Contributions of Low- and High-Frequency Sensorineural Hearing Deficits to Speech Intelligibility in Noise

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Abstract

This study investigates the role of hearing sensitivity, age and supra-threshold hearing to speech recognition in quiet, stationary, and modulated noise. Three participant groups were tested: young normal hearing (yNH), older normal-hearing (oNH), and older hearing-impaired (oHI) listeners. The relative importance of near and supra-threshold hearing deficits was assessed in different frequency regions by measuring speech reception thresholds (SRTs) using broadband speech targets and noise maskers (BB), but also low- and high-pass (LP & HP) filtered versions of these stimuli. Interrelations between SRTs in different conditions were studied and SRTs were compared to amplitude-modulation detection sensitivity as a metric for supra-threshold hearing ability in the spectral and temporal (envelope) domains. The main results are: *(i)* LP SRT performance dominates overall BB speech recognition. *(ii)* LP SRTs determine individual differences in BB SRTs for stationary noise while HP SRTs determine individual differences in BB SRTs for modulated noise. *(iii)* Masking release (the improvement in intelligibility produced by the modulations of noise) was

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present for BB, LP and HP conditions and related to the modulated (not stationary) SRT performance. *(iv)* Sensitivity to temporal-envelopes is important for HF masking release and SRTs in modulated noise, whereas spectral resolution is a better predictor of LF speech recognition in modulated noise. This study identified the role of near and supra-threshold cues in the perception of amplitude-modulation and speech-in-noise, and can steer the development of hearing-aid algorithms targeted to mediate supra-threshold hearing deficits.
Keywords: speech intelligibility, amplitude modulation, supra-threshold hearing deficits, speech in noise, ageing

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1. Introduction

Abbreviations PTA: pure tone average; SRT: speech reception threshold; AM DT: amplitude-modulation detection threshold; BB: broadband; LP: low-pass; HP: high-pass; LF: low-frequency; HF: high-frequency; NH: normal-hearing; HI: hearing-impaired; SSN: speech-shaped noise; ICRA: modulated International Collegium of Rehabilitative Audiology noise; TFS: temporal fine-structure; TENV: temporal envelope

A common complaint of older and hearing-impaired listeners is experiencing difficulty in understanding speech when it is presented in background noise. When seeking medical help for these problems, audiological practice mostly assesses hearing status using pure-tone audiograms or speech recognition in quiet. There are several reports showing that these standard clinical measures are poor predictors for speech recognition in noise (Festen & Plomp, 1983; Papakonstantinou et al., 2011), and there is growing physiological evidence that there may be supra-threshold hearing deficits caused by synaptopathy that impair processing of audible sound (Bharadwaj et al., 2014, 2015; Liberman et al., 2016). To offer the best treatment for people with self-reported speech recognition difficulties, there is hence a strong need to understand how the ageing process and peripheral hearing damage affect supra-threshold hearing and speech intelligibility in

noise.

A number of studies have investigated the role of age (Dubno et al., 2002; Goossens et al., 2017), cognition (Besser et al., 2013; Füllgrabe et al., 2015; Schoof & Rosen, 2014) and coding mechanisms such as temporal fine-structure coding (TFS) and envelope encoding (TENV) for speech intelligibility (Lorenzi et al., 2006; Hopkins & Moore, 2011; Papakonstantinou et al., 2011; Léger et al., 2012a,b), and demonstrated that hearing sensitivity alone cannot explain all aspects of degraded speech reception thresholds (SRTs). Specifically, hearing-impaired listeners fail to encode low-frequency (LF) TFS speech cues while their hearing thresholds in that same region are not necessarily compromised (Lorenzi et al., 2009; Léger et al., 2012b). At the same time, LF frequency discrimination (Papakonstantinou et al., 2011) and interaural phase detection thresholds (Strelcyk & Dau, 2009) do relate to reduced speech recognition in noise. Because temporal coding mechanisms and hearing sensitivity are frequency specific (Kale & Heinz, 2010), it is important to study how individual and frequency-specific combinations of degraded hearing sensitivity and/or supra-threshold coding mechanisms contribute to overall broadband speech recognition. We adopted a method in which we compared broadband (BB) speech recognition to speech recognition performance in low-pass (LP) and high-pass (HP) filtered versions of the BB stimuli.

It is presently not clear whether degraded supra-threshold hearing or hearing sensitivity is more detrimental to speech recognition, which motivates why we refrained from amplifying the LP or HP filtered speech in the study design. Traditional studies have amplified HP filtered speech to render the speech material equally audible in normal and hearing-impaired test groups, or to maintain an equal loudness percept for LP & HP filtered stimuli (e.g. Lorenzi et al., 2009; Hopkins et al., 2008; Goossens et al., 2017). While the named studies are well positioned to investigate whether supra-threshold hearing deficits persist when audibility is restored, they are not able to clarify which coding mechanism or frequency regions were responsible for degrading the overall SRT in the first place. We pose here that as long as the sound is audible in the tested frequency region

(albeit not necessarily with the same perceived loudness), deficits in both hearing sensitivity and supra-threshold hearing may contribute to degrade SRTs. Using an unamplified study design, we aim to disentangle and characterize contributions of hearing deficits and frequency regions to the overall broadband speech recognition. This method is complementary to traditional approaches which amplify speech before addressing supra-threshold hearing deficits, and is expected to provide insights to which hearing restoration strategies (e.g. restoring audibility, temporal coding,..) might be more beneficial for different frequency regions and individual listeners.

As our understanding of the physiology of hearing associates LP speech recognition with TFS coding ability (Léger et al., 2012b; Nelson et al., 2003; Füllgrabe et al., 2006; Hopkins & Moore, 2009), and HP speech recognition with robust envelope encoding in the presence of background noise (Carney et al., 2015; Henry et al., 2016), we first tested whether speech recognition in modulated noise and stationary noise rely on the same encoding mechanism in low-frequency (LF) and high-frequency (HF) speech encoding regions. The spectro-temporal characteristics of modulated noise are beneficial for SRTs resulting in lower (better) speech intelligibility thresholds than for stationary noise (Miller & Licklider, 1950; Takahashi & Bacon, 1992; Festen & Plomp, 1990; Gnansia et al., 2008). The modulated masker benefit is reduced or even absent in hearing-impaired (HI) listeners (Wagener, 2003; Versfeld & Dreschler, 2002). As elevated pure tone thresholds cannot fully account for all aspects of HI speech recognition in modulated noise (Wagener, 2003; Versfeld & Dreschler, 2002; Kollmeier et al., 2016), we investigate whether there are other supra-threshold deficits that may contribute to this degraded performance. Specifically, we examine whether processing of temporal envelopes TENV, age or hearing sensitivity are associated speech recognition in the selected LP and HP frequency bands.

We studied the above research questions by performing a regression analysis on individual and pooled data from subjects recruited in three groups: a young normal-hearing (yNH) group, an older normal-hearing (oNH) group and an age-matched older hearing-impaired (oHI) group. To further investigate how

supra-threshold hearing deficits impact speech recognition in LF and HF regions, the speech results were compared to amplitude-modulation detection thresholds (AM DTs) in corresponding frequency regions. As AM DTs are thought to assess individual supra-threshold TENV encoding ability (Bharadwaj et al., 2015), we aimed to isolate which aspects of degraded speech recognition are associated with degraded TENV encoding. We focused on characterizing TENV encoding mechanisms and their role in speech recognition because a recent study has postulated that synaptopathy might degrade the robust encoding of temporal envelopes (Shaheen et al., 2015). In humans, the relationship between synaptopathy and degraded AM DTs cannot directly be demonstrated, but it has been shown that AM DTs in oNH listeners can be degraded compared to yNH listeners with the same audiometric thresholds (Füllgrabe et al., 2015), and that individual differences in AM DTs relate to envelope-following responses as an indirect estimate of synaptopathy in NH listeners (Bharadwaj et al., 2015).

2. Methods

2.1. Study Participants

Fourteen young normal-hearing (yNH, 19-29 yr), 10 older normal-hearing listeners (oNH, 56-77 yr), and 10 older hearing-impaired listeners (oHI, 61-78 yr) participated in the study. Participants received written and oral information about the experiments and were paid for their participation. Experiments were approved by the ethics commission of Oldenburg University. The two older listener groups were age-matched ($p>0.05$) with a mean age of 68.4±7.2 years. The group of yNH had a mean age of 24.6±3.1 and differed significantly in age from both oNH and oHI groups ($p<0.001$). Hearing sensitivity was assessed using pure-tone audiometry. Mean audiograms with corresponding standard deviations are shown for each listener group in Fig.1A. A repeated-measures ANOVA with audiometric frequency as a within-subject factor and listener group as a between-subject factor yielded a significant effect of frequency [$F(3.15, 97.8)=83.37$, $p<0.001$ Greenhouse-Geisser correction)], listener group

[F(2, 166)=116, p<0.001] and interaction between frequency and listener group [F(6.31, 97.8)=17.2, p<0.001]. Post-hoc comparisons for each tested frequency (Bonferroni corrected) did not show significant differences in pure-tone detection threshold between yNH and oNH listeners for frequencies up to 2 kHz (p<0.05, Fig.1A), whereas significant group differences were found for higher frequencies (p<0.05). The hearing thresholds of the oNH listeners did not exceed 20 dB HL in the frequency range crucial for speech perception (0.125-4 kHz). Pure-tone thresholds significantly differed for all frequencies between yNH and oHI groups (p<0.05), and for frequencies > 500 Hz between oNH and oHI groups. The pure-tone average over the 0.5, 1, 2, and 4 kHz frequencies ($PTA_{0.5,1,2,4}$), averaged across listeners was 3.3±1.3, 7.6±2.8, and 25.8±6.4 dB HL for the yNH, oNH, and oHI groups, respectively. Figure 1B shows the relationship between $PTA_{0.5,1,2,4}$ and age of the study participants. It is important to note that the oNH listeners differed significantly from the yNH listeners in age *and* $PTA_{0.5,1,2,4}$, even though they were selected as a group for which the ageing effect would dominate performance over the yNH listeners in the psychoacoustic tasks. The significant difference in PTA between yNH and oNH is due to the differences in pure tone threshold for frequencies higher than 2 kHz.

2.2. Speech Recognition

A 1-up/1-down adaptive procedure with varying step size and word scoring was used to determine the SRT corresponding to 50% correct answers. The Oldenburg sentence test (Wagener et al., 1999; Brand & Kollmeier, 2002) with testing lists of 20 sentences were used in each measurement condition. Speech recognition measurements included: *(i)* SRT in quiet, *(ii)* SRT in speech-shaped noise (SSN) with broadband (BB), low-pass (LP), and high-pass (HP) filtered stimuli, and *(iii)*, SRT in modulated noise (ICRA5-250; Wagener et al., 2006) using BB, LP, and HP filtered stimuli. It is important to note that both speech and noise were filtered in the LP and HP conditions. The SSN was generated by multiple superpositions of the test material so that the long-term spectrum of the SSN matched that of the sentences. The ICRA5-250 noise matches the

envelope of a single male talker and includes pause durations up to 250 ms. The long-term spectrum of the ICRA5-250 noise was shaped according to the international long-term average speech spectrum (Wagener et al., 2006). Prior to the measurements, all listeners were trained with two test lists of BB stimuli and one list with the HP filtered stimuli, all presented in SSN.

The LP and HP condition were constructed by filtering the speech and noise signals using a 1024th order FFT filter with cut-off frequencies of 1.5 and 1.65 kHz, respectively. The cut-off frequencies of the filters were based on experimental auditory-nerve phase-locking limit data in cats and guinea pigs that show a steep roll-off in phase locking between 1 and 2 kHz (Palmer & Russell, 1986). As a consequence of the phase-locking limit, encoding of LP speech is expected to rely on robust AN phase-locking, whereas HP speech encoding might rather relate to envelope-based signal encoding (Kale & Heinz, 2010; Henry et al., 2016). The exact cut-off frequencies for the LP and HP filtered conditions were selected to avoid the roll-off area of the AN-phase-locking decline with frequency, while maximally allowing for the possibility of reconstructing the BB results from the LP and HP conditions. Furthermore, the selected cut-off frequencies split the speech signals into two parts of comparable importance, considering the Speech Intelligibility Index (SII) band importance function for speech in noise (ANSI, 1997). The sum of SII octave band importance weights is 0.457 for frequencies 0.25, 0.5, and 1 kHz (corresponding to the LP condition in this study) and 0.543 for frequencies 2, 4, and 8 kHz.

The filtered stimuli were not amplified in this study to ensure that both the BB and filtered stimuli had the same spectral level in the pass band. This method allows for the determination of the contribution of specific frequency regions to BB speech recognition, but resulted in lower overall SPL levels of the filtered speech. The difference in overall level was ≈0 dB between the BB and LP condition, and ≈19 dB between the BB and HP condition. In the SSN and ICRA5-250 BB conditions, the noise level was kept fixed at 70 dB SPL during the experiment while the speech level was varied adaptively to determine the SRT. Measurements were conducted in a double-walled sound-insulated booth and the

sentences were presented over free-field equalized HDA200 headphones. The speech recognition experiments were administered using the Oldenburg Measurement Platform (HörTech gGmbH) with the Earbox Highpower ear 3.0 sound card. The measurement setup was calibrated to dB SPL using Brüel & Kjær instruments (artificial ear type 4153 connected with the microphone type 4134, preamplifier type 2669, and amplifier type 2610).

2.3. Amplitude-modulation detection thresholds

To provide a psychoacoustic correlate of supra-threshold hearing and robust TENV encoding, the speech results were compared to amplitude-modulation detection thresholds (AM DTs) in corresponding frequency regions. AM DTs were measured using the AFC software platform in a three-alternative, one-up two-down forced-choice procedure. Stimuli were 500-ms long sinusoidally amplitude-modulated pure tones with a phase of 0. A Turkey window with a 5-ms ramp was used, and 500-ms gaps of silence were placed between the stimulus intervals. The initial modulation depth was -12 dB (m = 0.25; 20log10(m) = -12 dB) and the initial step size of 10 dB was reduced to 5 dB after the first reversal. The step size was further reduced to 3 dB and 1 dB after which the threshold was determined from the average across six reversals at the smallest step size. The experiment was performed at 70 dB SPL for center frequencies within the LP (0.5 kHz) and HP (2 and 4 kHz) speech regions. A very weakly audible, 1-16 kHz wide white noise with a spectral level of 80-dB below that of the carrier frequency was always present during the task. AM DTs were calculated as averages across three repetitions of the same task and were obtained for modulation frequencies of 5 and 100 Hz. The signals were presented over free-field equalized HDA200 headphones, and played using a 24-bit external sound card (RME Fireface) via the open-source port-audio and playrec software. The measurement setup was calibrated to dB SPL using Brüel & Kjær instruments (artificial ear type 4153 connected with the microphone type 4134, preamplifier type 2669, and amplifier type 2610).

2.4. Correlations, Variance and Multiple Comparisons

As we aimed to study whether individual differences in one metric are related to individual differences in another metric, it is important to perform a regression analysis. In general, all figures and tables will show the correlation coefficients (r) between considered variables as well as the significance (p-value) that corresponds to the application of the linear regression model. The correlation coefficient is informative when describing how two variables relate quantitatively, but does not quantify how well one variable predicts the other under a linear model. The R^2, or the % with which the linear model explains the variation of the data around the mean, is a better descriptor for this aspect.

We considered r and R^2 values for all listeners in the study (pooled across yNH, oNH and oHI; N=34), as well as for subgroups of NH (yNH+oNH; N=24) and older listeners (oNH+oHI; N=20). The division into different subgroups was motivated as follows: the main difference between the subgroups of the pooled NH group is age as they were selected to have normal audiograms, whereas it is hearing sensitivity in the age-matched older group (see Fig.1B).

In a few occasions throughout the study, it was necessary to compare correlation strengths between one variable Z and two independent variables (X and Y) to draw conclusions about which variable best explained the individual results in the Z variable. A significance value comparing the r or R^2 values between X & Z, and Y & Z were computed numerically using resampling technique in which the N samples of X-Z and Y-Z data-points were drawn from the N total pairs (with replacement). 200 of such draws were taken for each X-Z and Y-Z dataset, over which regressions were calculated. The normally-distributed $r_{\mathrm{X\text{-}Z}}$ and $r_{\mathrm{Y\text{-}Z}}$ values were compared in a t-test to yield a p-value.

Lastly, it is well known that hypothesis testing with many variables poses a multiplicity problem in which the probability of receiving false positives increases with the total number of possible comparisons. The Bonferroni correction is a common way to safeguard against type-I errors by reducing the p-value at which significance is reached by α/m where m refers to the number of variables tested. However, the Bonferroni correction also increases the proba-

bility for type-II errors. The Holm-Bonferroni correction limits the introduction of type-I and type-II errors by ordering the p-values of a multiple comparison study from low to high, and by determining the minimum value of k at which the p-value $p_k > \alpha/(m+1-k) = p_{\text{Holm-Bonferroni}i}$. The correlation/regression values belonging to p_k below $p_{\text{Holm-Bonferroni}}$ are rejected while those associated with k values above the threshold are kept. The application of the Holm-Bonferroni correction was performed for the values within each table and for the interrelation study in Fig.5. The values in the tables indicate significance according to the regular $p<0.05$, $p<0.01$, $p<0.001$ convention, as well as indicate the values that passed the $p_{\text{Holm-Bonferroni}}$ correction in bold.

3. Results

3.1. Speech Recognition in Quiet

Fig.2A illustrates that hearing sensitivity, as characterized by $\text{PTA}_{0.5,1,2,4}$, strongly correlates with the SRT (r=0.92) when speech was presented in the absence of noise and all listeners were included in the analysis. These results are in line with previous studies (e.g. Festen & Plomp, 1983; Smoorenburg, 1992) and lead us to conclude that age-related deficits in e.g. supra-threshold processing or cognitive ability were not dominant factors. Even though our results do not entirely rule out that age-related deficits might contribute to the individual SRT in quiet (Fig.2B), this effect is less strong than that of the $\text{PTA}_{0.5,1,2,4}$. There was an age effect in the NH listener subgroup but this age effect was not found in the older listener group. The resampling analysis showed that the r for $\text{PTA}_{0.5,1,2,4}$ and the SRT in quiet (r=0.92) was significantly greater ($p<0.001$) than the r for age and the SRT in quiet (r=0.78) providing additional support for the dominant role of $\text{PTA}_{0.5,1,2,4}$ in explaining individual differences in SRT in quiet. Although the SRTs in quiet for the oNH group were generally higher than for the yNH group, they fell within (with the exception of one listener) the reference range for normal-hearing subjects (Wagener, 2003).

3.2. Speech Recognition in Noise

There were significant between-group differences for SRTs in stationary noise [F(2,33)=6.1, p=0.006] and yNH listeners scored significantly better (post-hoc with Bonferroni correction) than oNH (p=0.034) and oHI (p=0.01) groups (Fig.3A). Relationships between the different SRT conditions and hearing sensitivity, age and SRT in quiet are given in Table 1 for all listeners combined, and for subgroups of NH (yNH+oNH) and older listeners (oNH+oHI). The group differences cannot be explained by hearing sensitivity differences alone since the significant relationship between SSN_{BB} and $PTA_{0.5,1,2,4}$ across all listeners was not observed for the older listener group (Table 1), who had significantly different $PTA_{0.5,1,2,4}$s (Fig.1B). This is further supported by the absent relation between the SRT in quiet and in SSN_{BB} (r_{older}=-0.01) in the older group, confirming earlier findings (Festen & Plomp, 1983). Instead, age-related deficits are predominantly associated with individual SRT performance in SSN_{BB} as a significant relationship with age was observed across all listeners *and* within the NH subgroup. In agreement with an age-related origin of individual SRT performance in SSN_{BB}, a correlation with age and SSN_{BB} was absent within the age-matched older group. Lastly, the resampling analysis showed that the r for age and SRT in SSN_{BB} was significantly greater (p<0.001) than the r for $PTA_{0.5,1,2,4}$ and SRT in SSN_{BB} across all listeners. Taken together, our observations motivate that there are age (not hearing sensitivity) related deficits on the basis of individual SRT performance in SSN_{BB}.

SRTs in modulated (ICRA) noise differed across participant groups (Fig.3B; [F(2,33)=29.4, p<0.001]) and post-hoc comparisons (Bonferroni corrected) revealed significant differences across the three groups (p<0.01). SRTs for $ICRA_{BB}$ showed a strong relation to $PTA_{0.5,1,2,4}$ (r_{all}=0.77), the SRT in quiet (r_{all}=0.76) and age (r_{all}=0.77; Table 1). Considering all listeners, age explained as much variance in the data (R^2_{all}=0.59) as the $PTA_{0.5,1,2,4}$ did (R^2_{all}=0.59, p=0.16; resampling analysis). Additionally, both the NH and older subgroups showed significant relationships between the SRT in $ICRA_{BB}$ and $PTA_{0.5,1,2,4}$, and age (Table 1). To conclude, the main difference between the broadband $ICRA_{BB}$

and SSN_{BB} conditions is that hearing sensitivity plays a bigger role in explaining individual performance in the $ICRA_{BB}$ condition than for the SSN_{BB}. Elevated pure tone thresholds might limit the use of speech information in the temporal gaps of modulated noise as an explanation for the different impact of hearing sensitivity on SRTs in the two masker types.

3.3. Masking Release Benefit

$ICRA_{BB}$ SRTs were on average 9.5 dB better than for the SSN_{BB} condition. Masking release (MR), defined as the difference in SRT between the SSN and ICRA condition, was significantly different across groups ($F(2,31)=156$, $p=0.001$; Fig.3C). The oNH and oHI groups benefited on average 3.2 and 6.7 dB less from the modulated noise than the yNH group. Table 2 shows that MR amounts were greater for lower SRTs in quiet ($r_{all,\ BB}=-0.8$, $p<0.001$) and better hearing sensitivity ($r_{all,\ BB}=-0.8$, $p<0.001$). Despite a relation between MR and hearing sensitivity ($r_{NH,\ BB}=-0.5$, $p=0.01$) in the NH group, age was also strongly related to the MR ($r_{NH,\ BB}=-0.61$, $p=0.001$) in this listener group, in line with several other studies which reported reduced MR in older NH listeners (Dubno et al., 2002; Grose et al., 2009; Goossens et al., 2017). The small amounts of MR reported for the oHI group in the BB condition are strongly attributed to reduced hearing sensitivity ($r_{older,\ BB}=0.73$, $p<0.001$), corroborating earlier reports (Festen & Plomp, 1990; Strelcyk & Dau, 2009; Christiansen & Dau, 2012).

3.4. LP & HP Speech Recognition in Stationary Noise

By comparing the SRTs in the SSN_{BB} condition to LP and HP filtered SSN conditions, we attempted to isolate which frequency regions determined performance in the BB condition. We found that for the SSN condition: *(i)* HP SRTs showed an effect of listener group [$F(2,33)=18.0$, $p<0.001$; Fig.3A] that was absent for the LP SRTs [$F(2,33=1.3)$, $p>0.05$]. *(ii)* The average performance in the LP condition was only 3-dB worse than for the BB condition, while a

significant SRT drop of 9 dB was observed for the HP condition (Fig.3A). Concomitantly, *(iii)* the resampling analysis showed that the variance explained by the LP SRT for the SSN_{BB} was greater (R^2_{all}= 0.59; Fig.4A) than by the HP condition (R^2_{all}=0.38; Fig.4B; p<0.001), suggesting a stronger contribution of LF cues to the overall BB performance. The LP SRTs were not related to age (Table 1).

The SRT in SSN_{HP} correlated strongly to both $PTA_{2,4}$ (r_{all}=0.59) and age (r_{all}=0.76), but age-related deficits explained 58% of the total variance in the SSN_{HP} condition while hearing sensitivity only explained 35% of the results (p<0.001; resampling analysis). Hearing sensitivity differences cannot explain why oNH listeners performed significantly worse in SSN_{HP} than yNH listeners (p<0.001) and similarly to the oHI listeners (p>0.99), even though the latter group was characterized by higher pure-tone thresholds. The absence of a correlation between $PTA_{2,4}$ and SSN_{HP} in the older listener group (R^2_{older}=0.06, p>0.05) further supports this statement. Taken together, this analysis suggests that there are age-related (non hearing-sensitivity related) factors on the basis of the SRT performance in the SSN_{HP} condition.

3.5. LP & HP Speech Recognition in Modulated Noise

In both LP and HP filtered ICRA conditions, yNH listeners performed consistently better than the older listeners (p<0.001) and no significant differences were found between the two groups of older listeners (p<0.05) that differed in hearing sensitivity, but not in age (Fig.3B). In the LP condition, $ICRA_{LP}$ SRT performance did not relate with $PTA_{0.5,1}$ in the NH or older subgroups (Table 1). The SRTs in the $ICRA_{HP}$ condition correlated with $PTA_{2,4}$ and the variance of this relationship was strong when all groups were considered (R^2_{all}=0.64, p<0.001) and within the NH group (R^2_{older}=0.57, p<0.001), but *not* within the older group (R^2_{older}=0.22, p<0.05) where the hearing sensitivity differences between subgroups were greatest. For the HP condition, age explained 80% of the variance when all listeners were considered, 78% when the NH subgroup were considered, and even 52% within the older subgroup. The combined

LP and HP analysis thus suggests that age-related factors (and not hearing sensitivity) may play a dominant role in determining the SRT in modulated noise, as supported by observations in other studies (Dubno et al., 2002; Goossens et al., 2017).

The $ICRA_{BB}$ SRT performance degraded by 6.2 dB (to -8.8 dB) in the LP condition and by 17.7 dB in the HP condition yielding overall positive SRTs (2.7 dB; Fig.3B). This implies that also for the modulated noise condition, the low-frequency region has a major contribution to the BB SRT performance. However, unlike the SSN condition where the LP SRT explained the variance of the BB SRT better than the HP SRT when all subgroups were considered (Figs.4A&B, $R^2_{\text{all, LP}}$=0.59 *vs* $R^2_{\text{all, HP}}$=0.38), the modulated noise condition showed the opposite relation. The resampling analysis showed that the HP condition explained the total variance of the BB SRT better ($R^2_{\text{all, HP}}$=0.72; Fig.4D) than the LP condition ($R^2_{\text{all, LP}}$=0.49, Fig.4C, $p<0.001$), suggesting that high-frequency cues determine the individual performance variation in the $ICRA_{BB}$ SRT.

3.6. LP & HP Masking Release Benefit

Band limiting the stimuli in the LP and HP conditions significantly affected MR ($F(2,31)=156$, $p<0.001$; Fig.3C). The drop in MR was more prominent for the HP than LP condition resulting in respective 9.4 and 4.2-dB MR drops (yNH group). In agreement with other studies, we found that *(i)* NH listeners showed MR in both LP and HP conditions (Oxenham & Simonson, 2009; Christiansen & Dau, 2012), and that *(ii)* larger MR values were observed for more negative SRTs in the SSN_{BB} conditions ($r_{\text{all, BB}}$=-0.53, p=0.001; Christiansen & Dau, 2012). However, the relationship between better SSN SRTs and larger amounts of MR disappeared for the LP condition. Most of the older listeners reached negative MR values in the HP condition reflecting poorer SRTs in modulated than SSN noise. As Table 2 indicates, more negative MR_{HP} were found with age within the older listener group ($r_{\text{older, HP}}$=-0.71). The added modulation can thus be detrimental for HP speech recognition in older listeners and lead to

negative MR values, or *modulation interference*.

The oNH group showed similar MR to the oHI group for both filtered conditions ($p>0.05$) despite the hearing sensitivity differences between these two subgroups (Fig.3C). This supports the view that an age-related decline of auditory system functioning is at least partly responsible for the poorer MR in oNH listeners. Table 2 supports this view by illustrating that age relates to the MR_{BB} ($r_{NH,\ BB}$=-0.61, p=0.001), the MR_{HP} ($r_{NH,\ HP}$=-0.66, $p<0.001$) and somewhat to the MR_{LP} ($r_{NH,\ LP}$=-0.44, $p<0.05$). A significant correlation between age and MR_{LP}, but not hearing threshold, was found in the NH group (that showed overall positive MRs), while MR_{LP} in the older group neither showed a relationship to age nor threshold (Table 2).

In terms of the additivity of LP and HP MR, we found a significant correlation between the BB MR and the sum of the LP and HP MR (R^2_{all}=0.5, $p<0.001$). MR additivity was earlier observed in a study where MR was found to increase gradually as the bandwidth of the speech was increased by using LP or HP filtered speech with decreasing or increasing cut-off frequencies, respectively (Christiansen & Dau, 2012).

3.7. Amplitude-Modulation Detection Thresholds

This study assessed performance on an AM detection task for different carrier frequencies and modulation rates (5 and 100 Hz) to assess individual supra-threshold TENV encoding within the HP and LP frequency regions. When the carrier and modulation side-bands fall within a single perceptual auditory filter (i.e., unresolved), it is generally assumed that the AM DT reflects sensitivity to TENV encoding (Kohlrausch et al., 2000). For all but one condition (i.e., AM $DT_{0.5kHz,\ 100Hz}$), the tested modulation frequencies fell within one ERB (i.e., 78, 240, 457 Hz for 0.5, 2 and 4 kHz resp.). Consistent with the view that AM DTs reflect a supra-threshold mechanism, none of the 5-Hz conditions related to hearing sensitivity at the corresponding carrier frequency (Table 4). For the 100 Hz condition, the correlation with hearing sensitivity was strongest for the AM

$DT_{0.5kHz,\ 100Hz}$, where AM perception ability relates to spectral resolvability due to the resolved AM side-band frequencies. The 2 and 4-kHz conditions showed both a relationship to hearing sensitivity and age within the NH group, where the main difference subgroups of yNH and oNH listeners was age.

Table 3 summarizes the group differences for the different AM conditions and shows that oNH listeners had significantly worse AM DTs than yNH listeners for the 100-Hz conditions ($p<0.03$), but not the 5-Hz conditions. Even though oNH listeners performed somewhat better than the oHI listeners, this difference was not significant ($p>0.05$).

3.8. Interrelations between metrics

To isolate which factors and coding mechanisms are related to individual performance in the various speech-in-noise recognition tasks, we analysed which correlations exist between hearing sensitivity, age, and the different SRTs, while taking into account which correlations disappeared when the conditions (i.e., noise type, filtering) changed. A regression analyses was performed between variables across all listeners (N=34), as well as across the NH (yNH+oNH; N=24) and older (oNH+oHI; N=20) subgroups. The idea behind this comparative regression analysis is as follows: A significant correlation r (and variance R^2) that is present for all listeners, is dominated by age-related effects when it is present in the NH group, *and* absent in the older group. Conversely, a significant correlation across all individual listeners is dominated by hearing sensitivity when the correlation is absent or weak in the NH group, *and* strong in the older group. Lastly, correlations that persist strongly in both subgroups and across all individuals reflect a relation between variables that is neither hearing sensitivity nor ageing dominated, but that might be sensitive to combinations of both.

The results of the regression analysis are graphically summarized in Fig.5. Grey coloured boxes indicate significant relationships between conditions (Holm-Bonferonni corrected p=0.0032) that yielded R^2 values above 0.25 with darker colors indicating higher R^2 values. Fig.5A shows the regression analysis for the

pooled data, Fig.5B for subgroups of normal-hearing (yNH+oNH), and Fig.5C for older (oNH+oHI) listeners. The blue and red dashed areas delineate regressions that are relevant for the LP and HP conditions, respectively.

3.8.1. Older Listeners

Performance in the SSN_{LP} and $ICRA_{LP}$ conditions did not correlate for the older listeners (oNH+oHI; blue dashed area in Fig.5C), and the $ICRA_{LP}$ condition determined the MR_{LP} benefit. Performance in the LP noise conditions was neither related to age nor threshold. These relationships (blue boxed conditions) point to two important mechanisms at low frequencies: (i) a mechanism that dominates the LP stationary noise performance that is neither determined by age or threshold. (ii) a second mechanism that enables the use of temporal dips in the noise signal and that leads to the masking release benefit.

The relations at basal, high-frequency (HF) cochlear regions (red dashed area in Fig.5C) are different from the LF cochlear region . Performance in the HP stationary and modulated noise condition were correlated and resulted in positive SRTs (red boxes). The MR was overall negative in this listener group (Fig.3C), reflecting that the added temporal noise dips degraded performance. The amount with which performance degraded (MR_{HP}) was related to age (but not threshold), and points to an age-related deficit that affected performance even though the listeners in this subgroup had marked hearing sensitivity differences.

3.8.2. Normal-Hearing Listeners

Relationships in the HP conditions for the normal-hearing group (yNH+oNH; red dashed area in Fig.5B) are challenging to analyse in light of $TENV_{HF}$ mechanisms since speech recognition in modulated noise changed from negative SRTs for the best listeners to positive SRTs in the worst listeners (Fig.3C).When comparing the HP relations in the NH group to those of the older listeners who had positive SRTs (red boxes in Fig.5B *vs* Fig.5C), the positive SNR relations found for the older listener group were maintained in the normal-hearing group. Ad-

ditional relationships appeared for the NH group (i.e., more gray boxes in the red dashed HP area) which reflect additional HF mechanisms responsible for encoding HP speech at negative SRTs. Individual differences in hearing threshold (and/or age) impacted the HP SSN condition, and consequently the HP masking release benefit in the NH group. Because age and threshold were not independent for frequencies > 2 kHz in the NH group, it was not possible to determine whether age or threshold differences drove this relationship.

A similar pattern of relations was observed for the LP condition (blue dashed area in Fig.5B): stationary and modulated noise SRTs correlated, and the MR benefit correlated to the SRT in modulated (but not stationary) noise.

3.9. Relation to amplitude-modulation detection

As TENV encoding is mostly associated with auditory-nerve firing properties above the phase-locking limit (Palmer & Russell, 1986), we investigated whether individual HP speech recognition performance related to individual AM DTs. Fig.6 shows the amount with which listeners benefited from temporal gaps in the noise (i.e., masking release) and its relation to temporal envelope detection sensitivity (AM DTs). We only included results from the NH listeners in the correlation analysis because oHI listeners showed positive SRTs for both $\mathrm{SSN_{HP}}$ and $\mathrm{ICRA_{HP}}$ conditions, resulting in negative MR values that were associated with an age-related modulation interference effect rather than with a MR benefit that can be related to $\mathrm{TENV_{HP}}$ encoding. The regression analysis for the NH listeners showed a clear trend towards larger MR benefits (i.e., more positive MR) for listeners with better AM detection sensitivity (i.e., more negative AM DTs), consistent with the view that ($\mathrm{ENV_{HP}}$) mechanisms might underlie HP MR. Significance was reached for the 2-kHz conditions.

While $\mathrm{MR_{HF}}$ related to AM detection sensitivity in the NH group, we also studied whether AM DTs related to speech recognition. Fig.7 shows a significant relationship between 100-Hz AM DTs and SRTs in both $\mathrm{SSN_{HF}}$ or $\mathrm{ICRA_{HF}}$ conditions for the NH listeners. HP speech recognition and AM DTs did not relate to the 5-Hz AM DTs (results not shown). The hypothesis that $\mathrm{TENV_{HP}}$,

as assessed by AM DTs at 100 Hz, is responsible for both the HP SRT in stationary and modulated noise is supported for NH ageing listeners. The relationship between HP SRTs and AM DTs disappeared when including HI listeners: their SRT performance fell in range with that of the oNH listeners, while their AM DTs resembled those of the yNH listeners. The relation between the two metrics is thus complex for oHI listeners: ageing worsened AM DTs and hearing sensitivity loss enhanced AM DTs, while ageing and hearing sensitivity loss both worsened speech recognition. Using HF AM DTs as a predictor for $\mathrm{TENV_{HP}}$ encoding ability and HP speech recognition is hence only established for listeners with normal HF hearing thresholds. However, the finding that HF AM DTs do not predict SRTs in the oHI subgroup does not affect the earlier described relationship between HP SRTs for stationary and modulated noise conditions, that were consistently reported for all groups (see Fig.5).

In studying the relation between LP speech recognition and AM DTs, it was possible to include all listeners in the regression analysis as they all had negative SRTs and positive MRs. As Figs.8A,C&E show, there was no relationship between LF AM DTs and the $\mathrm{MR_{LF}}$ for the 5-Hz AM condition but there was for the 100-Hz condition. Only the 5-Hz condition yielded unresolved modulation side-bands for the 0.5-kHz carrier frequency, so it does not make sense to analyse the 100-Hz AM DTs in light of $\mathrm{TENV_{LF}}$ mechanisms.

3.10. Discussion

By comparing BB SRT performance to (unamplified) LP and HP filtered versions of the same stimuli, we were able to determine the relative contribution of LF and HF cues to overall speech recognition in stationary and modulated noise. The grouping of study participants in NH and older listener groups made it possible to examine how individual differences related to main effects of age and hearing sensitivity, as well as identify dominant cues that emerged across all listeners. Even though the dataset was relatively small, and oNH listeners differed both significantly in hearing sensitivity for frequencies > 2 kHz *and* age from the yNH listeners, we interpreted the data with caution to suggest

which coding mechanisms dominate LP & HP frequency regions for stationary and modulated noise types. The interpretation of the present dataset is aimed to guide future studies that explore specific aspects of the identified coding mechanisms with larger cohorts. This will ultimately yield a more complete theory of how speech recognition is impacted by hearing sensitivity, age and supra-threshold hearing deficits.

3.10.1. Mechanisms for BB speech in noise

LF cues (<1.5 kHz) were shown to dominate overall BB speech recognition, both for the stationary and modulated noise types as the degradation in LP *vs* BB SRTs was less than for HP *vs* BB SRTs (Fig.3A&B). These results imply that even though HF sloping hearing losses and age impact HP speech recognition, the HF region contributes less strongly to BB speech recognition. The LF dominance occurred even though the cut-off frequency between the LP and HP regions was chosen to yield comparable Speech Intelligibility Index (SII) band-importance functions for the two conditions (ANSI, 1997). This discrepancy between our result and the expected SII outcome might relate to how the band-importance function was constructed. Generally, the band-importance function depends on the speech stimuli themselves with greater emphasis on higher frequency-content for isolated syllables than for running speech. Furthermore, different languages may also result in different band-importance functions (Wong et al., 2007). It was recently shown that SII predictions for the German Matrix test in noise were significantly worse than the empirical data for listeners with steeply sloping audiograms (rms error of 22.6 dB) (Hülsmeier et al., 2018), suggesting an overestimation of high-frequencies in the SII.

Because LP SRTs were unrelated to hearing sensitivity and $PTA_{0.5,1,2,4}$ did not predict the SSN_{BB} performance in the older group (Table 1), our results agree with the view that LF coding mechanisms (e.g., temporal, spectral) may be important for speech recognition in BB stationary noise. LF coding mechanisms were shown to explain individual differences across all listeners in SRT_{BB} for the stationary SSN condition better than HF coding mecha-

nisms (Fig.4A). In contrast, HF coding mechanisms explained the individual differences in SRT_{BB} for modulated noise better than LF coding mechanisms (Fig.4D). For the $ICRA_{HP}$ condition, the positive SRTs and associated negative MRs for the worst performing listeners may have had a detrimental effect on overall BB performance, hence driving the individual differences. As $ICRA_{LP}$ also correlated to the $ICRA_{BB}$ performance (Fig.4C), there might also be a role for TFS_{LF} and/or spectral resolvability (Fig.8D&F) in modulated noise SRTs.

3.10.2. LF coding mechanisms

The interrelation analysis in Fig.5 across the older listener group identified two important mechanisms at low frequencies: (i) a mechanism that dominates the LP stationary noise performance that is neither determined by age or threshold. (ii) a second mechanism that enables the use of temporal dips in the noise signal and that leads to the masking release benefit. We postulate that the first mechanism might relate to TFS coding ability based on earlier reports that have identified this mechanism and its independence of hearing sensitivity (Strelcyk & Dau, 2009; Hopkins & Moore, 2011; Papakonstantinou et al., 2011). The second mechanism might relate to dip-listening, that we associate here with TENV encoding of low-frequency temporal envelopes ($TENV_{LF}$) that could improve speech recognition for modulated over stationary noise conditions. The reason why we suggest a second LF coding mechanism is motivated by the finding that the MR amount was not related to the SSN performance itself, as postulated in other studies (Bernstein & Grant, 2009; Christiansen & Dau, 2012; Léger et al., 2012b).

To corroborate the view of two LP encoding mechanisms (TFS and $TENV_{LF}$) with the interrelations found across the NH group (Fig.5B), we need to assume that TFS encoding ability (unrelated to age/threshold) dominates performance in the SSN_{LP} condition, and that $TENV_{LF}$ encoding ability (related to age and/or threshold) is responsible for determining how well individuals benefit from temporal envelope gaps in the noise. To further explain the coexisting correlation between SRT in SSN and ICRA for NH listeners, it has to be as-

sumed that TFS and $\mathrm{TENV_{LF}}$ encoding ability performance are related in NH ageing listeners. The same (supra-threshold) deficit degrading TFS encoding, should thus also degrade LP "dip-listening" which might offer another view (i.e., temporal changes in dynamic range) of the same (supra-threshold) hearing deficit. As the relation between the LP stationary and modulated noise condition disappeared for the older listener group (Fig.5C), the proposed $\mathrm{TENV_{LF}}$ degradation might be unrelated to the individual $\mathrm{TFS_{LF}}$ degradation in listeners with elevated hearing thresholds.

3.10.3. HF coding mechanisms

The interrelations for the HP conditions were quite different from those identified for the LP conditions (Fig.5) which might relate to the absence of TFS encoding at high frequencies where auditory-nerve fibers can no longer encode TFS information (i.e. the phase-locking limit; Palmer & Russell, 1986). An explanation for the strong relation between $\mathrm{SSN_{HP}}$ and $\mathrm{ICRA_{HP}}$ across all listeners and subgroups of NH and older listeners (Fig.5) could stem from a HF temporal envelope encoding mechanism ($\mathrm{TENV_{HF}}$) that encodes speech in both noise type conditions. Because the added dips in the noise compromised the performance (as a function of age) particularly in those listeners who already performed badly in the stationary noise condition, compromised ($\mathrm{TENV_{HF}}$) encoding might be even more challenged when temporal noise dips are added and when a single $\mathrm{TENV_{HF}}$ mechanism is responsible for encoding both stationary and modulated noise.

One possible explanation for the more complex NH HP results (Fig.5B) is that the age-dominated HP MR decline in the positive SNR region (i.e., the red boxed area in Fig.5B&C) can be complemented by a HP MR benefit that is threshold (but not age) dependent when the modulated noise condition yields negative SNRs. Lastly, hearing sensitivity impacted performance in the HP stationary and modulated noise conditions, and was related to the HP MR benefit. However, a relationship between the SRT in SSN and MR benefit was absent, by which we conclude that the MR related more strongly to the

modulated-noise SRT performance, and did not depend on the stationary noise condition.

3.10.4. Masking Release

Masking release (i.e., the SRT benefit of modulated over stationary noise) was present for both the LP and HP conditions and related to the modulated-noise SRT in both frequency regions ($box_{9,10}$ and $box_{12,13}$ in Fig.5). MR was not linked to how well listeners performed in the stationary noise condition ($box_{8,10}$ and $box_{11,13}$ in Fig.5) and resulted in negative values in older listeners. Negative MRs, or modulation interference, has earlier been reported for NH listeners in consonant recognition (Kwon & Turner, 2001), for NH listeners performing at positive SRTs (Oxenham & Simonson, 2009), and for HI listeners who had positive SRTs (Christiansen & Dau, 2012; Goossens et al., 2017). Moreover, MR was age-dependent in the older listener subgroup by showing more modulation interference for the oldest listeners. Given that MR was also found to be additive (i.e., BB MR = LP MR + HP MR), there is certainly a benefit in avoiding modulated noise conditions for the HF regions where older listeners require positive SRTs to perform speech recognition.

3.10.5. Role of age-related deficits to speech recognition

The r for age and SRT in SSN was significantly greater than the r between $PTA_{0.5,1,2,4}$ and SRT in SSN across all listeners. Together with how age and $PTA_{0.5,1,2,4}$ related to SSN SRTs in the subgroups (Table 1), we suggests that there are age (not hearing sensitivity) related, cues on the basis of SRT performance in SSN_{BB}. This conclusion corroborates multiple other studies that reported degraded speech recognition in stationary noise for ageing listeners with normal audiograms (Dubno et al., 1984; Füllgrabe et al., 2015; Goossens et al., 2017). Given that LP mechanisms were shown to dominate the overall SSN_{BB} SRT, the origin of the SRT degradation is likely to stem from a supra-threshold hearing deficit in the LF region. We did not assess TFS sensitivity in the present study, so we cannot provide additional support for this statement.

There are two observations that suggest a contribution of (age-related) supra-threshold deficits to the HF encoding of speech in SSN noise. *(i)* The SRT in SSN_{HP} strongly correlated to both $PTA_{2,4}$ and age, but age-related deficits explained 57% of the total variance in the SSN_{HP} condition while hearing sensitivity explained only 35% of the results ($p<0.001$; resampling analysis). *(ii)* Hearing sensitivity differences cannot explain why oNH listeners performed significantly worse than yNH listeners ($p<0.001$) and similarly to the oHI listeners ($p>0.99$), even though the latter group was characterized by higher pure-tone thresholds. The absence of a correlation between $PTA_{2,4}$ and SSN_{HP} in the older listener group ($R^2_{older}=0.06$, $p>0.05$) further supports this statement.

3.10.6. Role of audibility

Overall, this study shows that (age-related) supra-threshold hearing deficits (unrelated to hearing sensitivity) contribute strongly to speech recognition in noise. However, to isolate the role of hearing sensitivity we adopted the PTA which only provides a very crude estimate of the frequency-specific aspects of hearing sensitivity. Hearing sensitivity and audibility aspects may be better isolated from supra-threshold deficits by using the SII (ANSI, 1997) or simulation framework for auditory discrimination experiments (i.e., FADE; Schädler et al., 2015; Kollmeier et al., 2016) that take into account sensitivity across the audible frequency range. Using these models, it might be possible to simulate which aspects of speech recognition cannot be explained by a hearing sensitivity loss alone.

Recent studies have shown that speech recognition is not only determined by the amount of audible speech information (i.e., above the individual pure-tone threshold or noise level) but that it is also influenced by the temporal-envelope fluctuations inherent to the noise (Stone et al., 2011, 2012). According to this concept, the modulations contained in the noise signal may also play an important role when apparent stationary maskers are used. Broader cochlear filtering in HI listeners can result in a reduction of inherent low-frequency noise fluctuations which could explain why they showed no MR. However, since broader

cochlear filters are not expected in oNH listeners, this concept cannot explain the MR loss observed in that group.

Lastly, from an empirical point of view, it would have been interesting to compare the SRT performance in LP & HP filtered speech stimuli (where ageing, audibility and hearing sensitivity might play a role) to the filtered speech-in-noise stimuli. This would have further helped to isolate which speech encoding mechanisms are mostly impacted by the added noise.

3.10.7. Role of TENV mechanisms to speech recognition

The identified relations between AM DTs and SRTs show that TENV encoding is an important mechanism for speech recognition, and that deficits to this mechanism (irrespective of hearing threshold degradations) may have a significant impact on speech recognition. At low frequencies, relationships between the SRT and AM DT are not immediately expected as there may be multiple coding mechanisms at play: e.g. $\mathrm{TFS_{LF}}$, $\mathrm{TENV_{LF}}$, or spectral resolution. The missing relation between the AM DT and SRT in $\mathrm{SSN_{LP}}$ further supports the view that LF speech recognition in stationary noise relies on a mechanism that is unrelated to envelope sensitivity, but rather relates to $\mathrm{TFS_{LF}}$ or other low-frequency encoding mechanisms. Even though dedicated TFS sensitivity tests (Hopkins & Moore, 2009; Strelcyk & Dau, 2009; Füllgrabe et al., 2006; Grose & Mamo, 2010; Papakonstantinou et al., 2011) were not performed in this study, the 0.5-kHz 100-Hz AM condition might shed some light on spectral resolution and TFS encoding as the side-band modulation components were in this case resolved. The 100-Hz AM condition related well to the $\mathrm{ICRA_{LP}}$ and $\mathrm{MR_{LP}}$ (Fig.8D,F) supporting the view that perhaps spectral resolution (and not $\mathrm{TENV_{LF}}$) plays a role in the LP modulated noise condition.

The 2- and 4-kHz AM DT conditions showed both a relationship to hearing sensitivity and age within the NH group, where main difference between yNH & oNH listeners was age. Age has been reported to influence AM DTs negatively in listeners with normal or mildly-impaired hearing (Takahashi & Bacon, 1992; Jin et al., 2014). The age effect on the 2 and 4-kHz results may thus point to a

role for an age-related supra-threshold hearing deficits in this task, in line with two studies showing that individual differences in AM DTs for listeners with normal audiograms relate to the robustness of subcortical temporal envelope encoding as assessed using EEG (Purcell et al., 2004; Bharadwaj et al., 2015).

Lastly, AM DTs to the 100-Hz condition were significantly worse for the oNH than yNH group, and were statistically similar to AM DTs in the oHI group. This could be explained by a counteracting effect in which ageing reduces AM sensitivity, and reduced hearing sensitivity might enhance AM sensitivity. Similar performance at AM detection for listeners with (flat) hearing loss and NH listeners was observed in an earlier study (Bacon & Gleitman, 1992). A possible explanation for enhanced AM sensitivity in listeners with elevated hearing thresholds relates to the rate-level characteristics of auditory-nerve fibers, which are more sensitive to AM in the mid-level range than in the higher stimulation level range (Shaheen et al., 2015; Joris & Yin, 1992). A reduction of the effective drive to AN fibers (as caused by a loss of hearing sensitivity) might result in an AM encoding benefit, that possibly counteracts the detrimental effect age has on AM encoding yielding near-normal AM DTs for oHI listeners.

3.10.8. Relating TENV encoding deficits to synaptopathy

Supra-threshold deficits deficits may stem from cochlear synaptopathy (or, cochlear neuropathy, hidden hearing loss) that in animal studies has been shown to degrade the number and types of auditory nerve fibers synapsing onto the inner-hair-cells while leaving hearing thresholds unaffected. Synaptopathy yields a fewer number of independent coding channels and can thus cause stochastic undersampling (Lopez-Poveda & Barrios, 2013) and limit the dynamic range of coding supra-threshold temporal envelope fluctuations (Bharadwaj et al., 2014; Carney, 2018). In light of specific LF and HF mechanisms, synaptopathy may affect $\mathrm{TFS_{LF}}$ as a jitter on the zero-crossings of the stimuli, while it may affect $\mathrm{TENV_{HF}}$ as a jitter on encoding temporal envelope fluctuations. Reduced dynamic ranges of coding have so far mostly been shown to affect $\mathrm{TENV_{HF}}$ encoding mechanisms (Bharadwaj et al., 2015; Verhulst et al., 2018).

While it remains challenging to link physiological correlates of synaptopathy (i.e., using auditory evoked potentials; Lin et al., 2011; Furman et al., 2013; Shaheen et al., 2015; Möhrle et al., 2016; Mehraei et al., 2016) to humans directly (Hickox et al., 2017; Prendergast et al., 2017), there are some studies that have related reduced auditory brainstem response (ABR) SP/AP ratio's as a human marker for synaptopathy to degraded speech intelligibility in listeners with normal audibility but various degrees of self-reported noise exposure history (Liberman et al., 2016). Additionally, degraded envelope-following responses (EFRs) to less than 100% modulated stimuli were shown to relate to degraded AM DTs in normal-hearing listeners (Bharadwaj et al., 2015). Given that our results show how degraded HF AM DTs yield smaller $\mathrm{SRT_{HP}}$ and $\mathrm{MR_{HP}}$, we postulate that there might be a relationship between EFR magnitudes and HF speech recognition. Using an additional physiological marker of $\mathrm{TENV_{HF}}$ might, in future studies, relate perceptual $\mathrm{TENV_{HF}}$ deficits more directly to synaptopathy as the EFR metrics can be obtained alongside a histological assessment of synaptopathy in animal studies.

4. Acknowledgements

The work was supported by the DFG Cluster of Excellence EXC 1077/1 'Hearing4all' (AW/SV) and has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme under grant agreement No 678120 RobSpear (SV). We thank Sabrina Pieper for the recruitment of study participants and data collection.

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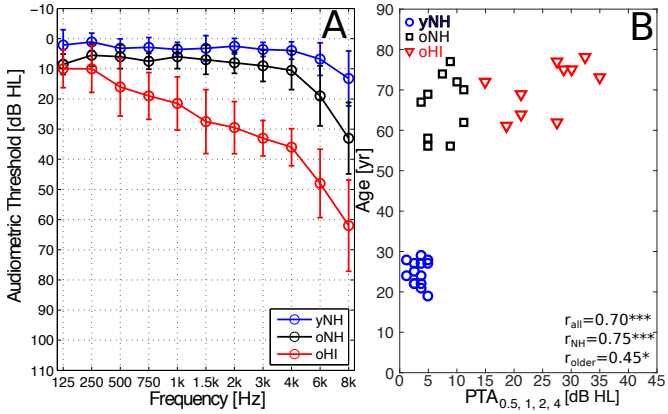

Figure 1: **A**: Mean pure tone thresholds with corresponding standard deviations for groups of young normal-hearing (NH, blue, N=14), older normal-hearing (oNH, black, N=10), and older hearing-impaired listeners (oHI, red, N=10). **B**: Relation between the participants' age and pure tone average ($\mathrm{PTA}_{0.5,1,2,4}$). r is given for all participants together (r_{all}), and for subgroups of normal-hearing (r_{NH}; yNH+oNH), and older listeners (r_{older}; oNH+oHI). *** for p<0.001, ** for p<0.01, * for p≤0.05.

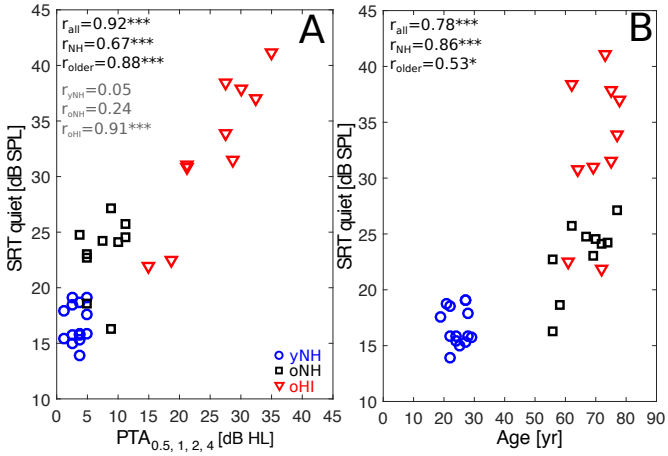

Figure 2: Relation between the individual SRT in quiet and $\mathrm{PTA}_{0.5,1,2,4}$ (**A**) or age (**B**). r is given for all participants together (r_{all}), and for subgroups of normal-hearing (r_{NH}; yNH+oNH), and older listeners (r_{older}; oNH+oHI). r within the groups is also reported for $\mathrm{PTA}_{0.5,1,2,4}$ in panel **A** (gray fonts). *** for p<0.001, ** for p<0.01, * for p≤0.05.

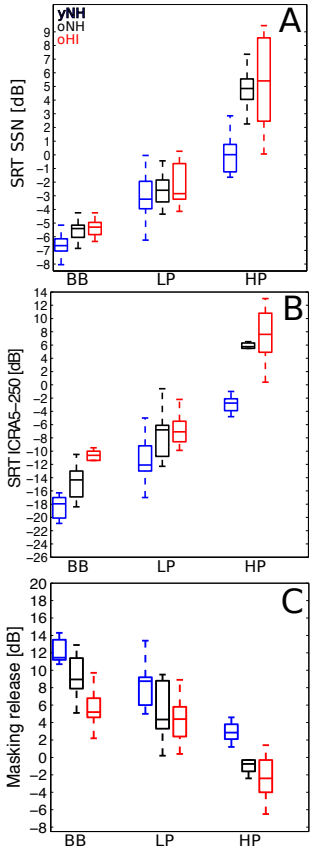

Figure 3: Boxplots of SRTs in the three participant groups (yNH, oNH, oHI) for broadband (BB), low-pass (LP) and high-pass (BB) filtered speech conditions. **A**: SRT in speech-shaped noise, **B**: SRT in modulated noise, **C**: Masking release defined as the SRT in ICRA - SRT in SSN.

Table 1: Correlation coefficients r between SRTs in SSN or ICRA noise and PTA, Age and SRT in quiet. Correlations were computed across all listeners, the NH listeners (yNH+oNH) or the older listeners (oNH+oHI). Significance: *** for p≤0.001, ** for p≤0.01, * for p≤0.05. r values that passed the Holm-Bonferroni correction for multiple comparisons in this table (p=0.003) are indicated in bold.

	BB SSN			LP SSN			HP SSN			BB ICRA			LP ICRA			HP ICRA		
	all	**NH**	**old**	**all**	**NH**	**old**	**all**	**NH**	**old**	**all**	**NH**	**old**	**all**	**NH**	**old**	**all**	**NH**	**old**
$PTA_{0.5,1,2,4}$	0.37*	0.41*	0.07	0.18	0.11	0.02	**0.59*** **	**0.63*** **	0.28	**0.77*** **	0.54**	**0.69*** **	**0.47** **	0.28	0.24	**0.70*** **	**0.71*** **	0.43
$PTA_{0.5,1}$	0.28	0.39	-0.10	0.11	0.07	-0.12	0.54**	0.48*	0.28	**0.64*** **	0.29	0.50*	0.40*	0.19	0.18	**0.58*** **	0.40	0.32
$PTA_{2,4}$	0.41*	0.33	0.17	0.22	0.11	0.11	**0.59*** **	**0.58** **	0.25	**0.8*** **	0.57**	**0.76*** **	**0.49** **	0.27	0.26	**0.73*** **	**0.75*** **	0.47*
Age	**0.55*** **	0.48*	0.16	0.31	0.26	0.24	**0.76** **	**0.79*** **	0.32	**0.77*** **	**0.65*** **	0.47*	**0.56*** **	0.45*	0.00	**0.89*** **	**0.88*** **	**0.72*** **
SRT quiet	0.33*	0.26	-0.01	0.2	0.21	0.09	**0.65*** **	**0.64*** **	0.3	**0.76*** **	0.56**	**0.67*** **	**0.46*** **	0.26	0.23	**0.78*** **	**0.82** **	0.51*

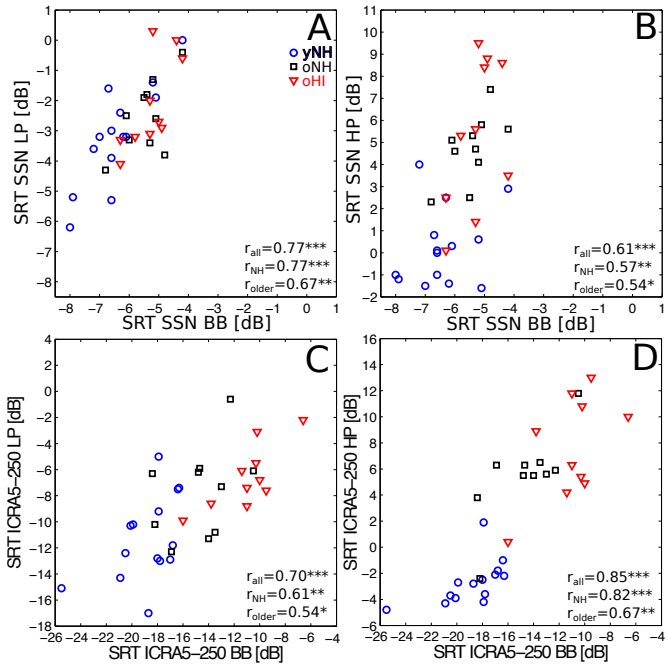

Figure 4: Relations between the BB SRTs and the SRT of the conditions in stationary noise (**A-B**) and in modulated ICRA-250 Hz noise **C-D**. r is given for all participants together (r_{all}), and for subgroups of normal-hearing (r_{NH}; yNH+oNH), and older listeners (r_{older}; oNH+oHI). *** for p<0.001, ** for p<0.01, * for p≤0.05.

Table 2: Correlation coefficients r between Masking Release [dB] and PTA, Age and SRT in quiet. Correlations were computed across all listeners, the NH listeners (yNH+oNH) or the older listeners (oNH+oHI). Significance: *** for p≤0.001, ** for p≤0.01, * for p≤0.05. r values that passed the Holm-Bonferroni correction for multiple comparisons in this table (p=0.009) are indicated in bold.

	$\mathbf{MR_{BB}}$			$\mathbf{MR_{LP}}$			$\mathbf{MR_{HP}}$		
	all	**NH**	**old**	**all**	**NH**	**old**	**all**	**NH**	**old**
$\mathbf{PTA_{all}}$	**-0.8*****	-0.5**	**-0.73*****	**-0.48*****	-0.29	-0.25	**-0.58*****	**-0.54*****	-0.34
$\mathbf{PTA_{0.5,\ 1}}$	**-0.68*****	-0.21	**-0.57*****	-0.44**	-0.20	-0.26	-0.43**	-0.18	-0.18
$\mathbf{PTA_{2,\ 4}}$	**-0.82*****	**-0.57*****	**-0.78*****	**-0.49*****	-0.28	-0.23	**-0.64*****	**-0.64*****	-0.42
Age	**-0.75*****	**-0.61*****	-0.47*	**-0.53*****	-0.44*	0.12	**-0.74*****	**-0.66*****	**-0.71*****
$\mathbf{SRT_{quiet}}$	**-0.80*****	**-0.58*****	**-0.73*****	**-0.46*****	-0.23	-0.21	**-0.65*****	**-0.70*****	-0.42

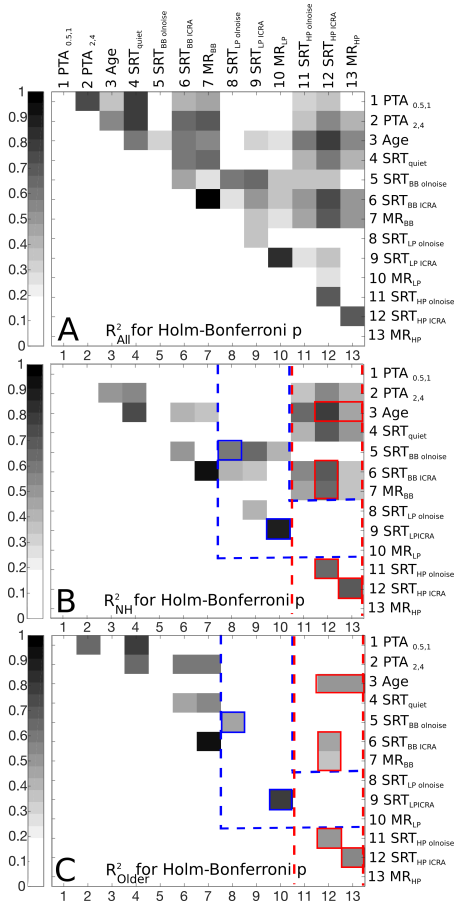

Figure 5: Relations between age, threshold measures and speech conditions for all listeners combined (**A**), and for subgroups of normal-hearing (yNH+oNH; **B**) and older listeners (oNH+oHI; **C**). R^2 above 0.25 are plotted, with larger R^2 values corresponding to darker colors. Only statistically significant relationships are shown, and multiple comparison biases were corrected for by adopting the Holm-Bonferroni corrected p-threshold. The LP speech conditions are delineated using the blue dashed lines and the HP speech conditions are marked with the dashed red line. The boxed conditions in the **B** and **C** panels correspond to significant relationships in the older listener group where audibility (not age) differences were largest across individuals.

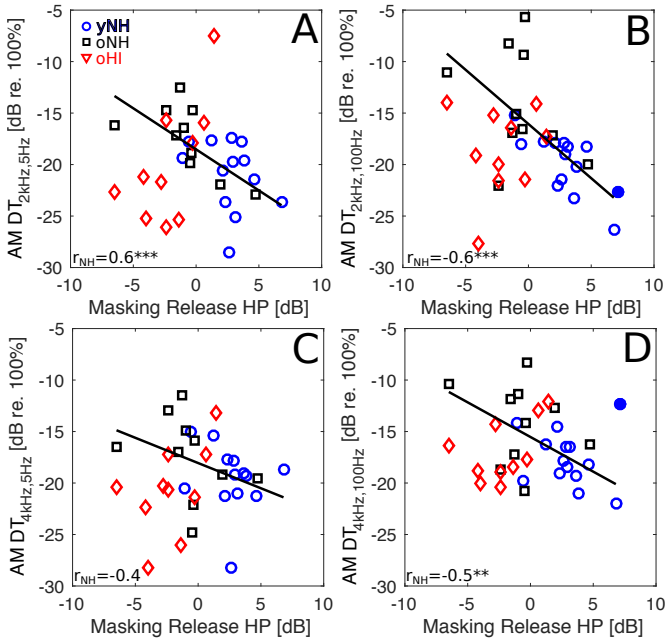

Figure 6: Relations between amplitude modulation detection thresholds and HP filtered speech recognition in stationary noise for all participants. A regression analysis was performed on the data of the the normal-hearing listeners (yNH+oNH). AM DTs were obtained for stimulation levels of 70 dB SPL at carrier frequencies of 2 (top) and 4 kHz (bottom) and for modulation frequencies of 5 and 100 Hz. One data-point (filled blue marker) from a yNH listener who had extreme difficulties performing the 5 Hz task (i.e., AM DT of -3.9 to -2.3) was omitted from the regression analysis.

Table 3: Mean AM detection thresholds (AM DTs) and standard deviations across the 3 participant groups: yNH (N=14), oNH (N=10) and oHI (N=10). Individual AM DTs were averaged across 3 repetitions of the same task

	AM $DT_{0.5kHz,\ 5Hz}$	**AM $DT_{2kHz,\ 5Hz}$**	**AM $DT_{4kHz,\ 5Hz}$**	**AM $DT_{0.5kHz,\ 100Hz}$**	**AM $DT_{2kHz,\ 100Hz}$**	**AM $DT_{4kHz,\ 100Hz}$**
yNH	-18.9±4.4	-19.7±5.6	-18.3±5.6	-27.8±6.1	-19.9±2.9	-17.6±2.7
oNH	-17.7±3.9	-17.5±3.3	-17.42±4.1	-20.7±5.5	-14.2±5.4	-14.1±3.9
oHI	-19.4±5.4	-19.9±5.8	-20.7±4.3	-20.9±5.3	-18.7±4.2	-17.0±2.9

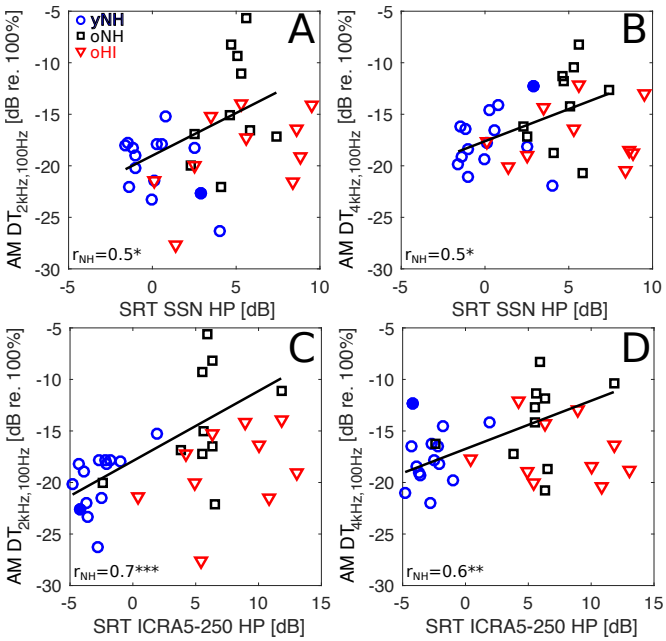

Figure 7: Relations between amplitude modulation detection thresholds and HP filtered speech recognition in the presence of stationary (olnoise) or modulated (ICRA-250Hz) noise for all listeners. A regression analysis was conducted for the normal-hearing listeners (yNH+oNH). AM DTs were collected for stimulation levels of 70 dB SPL at carrier frequencies of 2 (top) and 4 kHz (bottom) and for a modulation frequency of 100 Hz.

Table 4: Correlation coefficients r between AM DTs and PTA, Age and SRT in quiet. Correlations were computed across all listeners, the NH listeners (yNH+oNH) or the older listeners (oNH+oHI). Significance: *** for p≤0.001, ** for p≤0.01, * for p≤0.05. r values that passed the Holm-Bonferroni correction for multiple comparisons in this table (p=0.006) are indicated in bold.

	PT $TH_{0.5}$			**PT TH_2**			**PT TH_4**			**Age**			**SRT quiet**		
	all	**NH**	**old**	**all**	**NH**	**old**	**all**	**NH**	**old**	**all**	**NH**	**old**	**all**	**NH**	**old**
AM $DT_{0.5kHz,\ 5Hz}$	0.15	0.21	0.13	-0.16	0.19	-0.32	0	0.34	-0.08	-0.01	0.12	-0.28	0.01	0.18	-0.03
AM $DT_{2kHz,\ 5Hz}$	0.14	0.24	0.04	-0.12	0.24	-0.33	-0.05	0.22	-0.25	0.09	0.29	-0.15	0.04	0.27	-0.03
AM $DT_{4kHz,\ 5Hz}$	0.00	0.05	-0.03	-0.27	0.12	-0.39	-0.15	0.27	-0.23	-0.08	0.11	-0.15	-0.12	0.09	-0.12
AM $DT_{0.5kHz,\ 100Hz}$	0.31	0.14	0.77	0.43**	**0.57****	0.16	0.43*	0.48*	0.11	**0.55*****	0.50**	0.19	**0.53*****	**0.59*****	0.28
AM $DT_{2kHz,\ 100Hz}$	0.09	0.04	-0.37	-0.01	0.49*	-0.36	-0.02	0.28	0.44*	0.34*	**0.54*****	-0.04	0.11	**0.57*****	-0.24
AM $DT_{4kHz,\ 100Hz}$	-0.12	-0.10	-0.38	-0.01	0.43*	-0.42	0.02	0.44*	-0.38	0.19	0.41*	-0.45*	0.02	0.39	-0.32

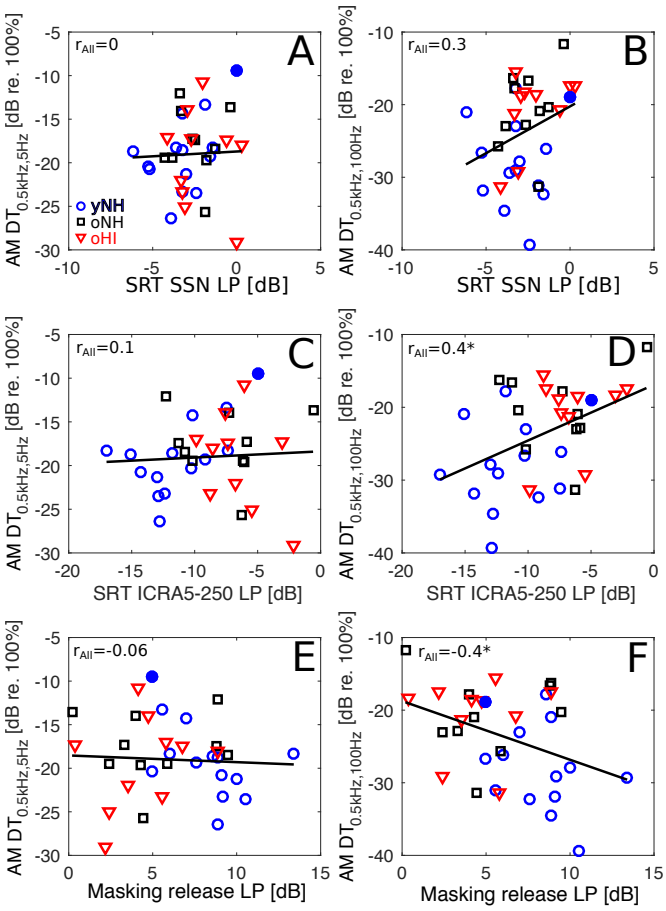

Figure 8: Relations between amplitude modulation detection thresholds (AM DTs) at 0.5 kHz and the LP modulation release (top panels) and LP filtered speech recognition in the presence of modulated (ICRA-250Hz) noise for all participants. AM DTs were obtained for stimulation levels of 70 dB SPL at and for modulation frequencies of 5 and 100 Hz.