating AM frequency selectivity, which revealed an age-related reduction in AM tuning and a
385 sharpening in AM tuning with hearing loss (Regev *et al.*, 2023a, 2023b). The aim of this study was to
386 determine if the effects of age and hearing loss on speech intelligibility in noise support the hypothesis
387 that the age-related reduction in AM tuning negatively impacts speech intelligibility, while the
388 improvement in AM tuning with hearing loss does not provide a benefit. Consistent with the
389 hypotheses, the results showed an age-related decline and an additional negative effect of hearing loss
390 on speech intelligibility. The detrimental effect of hearing loss on speech intelligibility suggests that
391 the underlying process responsible for the greater AM frequency selectivity observed in listeners with

hearing impairment (Regev *et al.*, 2023b) is connected to the mechanisms that ultimately lead to poorer speech intelligibility in noise. This finding aligns with the proposition made by Regev *et al.* (2023b) that the improved AM tuning in listeners with hearing impairment is an "apparent" effect resulting from reduced peripheral compression, which is known to contribute to other supra-threshold deficits that impair speech intelligibility. However, it remains unclear to what extent the apparent greater AM frequency selectivity itself may compensate for, or contribute to, deficits in speech intelligibility. With regards to the effects of age, the present results provided clear evidence of an age-related decline in speech intelligibility, which warrants further investigation into its potential association with a decrease in AM frequency selectivity. Although the age-related decline in AM frequency selectivity is consistent with the observed detrimental effects of age on speech intelligibility, this study does not establish a definitive link between these two aspects, as the employed speech intelligibility test is influenced by various other factors such as informational masking, energetic masking, and stream segregation. Therefore, a more controlled experimental paradigm that specifically examines envelope-based cues may be necessary to directly assess the effects of AM tuning on speech intelligibility.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflict of interest to report.

Ethics Approval

All participants provided written informed consent and were offered financial compensation for their participation. 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.

APPENDIX

A. Post-hoc analyses

Table 2 summarizes the results of the post-hoc analyses that compared the SRTs obtained with young and older NH listeners for each masker.

Table 2: Post-hoc analysis of the differences in SRT between young and older NH listeners for each masker. The effect sizes (M), standard errors (SE, and corrected p-values are reported. The significant p-values are highlighted in bold.

Masker	***M [dB]***	***SE [dB]***	***Corrected p-value***
SSN	0.75	0.68	0.279
ICRA-5	1.39		**0.047**
Male competing	4.53		**< 0.001**
Female competing	2.70		**< 0.001**
Cocktail party	1.53		**0.030**

Table 3 summarizes the results of the post-hoc analyses that compared the SRTs obtained with older NH and older HI listeners for each masker.

Table 3: Post-hoc analysis of the differences in SRT between older NH and older HI listeners for each masker. The effect sizes (M), standard errors (SE, and corrected p-values are reported. The significant p-values are highlighted in bold.

Masker	***M [dB]***	***SE [dB]***	***Corrected p-value***
SSN	2.36	1.14	**0.048**
ICRA-5	4.30		**< 0.001**
Male competing	3.60		**0.004**
Female competing	5.52		**< 0.001**
Cocktail party	2.24		0.060

Table 4 summarizes the results of the post-hoc analyses that compared the SRTs obtained with the different maskers for each of the three listener groups (young NH, older NH, and older HI). Since this post-hoc analysis was run twice for the older NH listeners (once for each statistical model applied), the values reported reflect the most conservative *p*-values and standard errors, obtained from the model fitted to the older NH and older HI listeners. However, the effect sizes and overall statistical outcomes did not differ between the analyses run in the two models.

Table 4: Post-hoc analysis of the differences in SRT between older the different maskers for each group. The effect sizes (M), standard errors (SE, and corrected p-values are reported. The significant p-values are highlighted in bold.

Listener group	***Maskers compared***	***M [dB]***	***SE [dB]***	***Corrected p-value***
Young NH	SSN - ICRA-5	2.35	0.48	**< 0.001**
	SSN – Male competing	0.83		0.086
	SSN – Female competing	9.23		**< 0.001**
	SSN – Cocktail party	-1.42		**0.008**
	ICRA-5 – Male competing	-1.52		**0.006**
	ICRA-5 – Female competing	6.88		**< 0.001**
	ICRA-5 – Cocktail party	-3.77		**< 0.001**
	Male competing – Female competing	8.40		**< 0.001**
	Male competing – Cocktail party	-2.25		**< 0.001**
	Female competing – Cocktail party	-10.65		**< 0.001**
Older NH	SSN - ICRA-5	1.71	0.60	**0.011**
	SSN – Male competing	-2.95		**< 0.001**
	SSN – Female competing	7.28		**< 0.001**
	SSN – Cocktail party	-2.20		**0.001**
	ICRA-5 – Male competing	-4.66		**< 0.001**
	ICRA-5 – Female competing	5.57		**< 0.001**
	ICRA-5 – Cocktail party	-3.91		**< 0.001**

	Male competing – Female competing	10.23		**< 0.001**
	Male competing – Cocktail party	0.75		0.212
	Female competing – Cocktail party	-9.48		**< 0.001**
Older HI	SSN - ICRA-5	-0.23	0.60	0.696
	SSN – Male competing	-4.20		**< 0.001**
	SSN – Female competing	4.12		**< 0.001**
	SSN – Cocktail party	-2.09		**0.003**
	ICRA-5 – Male competing	-3.96		**< 0.001**
	ICRA-5 – Female competing	4.35		**< 0.001**
	ICRA-5 – Cocktail party	-1.85		**0.006**
	Male competing – Female competing	8.32		**< 0.001**
	Male competing – Cocktail party	2.11		**0.003**
	Female competing – Cocktail party	-6.20		**< 0.001**

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