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# Interactions between amplitude modulation and frequency modulation processing: Effects of age and hearing loss

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Frequency modulation (FM) and amplitude modulation (AM) detection thresholds were measured for a 500-Hz carrier frequency and a 5-Hz modulation rate. For AM detection, FM at the same rate as the AM was superimposed with varying FM depth. For FM detection, AM at the same rate was superimposed with varying AM depth. The target stimuli always contained both amplitude and frequency modulations, while the standard stimuli only contained the interfering modulation. Young and older normal-hearing listeners, as well as older listeners with mild-to-moderate sensorineural hearing loss were tested. For all groups, AM and FM detection thresholds were degraded in the presence of the interfering modulation. AM detection with and without interfering FM was hardly affected by either age or hearing loss. While aging had an overall detrimental effect on FM detection with and without interfering AM, there was a trend that hearing loss further impaired FM detection in the presence of AM. Several models using optimal combination of temporal-envelope cues at the outputs of off-frequency filters were tested. The interfering effects could only be predicted for hearing-impaired listeners. This indirectly supports the idea that, in addition to envelope cues resulting from FM-to-AM conversion, normal-hearing listeners use temporal fine-structure cues for FM detection. © 2016 Acoustical Society of America.

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## I. INTRODUCTION

Speech sounds are decomposed by the cochlear filters into narrowband signals containing strong amplitude modulation (AM) and frequency modulation (FM). Many studies suggest that these modulation cues play important roles in speech identification, with FM playing a possible role in the segregation of speech from competing sound sources (e.g., Zeng *et al.*, 2005; Strelcyk and Dau, 2009; Shamma and Lorenzi, 2013; Mehraei *et al.*, 2014; Johannesen *et al.*, 2016).

Numerous psychophysical studies have investigated whether the ability to detect FM is based on a single type or two distinct types of sensory information: spatial (rate/place) and temporal fine structure (TFS). Rate/place information is generated by dynamic changes in the excitation pattern evoked by the FM sound along the basilar membrane in the cochlea. The changes in frequency may be perceived by monitoring changes in excitation level—that is, temporal-envelope cues—at one place or at multiple places on the excitation pattern (Zwicker, 1952; Moore and Sek, 1994). This mechanism is often referred to as “FM-to-AM conversion”

because frequency-dependent attenuation of the FM caused by the cochlear filters results in AM that is encoded via fluctuations in the mean discharge rate of auditory-nerve fibers.

TFS information about FM is conveyed by changes in the phase-locked firing pattern of auditory-nerve fibers. For most mammals, the precision of neural phase locking is constant for frequencies up to about 600–2000 Hz (Palmer and Russell, 1986). Several studies have suggested that changes over time in the pattern of neural phase-locking may be used to perceive FM, at least for low FM rates and for low carrier frequencies (Demany and Semal, 1989; Moore and Sek, 1996; Moore and Skrodzka, 2002). These researches also pointed out that TFS cues are not used to detect FM with modulation rates above about 10 Hz, arguing that the phase-locking mechanism is sluggish. Nevertheless, the respective roles of TFS and place information in FM perception remain heavily debated (Greenish *et al.*, 2007; Ernst and Moore, 2010; Ives *et al.*, 2013; Whiteford and Oxenham, 2015).

Among other psychophysical methods, *interference effects* between AM and FM have been studied to assess the relative roles of rate/place and TFS information in FM detection (Moore and Sek, 1996; Moore and Skrodzka, 2002; Ernst and Moore, 2010). These studies measured FM detection thresholds with and without an “interfering” AM in all intervals of a forced-choice trial. The AM was intended to

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disrupt rate/place (excitation-pattern) cues for FM detection by introducing salient temporal-envelope fluctuations that were independent of the FM and, thus, uninformative as to the presence of the FM. The results of these studies consistently showed that the added AM adversely affected performance; for carrier frequencies  $f_c$  below 4000 Hz, the adverse effect increased with increasing modulation rate  $f_m$ , consistent with the idea that rate/place cues play a greater role for higher  $f_m$ . For  $f_c = 6000$  Hz, the adverse effect of the added AM was similar for all  $f_m$ , consistent with the idea that, for very high  $f_c$ , rate/place cues dominate for all  $f_m$ .

The goal of the present work was to extend the investigations of interference effects. This was achieved by studying the interference caused by AM on FM detection and, conversely, the interference caused by FM on AM detection, with various fixed modulation depths for the interfering modulation. The target stimuli had both AM and FM, while the standard stimuli included the interferer only (either AM or FM). Low  $f_c$  (500 Hz) and low  $f_m$  (5 Hz) values were used to allow both sensory codes (rate/place and TFS) to contribute to FM detection for normal-hearing listeners (Moore and Sek, 1996). An interference effect should be observed for both AM and FM detection if FM is encoded using rate/place information. If this is the case, the interference effect observed could be accounted for by AM masking (e.g., Houtgast, 1989).

With both aging and sensorineural hearing loss, sensitivity to TFS cues may decrease, as suggested by several studies (Moore and Skrodzka, 2002; Lacher-Fougère and Demany, 2005; Grose and Mamo, 2010; Hopkins and Moore, 2011; Ernst and Moore, 2012; King *et al.*, 2014). This may explain why FM detection is usually found to worsen with aging (He *et al.*, 2007; Grose and Mamo, 2012; however, see Schoof and Rosen, 2014 for inconsistent findings) or hearing loss (Moore and Skrodzka, 2002; Buss *et al.*, 2004; Strelcyk and Dau, 2009). The detrimental effect of cochlear hearing loss on FM detection may also result from broadening of cochlear filters caused by dysfunction of outer hair cells (Moore, 2007), which in turn results in reduced FM-to-AM conversion at the output of the cochlear filters. This explanation is unlikely to apply to elderly listeners with normal hearing, as several studies indicate that frequency selectivity is not affected by age, provided that absolute thresholds remain within the normal range (Lutman *et al.*, 1991; Hopkins and Moore, 2011). Thus, the excitation patterns evoked by modulated signals should be comparable for young and older listeners with normal hearing, and any detrimental effect of age on FM detection may therefore result from impoverished TFS coding only. Interference effects due to AM masking are expected to be similar for young and older normal-hearing listeners (Takahashi and Bacon, 1992). AM masking was also found to be similar for normal-hearing and hearing-impaired listeners (Lorenzi *et al.*, 1997; Sek *et al.*, 2015). However, the use of higher sound levels to compensate for reduced audibility (and if observed, broadened auditory filters caused by dysfunction of outer hair cells) should reduce FM-to-AM conversion for hearing-impaired listeners. This, in turn, should decrease the interference effects caused by FM on AM detection for

hearing-impaired listeners. Cochlear damage should reduce interference effects of FM on AM, whereas aging should not have any effect. To test these hypotheses, AM and FM detection and interference effects were assessed for three groups of listeners: young normal-hearing, older normal-hearing, and older hearing-impaired.

Although models have been developed to account for AM detection (e.g., Viemeister, 1979; Dau *et al.*, 1997; Ewert and Dau, 2000), FM detection (Hartmann and Klein, 1980), as well as level and frequency discrimination (e.g., Heinz *et al.*, 2001), so far no model has quantitatively and systematically assessed the role of temporal-envelope (rate/place) cues at the outputs of cochlear filters for AM and FM detection in the presence of interferers. Thus, a simple model was developed in order to predict the present data based on temporal-envelope cues. Different strategies for combining those temporal envelope cues across auditory filters in order to optimally use rate/place cues were assessed. The model predictions made it possible to quantify the extent to which the observed detection and interference effects could be explained on the sole basis of temporal-envelope (rate/place) cues.

## II. METHOD

### A. Listeners

Data presented here were obtained from three groups of listeners: (i) ten young listeners with normal hearing (NH<sub>y</sub>) aged between 19 and 40 years, (ii) ten older listeners with normal hearing (NH<sub>o</sub>) aged between 46 and 67 years, and (iii) ten older hearing-impaired listeners (HI<sub>o</sub>) aged between 46 and 64 years. The mean absolute thresholds at 500 Hz for the three groups of listeners are shown in Table I. The HI<sub>o</sub> listeners showed bilateral and symmetric mild-to-moderate sensorineural hearing loss and all normal-hearing listeners (NH<sub>y</sub> and NH<sub>o</sub>) had audiometric thresholds <20 dB hearing level (HL) for octave frequencies between 0.25 and 3 kHz. Some of the NH<sub>o</sub> listeners had elevated audiometric thresholds above 3 kHz ( $\leq 35$  dB HL). Independent samples *t*-tests showed no significant difference between absolute thresholds at 500 Hz for the two NH groups, NH<sub>y</sub> and NH<sub>o</sub> [ $t(18) = -0.91$ ;  $p = 0.37$ ], nor in age for the two groups of older listeners, NH<sub>o</sub> and HI<sub>o</sub> [ $t(18) = -0.06$ ;  $p = 0.94$ ]. Figure 1 shows the mean absolute thresholds between 0.25 and 8 kHz for each group. Listeners had no former experience with such experimental conditions and no training before the tests. All participants were fully informed about the goal of the study and provided written consent before their participation. The study was approved by the French Regional Ethics Committee (IRB number: 0143200001072).

### B. Stimuli

All stimuli were generated digitally using an in-house program run with MATLAB (MathWorks, Natick, MA). Stimuli were initially equalized to have the same root-mean-square level and presented at a nominal sensation level (SL) of 40 dB SL with  $\pm 1.5$  dB level roving, based on a continuous uniform distribution. Stimuli were presented using Sennheiser HD 580 headphones (Old Lyme, CT) and an

TABLE I. Demographic data for the listeners in each group (NHy, NHo, and HIo), with mean age (mean  $\pm$ SD), absolute thresholds at 500 Hz, and measures of frequency selectivity calculated as differences in tone detection thresholds (dB) between no-notch and notched conditions.

Group	Number of listeners	Mean age (years)	Mean absolute threshold at 500 Hz (dB HL)	No-notch minus 0.3 $f_c$ notch (dB)	No-notch minus 0.6 $f_c$ notch (dB)
NHy	10	27 $\pm$ 6	12 $\pm$ 3	6 $\pm$ 3	16 $\pm$ 3
NHo	10	58 $\pm$ 7	13 $\pm$ 3	5 $\pm$ 2	12 $\pm$ 5
HIo	10	58 $\pm$ 6	35 $\pm$ 8	5 $\pm$ 3	14 $\pm$ 4

external soundcard (ECHO Indigo DJ 1–2, Santa Barbara, CA; 16-bit resolution). Each ear of each listener was tested separately monaurally. Each trial contained a target and a standard stimulus, in random order, with a silent interval of 600 ms between them. For each AM and FM stimulus, 100-ms raised-cosine ramps were applied at the onset and at the offset, and the total duration of each signal was 800 ms, including the ramps. The carrier was always a sinusoid with  $f_c = 500$  Hz and  $f_m = 5$  Hz. All conditions were presented in random order.

### 1. Measure of AM detection

*a. AM detection without interfering FM.* The carrier was either unmodulated to produce the standard stimulus, or modulated sinusoidally in amplitude to produce the target stimulus. Equation (1) describes the target stimulus  $T(t)$ :

$$T(t) = \text{AM} \sin(2\pi f_c t + \Phi_2) \quad (1)$$

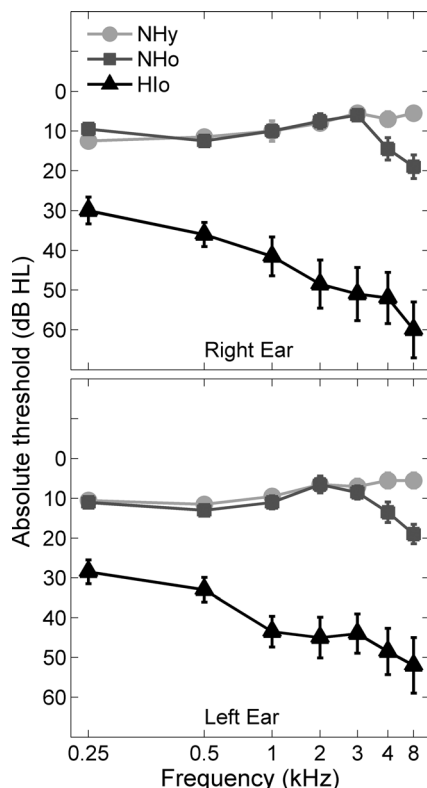


FIG. 1. Absolute pure-tone thresholds for young (NHy, circles) and old (NHo, squares) normal-hearing listeners and for old hearing-impaired listeners (HIo, upward-pointing triangles). Each panel shows the mean and standard error for each group of listeners.

with  $\text{AM} = [1 + m \sin(2\pi f_m t + \Phi_1)]$ , where  $\Phi_1$  is the starting phase of the modulator,  $\Phi_2$  is the starting phase of the carrier, and  $t$  is time (expressed in s). The values of  $\Phi_1$  and  $\Phi_2$  were randomly chosen for each stimulus. The modulation depth,  $m$ , was adaptively varied to determine the AM detection threshold.

*b. AM detection with interfering FM.* The target stimuli had both AM and interfering FM [as shown in Eq. (2)], while the standard stimuli contained only FM ( $\text{AM} = 1$ ).

$$T(t) = \text{AM} \sin[(2\pi f_c t + \Phi_2) + \beta(\sin(2\pi f_m t + \Phi_3))] \quad (2)$$

with  $\beta = \Delta f / f_m$ , and AM defined in Eq. (1), where  $\Delta f$  is the frequency excursion in Hz,  $\Phi_1$  is the starting phase of the AM,  $\Phi_2$  is the starting phase of the carrier, and  $\Phi_3$  is the starting phase of the FM. All values of  $\Phi$  were randomly and independently chosen for each stimulus. The frequency excursion ( $\Delta f$ ) was fixed for all trials and set to one of four values: 2.6, 5.3, 10.6, or 21.1 Hz. The values of  $\Delta f$  were calculated as multiples (1/2, 1, 2, 4) of an initial estimate of the FM detection threshold without interfering AM. This estimate was taken from a pilot study conducted on young normal-hearing listeners ( $n = 5$ ) and corresponded to 5.3 Hz on average across listeners.

### 2. Measure of FM detection

*a. FM detection without masking AM.* The carrier with  $f_c = 500$  Hz was either unmodulated to produce the standard stimulus, or modulated sinusoidally in frequency ( $f_m = 5$  Hz) to produce the target stimulus. Equation (2) describes the target stimulus  $T(t)$ , except that  $\text{AM} = 1$ .

*b. FM detection with masking AM.* Equation (2) describes the target stimulus  $T(t)$ , which contained both FM and interfering AM. The standard stimulus contained the interfering AM only. The value of  $\Delta f$  for the target was adaptively varied to determine the FM detection threshold. The modulation depth of the masking AM ( $m$ ) was fixed for all trials and set to one of three values: 0.33, 0.66, or 1.0.

### C. Procedure

Detection thresholds were measured using a two-interval, two-alternative forced-choice (2I, 2AFC) adaptive procedure estimating the 70.7% point on the psychometric function (Levitt, 1971). Each interval was marked by a light on the computer screen. Listeners were asked to indicate which interval contained a fluctuation in loudness for the



AM detection task and a fluctuation in pitch for the FM detection task. Visual feedback as to the correct answer was provided after each response. The tracking variable was  $m$  for the AM detection task, and  $\Delta f$  for the FM detection task. A run started with the tracking variable well above the estimated detection threshold. The step size was a factor of 1.58 up to the first two reversals and 1.26 thereafter. Fourteen reversals were obtained for each run, and the threshold estimate for that run was taken as the geometric mean of the tracking variable at the last six reversals. Two threshold estimates were obtained for each task and for each ear. No significant differences were found between thresholds obtained for the left and right ears for all tasks and groups. Hence, for each detection task, the final estimate of threshold was taken as the arithmetic mean of the four threshold estimates.

#### D. Measure of frequency selectivity

A measure of frequency selectivity at 500 Hz was obtained for all subjects using a simplified version of the notched-noise masking method (Patterson, 1976; Staffell *et al.*, 1990). The thresholds for detecting a 0.5-kHz sine wave in a 600-Hz wide noise with a spectral notch centered at  $f_c = 0.5$  kHz were measured using three notch widths: 0,  $0.3f_c$ , and  $0.6f_c$ . The masking noise spectrum level was kept constant (45 dB/Hz), while the tone level was adjusted using a 2I, 2AFC adaptive procedure. Two threshold estimates were obtained for each condition and for each ear.

Paired samples  $t$ -tests showed no significant difference between detection thresholds for the left and right ears for the normal-hearing groups {NH<sub>y</sub> [ $t(29) = -0.37$ ;  $p = 0.71$ ]; NH<sub>o</sub> [ $t(29) = -0.92$ ;  $p = 0.36$ ]}, but this was not the case for the hearing-impaired group [ $t(29) = 2.01$ ;  $p = 0.05$ ]. Since the difference in thresholds between ears was only just significant at the 0.05 level for the HI<sub>o</sub> group, the final estimate of detection threshold for each listener (irrespective of group) was taken as the arithmetic mean of the four threshold estimates obtained at the two ears. Finally, measures of frequency selectivity were calculated as the difference between detection threshold for the notched conditions ( $0.3f_c$  and  $0.6f_c$  notch widths) and the no-notch condition (0). The mean measures of frequency selectivity for each group are given in Table I.

A mixed-design analysis of variance (ANOVA) with between-subjects factor group (three levels) and within-subjects factor notch width (two levels) was conducted on the measures of frequency selectivity. The analysis showed that the main effect of notch width was significant [ $F(1,27) = 258.41$  ( $p < 0.0001$ )]. Neither the main effect of group [ $F(2,27) = 1.72$  ( $p = 0.19$ )] nor the interaction between group and notch width [ $F(2,27) = 1.49$  ( $p = 0.24$ )] were significant. The absence of significant difference in estimates of frequency selectivity between the three groups could be expected given that frequency selectivity does not worsen with age and often does not worsen until hearing loss exceeds about 30 dB HL (cf. Moore, 2007). The HI<sub>o</sub> listeners in our study had mild-to-moderate sensorineural hearing loss, with a mean absolute threshold at 500 Hz = 35 dB HL. Moreover, the active mechanism plays a smaller role at

lower frequencies than at higher frequencies. As a consequence, cochlear damage would have a smaller effect on frequency selectivity at low audio frequencies (such as 500 Hz, as used here) than at high audio frequencies.

#### E. Model

Figure 2 shows a schematic of the basic model used. Frequency selectivity was modeled by a set of linear fourth-order Gammatone (GT) filters with one equivalent rectangular bandwidth (ERB<sub>N</sub>; Glasberg and Moore, 1990) spacing and bandwidth. At the output of each simulated auditory filter, half-wave rectification followed by a first-order low-pass filter (cut-off frequency of 1 kHz) was applied to mimic the function of inner hair cells, as in Dau *et al.* (1997). The low-rate (5 Hz) temporal-envelope fluctuations were extracted by applying a first-order low-pass filter with a cut-off frequency of 8 Hz (Dau *et al.*, 1996).<sup>1</sup> The variance was calculated and normalized by the mean power of the signal to yield the AC-coupled envelope power (Viemeister, 1979; Ewert and Dau, 2000). The AC-coupled envelope power is a measure of the AM depth of the signal and is independent of signal level. To avoid onset and offset effects caused by filter ringing, the initial and final 150 ms were not considered for calculation of the AC-coupled envelope power.

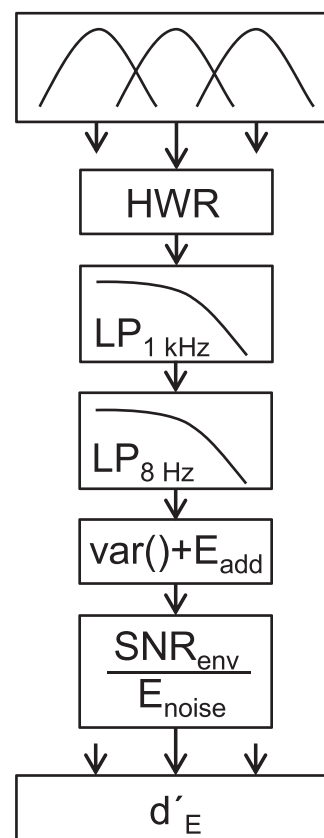


FIG. 2. Schematic diagram of the proposed model to simulate AM and FM detection and interference effects. The model processes independently the target and the standard signals. A linear GT filter bank, half-wave rectification, and low-pass filtering are applied to the input. The processing then yields a detectability index based on envelope features ( $d'_E$ ; including FM-to-AM conversion). See text for details.

To simulate both AM and FM detection thresholds, the same 2I, 2AFC paradigm as in the empirical data collection was applied, except that level roving was not applied since the model is level independent. On each trial, the model processed the target stimulus and reference stimulus independently. The ratio of the envelope power values for the target and standard was calculated. This is equivalent to an envelope signal-to-noise ratio ( $\text{SNR}_E$ ) as used in the envelope-power spectrum model (EPSM; Ewert and Dau, 2000) and later versions (e.g., Jørgensen *et al.*, 2013). The calculation of the envelope power ratio included an additive noise term (Ewert and Dau, 2000, 2004), simulated by a scalar value,  $E_{\text{add}}$ , which was added to the AC-coupled powers (for target and standard) prior to  $\text{SNR}_E$  calculation. A multiplicative internal noise source (Ewert and Dau, 2000, 2004) was implemented as a scalar scaling factor  $1/E_{\text{noise}}$  for  $\text{SNR}_E$ . A detectability index  $d'_{E,i}$  was then computed from the  $\text{SNR}_E$  for the increase in AM depth in each of the channels,  $i$ . For this, only positive  $\text{SNR}_E$  values were considered, corresponding to an increase in envelope power in the target interval. Otherwise  $d'_{E,i}$  was set to 0, indicating that an increase in envelope power in the target interval could not be detected in channel  $i$ . Detectability of the increase in AM was then optimally combined across auditory channels to yield the final detectability index  $d'_E = \sqrt{\sum d'^2_{E,i}}$  (see Ewert and Dau, 2000). As described later in the model results section (Sec. III), two off-frequency auditory channels centered one ERB above and below the carrier frequency (500 Hz) were sufficient to be considered here.

Finally, it was assumed that the target was correctly detected if  $d'_{E,i} > 1$ . In this case, the correct interval was selected in the simulated 2I, 2AFC procedure; otherwise, the correct or wrong interval was selected randomly with a probability of 0.5 each to simulate the chance level. All reported thresholds corresponded to the average of 20 simulations. Overall, the model had only two parameters: (i) the additive internal noise  $E_{\text{add}}$ , which was adjusted to match the AM detection thresholds in the absence of FM, and (ii) the multiplicative internal  $E_{\text{noise}}$ . In the current study,  $E_{\text{noise}}$  had to be chosen to 2.5 dB to match the AM detection data with and without interfering FM, in contrast to Ewert and Dau (2004) where 1 dB was used to predict the threshold for detecting an increase in AM depth for a baseline AM depth of  $-18$  dB and above. This higher  $E_{\text{noise}}$  value used here is most likely related to the absence of training of the subjects.

In addition to the basic model described above, three model modifications were implemented in order to assess the effects of filter asymmetry, compression, and strategy for combining envelope information across channels: (1) the linear GT filters were replaced by linear Gammachirp (GC) filters (Irimo and Patterson, 1997) derived at 50 dB or 75 dB sound pressure level (SPL); (2) power-law compression (using an exponent of 0.6) was introduced at the output of the GC filters to mimic (residual) cochlear compression; (3) the 8-Hz low-pass filtered envelopes derived from the outputs of two auditory filters centered one ERB above and below the carrier frequency (500 Hz) were either added or subtracted and  $\text{SNR}_E$  (as described above) was calculated

from this combined envelope. In contrast to the optimal combination of envelope power across filters in the basic model, the additive and subtractive approaches consider *envelope phase* information. The additive approach is sensitive to coherent envelope fluctuations across filters as caused by AM and can be considered as an efficient strategy for detecting AM in the presence of interfering FM. The subtractive approach is sensitive to envelope phase shifts across filters as caused by FM and can be thought of as detecting peak shifts of the excitation pattern along the basilar membrane, which occur for FM but not for AM. Thus, the subtractive strategy can be assumed to be suited for detection of FM as it would reduce the interference of AM.

### III. RESULTS

#### A. Behavioral data

##### 1. AM data

Figure 3 shows mean AM detection thresholds with standard errors for each group of listeners as a function of  $\Delta f$ . The results were very similar for the three groups of listeners. The interference effect caused by the additional FM reached  $\sim 15$  dB when the FM modulation depth ( $\Delta f$ ) was increased from 2.6 to 21.1 Hz. Shapiro-Wilk tests indicated that the AM detection thresholds for each group were normally distributed (except for one condition: data for the HIO group obtained with  $\Delta f = 21.1$  Hz). A mixed-design ANOVA conducted on the AM detection thresholds with between-subjects factor group (three levels) and within-subjects factor FM depth (five levels) showed a significant main effect of FM depth [ $F(4,108) = 172.16$ ;  $p < 0.0001$ ]. However, neither the main effect of group [ $F(2,27) = 0.07$ ] nor the interaction between group and interfering FM were significant [ $F(8,108) = 0.32$ ]. *Post hoc* comparisons with Bonferroni corrections showed that AM detection thresholds measured with interfering FM differed significantly from AM detection thresholds without FM, when the FM depth was  $\geq 5.3$  Hz ( $p < 0.001$ ).

The AM detection thresholds measured without superimposed FM for NHy (circles) and NHo listeners (squares) were 5 dB higher (worse) than those measured in previous work conducted by He *et al.* (2008), using a comparable stimulus configuration ( $f_c = 0.5$  kHz;  $f_m = 5$  Hz). However, it is important to note that the listeners tested by He *et al.* (2008) were initially trained for 1–2 h, whereas the present listeners had no prior experience with any of the tasks. AM (without superimposed FM) detection thresholds were similar for the NHy listeners [mean =  $-20.1$  dB; standard deviation (SD) = 3.0 dB] and NHo listeners (mean =  $-19.6$  dB; SD = 3.1 dB); suggesting that aging *per se* does not degrade AM sensitivity. Although inconsistent with previous work showing poorer AM sensitivity for elderly listeners with normal hearing (Füllgrabe *et al.*, 2015), the current results are consistent with recent work conducted by Schoof and Rosen (2014). The discrepancy across studies remains to be explained, but it may likely be due to differences in group size, age range, and processing efficiency of participants.

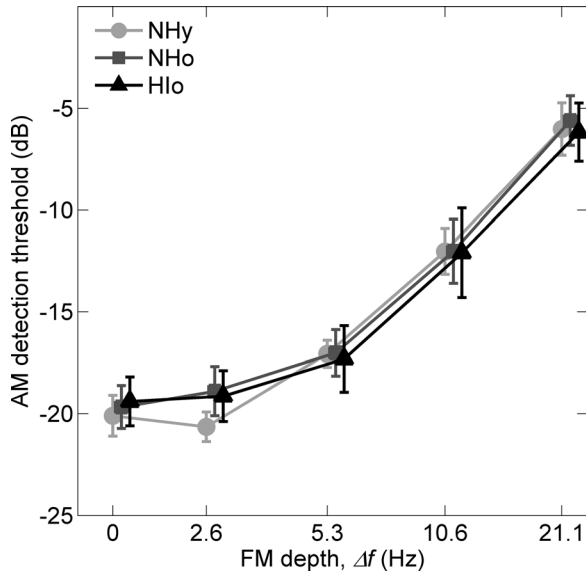


FIG. 3. AM detection thresholds for each group of listeners, as a function of  $\Delta f$  (Hz), the FM modulation depth (or frequency excursion). AM detection thresholds are expressed in dB  $[20 \log_{10}(m)]$ . Each panel shows the mean and standard error about the mean for each group of listeners, with NHy represented by grey circles, NHo by dark grey squares, and Hlo by black triangles.

The AM detection thresholds measured for the present Hlo listeners (mean =  $-19.4$  dB; SD =  $3.6$  dB) are similar to those measured for the NHy and NHo listeners. This is inconsistent with previous work reporting better-than-normal AM sensitivity for hearing-impaired listeners (e.g. Moore *et al.*, 1996; Füllgrabe *et al.*, 2003). The better AM sensitivity for hearing-impaired listeners has often been interpreted in terms of the effects of loudness recruitment. Cochlear damage and more specifically damage to outer hair cells leads to loss of the fast-acting compression operating in the normal cochlea, resulting in an abnormally rapid growth in loudness as the SL of a sound is increased (Moore, 2007). Since amplitude fluctuations of incoming sounds are no longer compressed, loudness recruitment has the effect of perceptually magnifying these amplitude fluctuations (Moore *et al.*, 1996) and may explain why improved AM detection is often observed for hearing-impaired listeners. It may be the case that the present Hlo listeners did not suffer from substantial damage to outer hair cells located in the apical region of the basilar membrane, consistent with the finding that the measures of frequency selectivity at 500 Hz were not significantly different across groups.

## 2. FM data

Figure 4 shows the mean FM detection thresholds for the three groups of listeners, together with the standard errors, as a function of  $m$ . Shapiro-Wilk tests indicated that log-transformed FM detection thresholds were normally distributed for each group. FM detection thresholds without superimposed AM differed across groups. NHy listeners (circles) had significantly better thresholds ( $t = -2.3$ ,  $p = 0.03$ ) than the NHo listeners (squares), and the latter had better thresholds than the Hlo listeners (triangles),

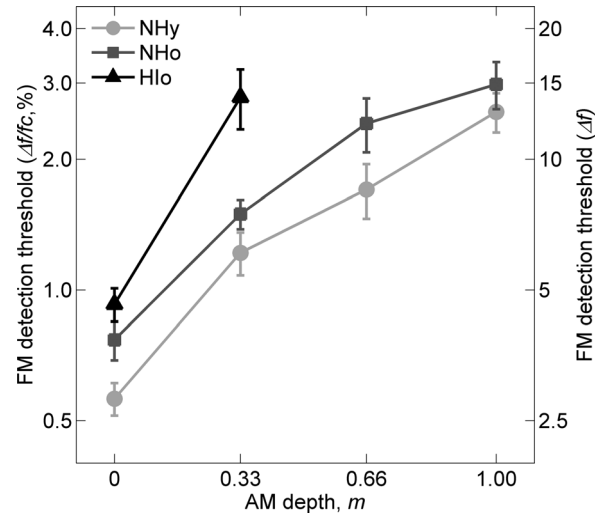


FIG. 4. FM detection thresholds for each group of listeners, as a function of  $m$ , the AM modulation depth. FM detection thresholds are expressed both as  $\Delta f$  and  $\Delta f/f_c$ . Each panel shows the mean and standard error about the mean for each group of listeners, with NHy represented by grey circles, NHo by dark grey squares, and Hlo by black triangles.

although not significantly better ( $p = 0.15$ ). For all groups, FM detection thresholds increased markedly with increasing AM depth,  $m$ . The mean interference effect produced when the AM depth was increased from 0 to 0.33 led to a degradation of FM threshold by a factor of 2.3 for the NHy listeners, 2.1 for NHo listeners, and 3.2 for Hlo listeners (FM ratio = FM with interfering AM at  $m = 0.33$ /FM without interfering AM).

Two repeated-measures ANOVAs were computed on the log-transformed FM data. The first ANOVA was computed on the FM detection thresholds with between-subjects factor group (three levels: NHy, NHo, Hlo) and within-subjects factor AM depth,  $m$ , by considering only the first two levels, that is, FM without interfering AM and FM with interfering AM at  $m = 0.33$ . The main effect of group was significant [ $F(2,27) = 17.5$ ;  $p < 0.001$ ], as well as the main effect of AM depth [ $F(1,27) = 101.3$ ;  $p < 0.001$ ]. The interaction between factor group and factor AM depth was not significant [ $F(2,27) = 1.6$ ;  $p = 0.21$ ]. The second ANOVA was computed on the FM detection thresholds with between-subjects factor group (two levels: NHy, NHo) and within-subjects factor AM depth by considering all four levels. In this case, the main effect of group was significant [ $F(1,18) = 5.4$ ;  $p < 0.05$ ], as well as the main effect of AM depth [ $F(3,54) = 91.5$ ;  $p < 0.001$ ]. The interaction between factor group and factor AM depth was not significant [ $F(3,54) = 0.73$ ;  $p = 0.54$ ].

Figure 5 (upper panel) shows individual FM detection thresholds measured without interfering AM (open circles) and with interfering AM at  $m = 0.33$  (filled circles). The lower panel of Fig. 5 shows the ratio between thresholds measured with and without interfering AM ( $m = 0.33$ ) for each group of listeners.

The FM detection thresholds measured without interfering AM for the NHy listeners are comparable to (although slightly worse than) those reported in the literature (e.g.,



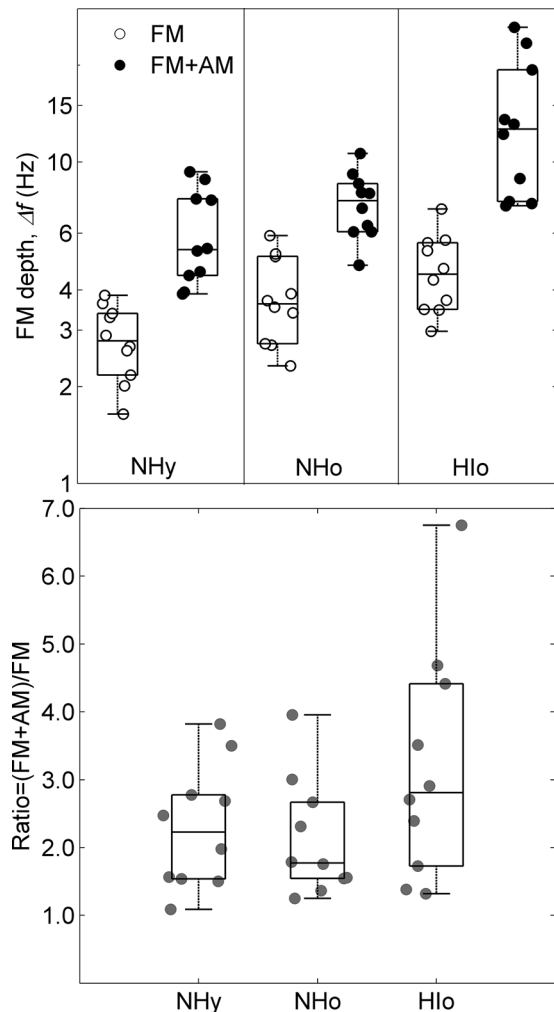


FIG. 5. The upper panel shows individual FM detection thresholds for the three groups of listeners with (black filled circles;  $m=0.33$ ) and without interfering AM (open circles). The lower panel shows the amount of interference caused by the interfering AM, quantified by the ratio between FM detection thresholds measured with and without AM. In each panel, the bold lines show median values, and the lower and upper boundaries of the boxes show the first and third quartiles.

Moore and Sek, 1996; Moore and Skrodzka, 2002). The results are also consistent with previous work showing a detrimental effect of age (He *et al.*, 2007; Grose and Mamo, 2012; Kortlang *et al.*, 2016) and cochlear damage (Moore and Skrodzka, 2002; Buss *et al.*, 2004; Strelcyk and Dau, 2009; Ernst and Moore, 2012; Kortlang *et al.*, 2016) on FM sensitivity, although the hearing-impaired listeners were generally much older than the normal-hearing controls in these studies. The interference effects reported here for young and older normal-hearing listeners are globally consistent with previous studies (Moore and Sek, 1996; Moore and Skrodzka, 2002; Ernst and Moore, 2010). The absence of significant interaction between factor group and AM depth in the first ANOVA suggests that the interference effect observed for the Hlo listeners is not different from that observed for NHy and NHo listeners. Thus, as a group, Hlo listeners did not seem to show greater interference for FM detection. Still, it is important to note that the distribution of individual FM detection thresholds shown in Fig. 5 (upper panel) is considerably larger for Hlo compared to

NHy and NHo listeners. It is obvious that three among the ten Hlo listeners performed very similarly to the NHy and NHo listeners when FM was presented with AM ( $m=0.33$ ). Again, the distribution of the ratios of FM with and without AM is considerably larger for the Hlo group and in this case, three among the ten Hlo listeners show considerably larger ratios than NHy and NHo listeners. This trend for a greater interference for Hlo listeners is consistent with the results of a previous study conducted by Moore and Skrodzka (2002).

## B. Modeling AM and FM data

### 1. Modeling results for NHy listeners

Figure 6 compares model simulations (open symbols) with the empirical data (filled grey circles) for the NHy group, replotted from Figs. 3 and 4. The upper panel is for AM detection and the lower panel for FM detection. The symbols are slightly jittered along the  $x$  axis for clearer visibility. The additive internal noise ( $E_{add}$ ) of the model was adjusted to predict an AM detection threshold of  $-20$  dB in the absence of FM (left-most data point in the upper panel of Fig. 6).

For AM, predictions from the basic model using linear GT filters (referred to as GT, upward-pointing triangle symbols) followed the pattern observed in the empirical data. In order to best account for the data, the two off-frequency auditory channels (here, with  $\pm 1$ -ERB spacing around 500 Hz; center frequencies of 425 Hz and 583 Hz) had to be considered. These channels showed a considerable amount of FM-to-AM conversion, leading to a substantial increase of AM detection thresholds with increasing FM depth. Nevertheless, for large FM depths, the model predicted slightly better AM thresholds than observed, indicating that AM masking caused by FM-to-AM conversion is underestimated by the model. The strength of the interference effect in the model depends on the choice of the multiplicative noise ( $E_{noise}$ ). Overall, the best match was obtained with a 2.5-dB criterion. A reduction of the criterion would reduce the simulated interference effect and flatten the simulated pattern. Additionally, all thresholds would be shifted to lower values and an increased additive internal noise ( $E_{add}$ ) would have to be assumed in order to match the AM-alone detection threshold (when  $\Delta f=0$  Hz).

In contrast to the basic model using the optimal combination of envelope power, the model with the additive strategy of combining envelopes of off-frequency filters (GT add/sub; diamonds) showed no interference effect. Introduction of filter asymmetry by using linear GC filters (GC add/sub; downward-pointing triangles) had no effect. Further addition of compression to the additive GC model (GC add/sub Comp; square symbols) caused a small interference effect of about 2 dB for the largest interfering FM depth (when  $\Delta f=21.1$  Hz). Taken together, all models except for the basic model predict considerably lower thresholds than observed in the data. This means that listeners cannot use the additive strategy, even though they could potentially benefit from a reduced interference effect.

For the model predictions of the FM detection thresholds in the lower panel of Fig. 6, both internal noises were kept fixed

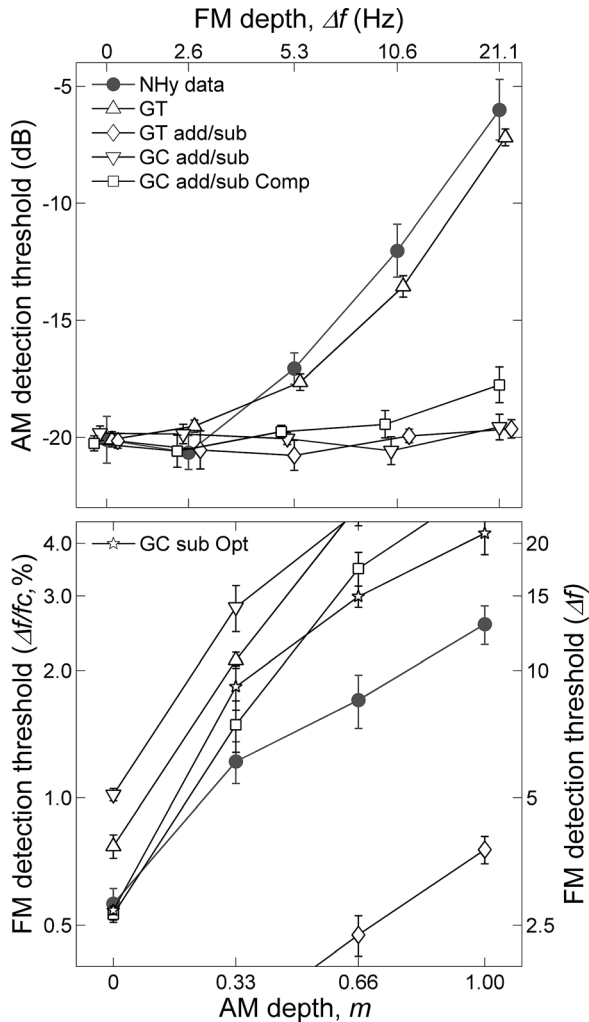


FIG. 6. Model simulations (black open symbols) and NHy data (filled grey circles; replotted from Figs. 3 and 4), showing mean and standard error. The upper panel shows AM detection thresholds, the lower panel shows FM detection thresholds. The models used two off-frequency filters spaced by  $\pm 1$  ERB around the carrier frequency of 500 Hz. The basic model (upward-pointing triangles) discarded AM phase information and used a 2.5-dB AM depth criterion. The other models preserved AM phase information and used an additive or subtractive strategy when combining envelopes of off-frequency filters for AM and FM detection, respectively. Different implementations were considered: (i) diamond symbols show the results for a GT filterbank; (ii) downward-pointing triangles show the results for asymmetric GC filters derived at 50 dB SPL; (iii) squares show the results of further addition of non-linear compression to the GC model; (iv) star symbols show the results for the subtractive GC model with optimized filter center frequency for FM detection. See text for details.

at the values fitting the AM detection data, and the same two channels used for simulation of AM detection were considered. Here, all model versions failed to explain the data. The basic model (upward-pointing triangles) somewhat overestimated the FM detection threshold without interfering AM (left-most data point) and considerably overestimated the interference effect in the presence of additional AM. The GT-based subtractive model (GT add/sub; diamonds) considerably underestimated all four thresholds by 76% on average. The GC-based model (GC add/sub) overestimated the thresholds by 138% on average for all four FM detection thresholds. The compressive GC model (GC add/sub Comp) accounted well for the FM threshold without interfering AM but markedly overestimated the interference

effect. In an optimized version of the subtractive GC model (GC sub Opt; star symbols), the center frequencies of both off-frequency filters were modified (increased by 2.5%) until the FM threshold without interfering AM was accounted for. This optimized the cancellation of the interfering AM, resulting in a smaller interference effect than for the other GC models (when  $m = 0.66$  and 1.00). However, the predicted interference was still stronger than observed in the empirical data.

## 2. Modeling results for NHo listeners

Comparison of the model predictions to data of the NHo listeners (not shown), indicated that the basic GT model slightly underestimated the AM data. Regarding FM detection, the NHo FM threshold without interfering AM could be accounted for by the basic GT model, while the interference effect was considerably overestimated. As for the NHy group in Fig. 6, all other model versions (GT add/sub, GC add/sub, and GC add/sub Comp) could not account for the data.

## 3. Modeling results for HIo listeners

Figure 7 shows model predictions (open symbols) and data (filled grey circles) for the HIo group. As in Fig. 6, the upward-pointing triangles show the basic model predictions (GT). In this case, the AM data (upper panel) were well matched but only the slope of the FM data (lower panel) was well matched. The FM detection thresholds were underestimated by about 20%. The leftward-pointing triangles correspond to the basic model with a 3-dB AM depth criterion (GT 3 dB). Increasing  $E_{\text{noise}}$  mainly caused a vertical offset of the predicted thresholds for both AM and FM. This model version accounted best for both the AM and FM data. The open star symbols show predictions with the additive/subtractive strategy with GC filters derived at 75 dB SPL (GC add/sub 75 dB SPL), a level typically used for the present HIo listeners. This model version showed a reduced interference effect for the AM data, while the FM thresholds were markedly overestimated. Widened auditory filters (not shown) reduced the interference effect for the AM data, reflecting decreased FM-to-AM conversion. For FM, widened filters resulted in elevated detection thresholds as expected from a decrease of FM-to-AM conversion.

Taken together, the modeling results suggest that, for the HIo listeners, AM and FM data can be well explained based on the optimal combination of temporal-envelope power cues (basic GT model) and that  $E_{\text{noise}}$  might be slightly increased (to 3 dB) in comparison to NH listeners (2.5 dB). Otherwise, the data cannot be consistently explained by any of the model versions for normal-hearing listeners, indicating that AM and FM detection, as well as the interference effects, cannot be fully explained based on a rate/place code model alone.

## IV. DISCUSSION

### A. Interactions between AM and FM

#### 1. Effects of FM on AM detection

FM had a strong interference effect on AM detection, and this effect was similar across the three groups of listeners. Not surprisingly, the interference effect occurred when

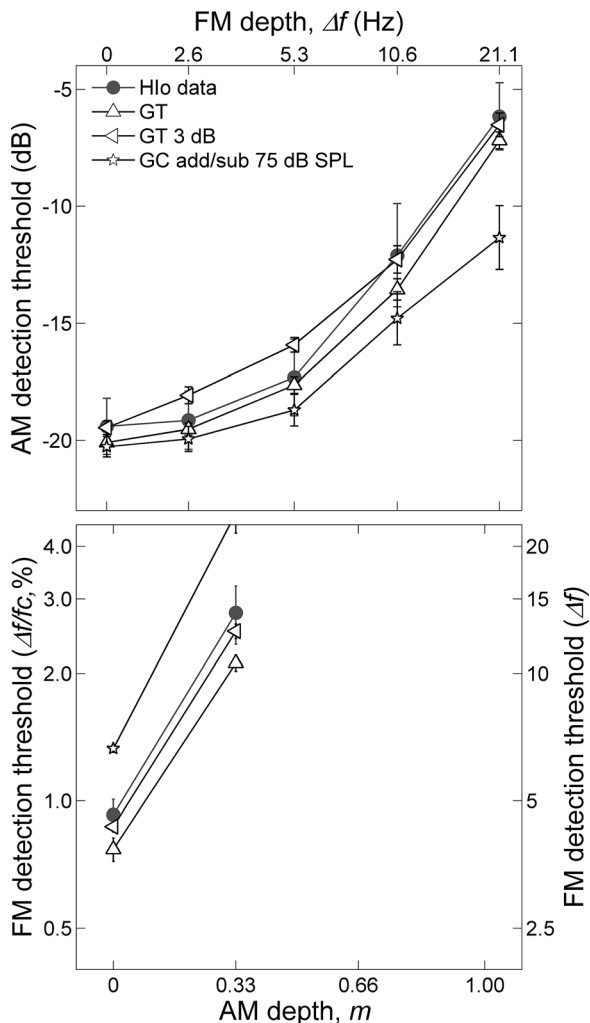


FIG. 7. Model simulations (black open symbols) and HIO data (filled grey circles), showing mean and standard error. The upward-pointing triangles show the predictions of the basic model using a 2.5-dB AM depth criterion, as shown in Fig. 6. The leftward-pointing triangles show the predictions of the basic model with a 3.0-dB AM depth criterion. The star symbols show predictions with the additive/subtractive strategy with GC filters derived at 75 dB SPL.

the FM depth was greater than the mean FM detection threshold across groups (NH<sub>y</sub>, 2.8 Hz; NH<sub>o</sub>, 3.8 Hz; HIO, 4.6 Hz), measured without interfering AM. Consistent with the initial expectation, the modeling confirmed that the main source of interference is FM-to-AM conversion occurring at the outputs of the auditory filters. This suggests that this form of interference can be explained by peripheral processes and AM masking. The modeling also revealed that the main source of interference is the FM-to-AM conversion occurring at the output of *off-frequency* auditory filters. The use of only *off-frequency* filters in the model can be justified by the fact that compression and particularly saturation in auditory-nerve fibers are assumed to strongly reduce the representation of AM cues at the output of the *on-frequency* filter. The inclusion of the *on-frequency* auditory filter in the model would lead to reduced FM-to-AM conversion and thus a reduction in the predicted interference effect. This is in line with other modeling studies using compressive auditory filters and more elaborate auditory-nerve fiber models,

in which the *off-frequency* filters dominated the model's output (Heinz *et al.*, 2001). With the assumption of compression in *off-frequency* filters at low frequencies as used here (e.g., Lopez-Poveda *et al.*, 2003; Plack and Drga, 2003; Lopez-Poveda and Alves-Pinto, 2008), the interference effect for AM detection remains unchanged (simulations not shown). The reason for this is that both AM and FM-to-AM conversion cues are compressed to the same extent. As expected, simulations indicated that degraded frequency selectivity would reduce the interference effect as a consequence of reduced FM-to-AM conversion. However, the data for the HIO listeners could be accounted for without any broadening of the auditory filters, consistent with the empirical finding of normal frequency selectivity at 500 Hz for the present HIO listeners.

## 2. Effects of AM on FM detection

For all listeners, AM had a strong interference effect on FM detection thresholds. This effect increased monotonically as the AM depth was increased to one. Both aging and moderate sensorineural hearing loss degraded FM detection in all conditions, with a trend for greater interference effect for the HIO listeners. The modeling showed that the main source of interference is again FM-to-AM conversion occurring at the outputs of auditory filters and AM masking. Modeling also indicated that the envelope cues for FM resulting from FM-to-AM conversion are not totally disrupted when the interfering AM depth is 0.33 (as often used in previous work, e.g., Moore and Sek, 1996). For the NH<sub>y</sub> listeners, the basic model overestimated FM detection thresholds measured without interfering AM. This suggests that additional cues (e.g., TFS) might contribute to FM detection without interfering AM, although this cannot be captured by the current model. An alternative explanation could be that cochlear filters are slightly narrower than assumed here, which might be the case given the relatively low level of stimulation. Slightly narrower filters would have lowered the FM detection thresholds as a consequence of stronger FM-to-AM conversion and this might also have improved the model predictions.

The behavioral data showed that greater age was associated with poorer FM detection with and without interfering AM. The detrimental effect of age on FM detection was accounted for by the basic model for FM without interfering AM (not shown). However, as for the NH<sub>y</sub> listeners, none of the current models could account for FM detection thresholds with interfering AM. This is likely related to the fact that the FM thresholds estimated by the current model simulations are based solely on FM-to-AM conversion.

The detrimental effect of hearing loss on FM detection with interfering AM could be well accounted for by the basic model with slightly increased  $E_{\text{noise}}$ . The fact that the FM data for HIO listeners can be accounted for by only using temporal-envelope cues (as captured by the basic model) is consistent with the notion that cochlear damage alters the capacity to encode and/or use TFS cues (for a review, see Moore, 2014). The model could account for the FM detection thresholds of the HIO listeners without any broadening



of the auditory filters, since the HI subjects tested in this study had similar frequency selectivity to the NH subjects. Finally, modeling suggests that mild-to-moderate hearing loss might be associated with a slight increase of  $E_{\text{noise}}$  or a general decline of processing efficiency (“central” noise). Such an increase in central noise in HI listeners has also been suggested by Moore *et al.* (1996) for AM detection or in more general terms regarding intensity discrimination by Jepsen and Dau (2011).

## B. Limitations of the modeling approach

The main goal of the current study was to assess the basic mechanisms of using temporal envelope cues within a simple model. The details of the predictions might depend on the specific implementation of the model (filter shape, width, level dependence of cochlear filtering, number of filters, etc.). The main finding based on the current model simulations, indicating that AM and FM interference for NH listeners cannot be consistently accounted for by the use of temporal envelope cues (rate/place code) alone, hints in two directions. A more sophisticated extension of the subtractive approach using different filter combinations might better account for the observed interference of AM on FM detection. However, it has already been demonstrated here that even with the selection of the two optimal filters which—after cancellation—accounts for FM detection in the absence of AM predicts too much interference. It should also be noted that another pair of filters could be found in additional simulations (not shown), which strongly reduces the interference effect by cancelling the AM; however, in this case simulated FM thresholds are considerably lower than the observed data. This indicates that the listeners cannot use such a strategy, as they also cannot use the additive strategy for AM. Another possibility is the incorporation of a TFS path in the model as suggested in Kortlang and Ewert (2013). This would enable detection of FM by changes in the TFS pattern independent of FM-to-AM conversion.

## V. CONCLUSIONS

The results show clear perceptual interference effects between AM and FM:

- (i) AM detection was impaired by interfering FM similarly across all three groups. Thus, the interference effect was found to be independent of age and hearing loss.
- (ii) FM detection was impaired by interfering AM for all groups. FM detection was also globally impaired by age and hearing loss. The interference effect was similar across groups, although there was a trend for stronger interference for some hearing-impaired listeners.

Model simulations showed that a good match to the AM data and to the FM data for the hearing-impaired group only was obtained when optimally combining envelope power at the outputs of off-frequency filters. Alternative models adding or subtracting temporal envelopes at the outputs of off-frequency filters could account for the AM and FM data

without any interfering modulation, but failed to account for the interference effects.

Taken together, these psychophysical and modeling results indicate that the ability to detect AM and FM in the presence of interfering modulations can be accounted for on the sole basis of temporal-envelope cues at the output of off-frequency filters for elderly hearing-impaired listeners only. This suggests that normal-hearing listeners use additional cues—such as TFS—to detect FM, and that aging and hearing loss degrade and even abolish the capacity to encode and/or use these additional cues.

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<sup>1</sup>The cut-off frequency of 8 Hz was chosen as a simple model of AM processing motivated by Dau *et al.* (1996). Any cut-off frequency above 5 Hz and sufficiently below 500 Hz to suppress the carrier in the envelope extraction would have led to the same results as in the current study.

- Buss, E., Hall, J. W., 3rd, and Grose, J. H. (2004). “Temporal fine structure cues to speech recognition and pure tone modulation in observers with sensorineural hearing loss,” *Ear Hear.* **25**, 242–250.
- Dau, T., Kollmeier, B., and Kohlrausch, A. (1997). “Modeling auditory processing of amplitude modulation: I. Modulation detection and masking with narrow-band carriers,” *J. Acoust. Soc. Am.* **102**, 2892–2905.
- Dau, T., Püschel, D., and Kohlrausch, A. (1996). “A quantitative model of the ‘effective’ signal processing in the auditory system: I. Model structure,” *J. Acoust. Soc. Am.* **99**, 3615–3622.
- Demany, L., and Semal, C. (1989). “Detection thresholds for sinusoidal frequency modulation,” *J. Acoust. Soc. Am.* **85**, 1295–1301.
- Ernst, S. M. A., and Moore, B. C. J. (2010). “Mechanisms underlying the detection of frequency modulation,” *J. Acoust. Soc. Am.* **128**, 3642–3648.
- Ernst, S. M. A., and Moore, B. C. J. (2012). “The role of time and place cues in the detection of frequency modulation by hearing-impaired listeners,” *J. Acoust. Soc. Am.* **131**, 4722–4731.
- Ewert, S. D., and Dau, T. (2000). “Characterizing frequency selectivity for envelope fluctuations,” *J. Acoust. Soc. Am.* **108**, 1181–1196.
- Ewert, S. D., and Dau, T. (2004). “External and internal limitations in amplitude-modulation processing,” *J. Acoust. Soc. Am.* **116**, 478–490.
- Füllgrabe, C., Meyer, B., and Lorenzi, C. (2003). “Effect of cochlear damage on the detection of complex temporal envelopes,” *Hear. Res.* **178**, 35–43.
- Füllgrabe, C., Moore, B. C. J., and Stone, M. A. (2015). “Age-group differences in speech identification despite matched audiometrically normal hearing: Contributions from auditory temporal processing and cognition,” *Front. Aging. Neurosci.* **6**, 347.
- Glasberg, B. R., and Moore, B. C. J. (1990). “Derivation of auditory filter shapes from notched-noise data,” *Hear. Res.* **47**, 103–138.
- Greenish, H., Moore, B. C. J., and Stone, M. A. (2007). “The surprising lack of effect of added AM on low-rate FM detection at high carrier frequencies,” *Int. J. Audiol.* **46**, 646–647.
- Grose, J. H., and Mamo, S. K. (2010). “Processing of temporal fine structure as a function of age,” *Ear Hear.* **31**, 755–760.
- Grose, J. H., and Mamo, S. K. (2012). “Frequency modulation detection as a measure of temporal processing: Age-related monaural and binaural effects,” *Ear Hear.* **294**, 49–54.
- Hartmann, W. M., and Klein, M. A. (1980). “Theory of frequency modulation detection for low modulation frequencies,” *J. Acoust. Soc. Am.* **67**, 935–946.



- He, N. J., Mills, J. H., Ahlstrom, J. B., and Dubno, J. R. (2008). "Age-related differences in the temporal modulation transfer function with pure-tone carriers," *J. Acoust. Soc. Am.* **124**, 3841–3849.
- He, N. J., Mills, J. H., and Dubno, J. R. (2007). "Frequency modulation detection: Effects of age, psychophysical method, and modulation waveform," *J. Acoust. Soc. Am.* **122**, 467–477.
- Heinz, M. G., Colburn, H. S., and Carney, L. H. (2001). "Evaluating auditory performance limits: I. One-parameter discrimination using a computational model for the auditory nerve," *Neural Comp.* **13**, 2273–2316.
- Hopkins, K., and Moore, B. C. J. (2011). "The effects of age and cochlear hearing loss on temporal fine structure sensitivity, frequency selectivity, and speech reception in noise," *J. Acoust. Soc. Am.* **130**, 334–349.
- Houtgast, T. (1989). "Frequency selectivity in amplitude-modulation detection," *J. Acoust. Soc. Am.* **85**, 1676–1680.
- Irino, T., and Patterson, R. D. (1997). "A time-domain, level-dependent auditory filter: The gammachirp," *J. Acoust. Soc. Am.* **101**, 412–419.
- Ives, D. T., Calcutt, A., Kalluri, S., Strelcyk, O., Sheft, S., and Lorenzi, C. (2013). "Effects of noise reduction on AM and FM perception," *J. Assoc. Res. Otolaryngol.* **14**, 149–157.
- Jepsen, M. L., and Dau, T. (2011). "Characterizing auditory processing and perception in individual listeners with sensorineural hearing loss," *J. Acoust. Soc. Am.* **129**, 262–281.
- Johannesen, P. T., Pérez-González, P., Kalluri, S., Blanco, J. L., and Lopez-Poveda, E. A. (2016). "The influence of cochlear mechanical dysfunction, temporal processing deficits, and age on the intelligibility of audible speech in noise by hearing-impaired listeners," *Trends Hear* (in press).
- Jørgensen, S., Ewert, S. D., and Dau, T. (2013). "A multi-resolution envelope-power based model for speech intelligibility," *J. Acoust. Soc. Am.* **134**, 436–446.
- King, A., Hopkins, K., and Plack, C. J. (2014). "The effects of age and hearing loss on interaural phase difference discrimination," *J. Acoust. Soc. Am.* **135**, 342–351.
- Kortlang, S., and Ewert, S. D. (2013). "Assessment, modeling, and compensation of inner and outer hair cell damage," in *Auditory Plasticity—Listening with the brain, 4th ISAAR Meeting*, Nyborg Strand, Denmark.
- Kortlang, S., Mauermann, M., and Ewert, S. D. (2016). "Suprathreshold auditory processing deficits in noise: Effects of hearing loss and age," *Hear. Res.* **331**, 27–40.
- Lacher-Fougère, S., and Demany, L. (2005). "Consequences of cochlear damage for the detection of interaural phase differences," *J. Acoust. Soc. Am.* **118**, 2519–2526.
- Levitt, H. (1971). "Transformed up-down methods in psychoacoustics," *J. Acoust. Soc. Am.* **49**, 467–477.
- Lopez-Poveda, E. A., and Alves-Pinto, A. (2008). "A variant temporal-masking-curve method for inferring peripheral auditory compression," *J. Acoust. Soc. Am.* **123**, 1544–1554.
- Lopez-Poveda, E. A., Plack, C. J., and Meddis, R. (2003). "Cochlear nonlinearity between 500 and 8000 Hz in normal-hearing listeners," *J. Acoust. Soc. Am.* **113**, 951–960.
- Lorenzi, C., Michey, C., Berthommier, F., and Portalier, S. (1997). "Modulation masking in listeners with sensorineural hearing loss," *J. Speech Lang. Hear. Res.* **40**, 200–207.
- Lutman, M. E., Gatehouse, S., and Worthington, A. G. (1991). "Frequency resolution as a function of hearing threshold level and age," *J. Acoust. Soc. Am.* **89**, 320–328.
- Mehraei, G., Gallun, F. J., Leek, M. R., and Bernstein, J. G. (2014). "Spectrotemporal modulation sensitivity for hearing-impaired listeners: Dependence on carrier frequency and the relationship to speech intelligibility," *J. Acoust. Soc. Am.* **136**, 301–316.
- Moore, B. C. J. (2007). *Cochlear Hearing Loss: Physiological, Psychological, and Technical Issues*, 2nd ed. (Wiley, Chichester).
- Moore, B. C. J. (2014). *Auditory Processing of Temporal Fine Structure: Effects of Age and Hearing Loss* (World Scientific, Singapore).
- Moore, B. C. J., and Sek, A. (1994). "Effects of carrier frequency and background noise on the detection of mixed modulation," *J. Acoust. Soc. Am.* **96**, 741–751.
- Moore, B. C. J., and Sek, A. (1996). "Detection of frequency modulation at low modulation rates: Evidence for a mechanism based on phase locking," *J. Acoust. Soc. Am.* **100**, 2320–2331.
- Moore, B. C. J., and Skrodzka, E. (2002). "Detection of frequency modulation by hearing-impaired listeners: Effects of carrier frequency, modulation rate, and added amplitude modulation," *J. Acoust. Soc. Am.* **111**, 327–335.
- Moore, B. C. J., Wojtczak, M., and Vickers, D. A. (1996). "Effect of loudness recruitment on the perception of amplitude modulation," *J. Acoust. Soc. Am.* **100**, 481–489.
- Palmer, A. R., and Russell, I. J. (1986). "Phase-locking in the cochlear nerve of the guinea-pig and its relation to the receptor potential of inner hair-cells," *Hear. Res.* **24**, 1–15.
- Patterson, R. D. (1976). "Auditory filter shapes derived with noise stimuli," *J. Acoust. Soc. Am.* **59**, 640–654.
- Plack, C. J., and Drga, V. (2003). "Psychophysical evidence for auditory compression at low characteristic frequencies," *J. Acoust. Soc. Am.* **113**, 1574–1586.
- Schoof, T., and Rosen, S. (2014). "The role of auditory and cognitive factors in understanding speech in noise by normal-hearing older listeners," *Front. Aging Neurosci.* **6**, 307.
- Sek, A., Baer, T., Crinnion, W., Springgay, A., and Moore, B. C. J. (2015). "Modulation masking within and across carriers for subjects with normal and impaired hearing," *J. Acoust. Soc. Am.* **138**, 1143–1153.
- Shamma, S., and Lorenzi, C. (2013). "On the balance of envelope and temporal fine structure in the encoding of speech in the early auditory system," *J. Acoust. Soc. Am.* **133**, 2818–2833.
- Staffel, J. G., Hall, J. W., Grose, J. H., and Pillsbury, H. C. (1990). "NoSo and No $\pi$  detection as a function of masker bandwidth in normal-hearing and cochlear-impaired listeners," *J. Acoust. Soc. Am.* **87**, 1720–1727.
- Strelcyk, O., and Dau, T. (2009). "Relations between frequency selectivity, temporal fine-structure processing, and speech reception in impaired hearing," *J. Acoust. Soc. Am.* **125**, 3328–3345.
- Takahashi, G. A., and Bacon, S. P. (1992). "Modulation detection, modulation masking and speech understanding in noise in the elderly," *J. Speech Hear. Res.* **35**, 1410–1421.
- Viemeister, N. F. (1979). "Temporal modulation transfer functions based upon modulation thresholds," *J. Acoust. Soc. Am.* **66**, 1364–1380.
- Whiteford, K. L., and Oxenham, A. J. (2015). "Using individual differences to test the role of temporal and place cues in coding frequency modulation," *J. Acoust. Soc. Am.* **138**, 3093–3104.
- Zeng, F. G., Nie, K., Stickney, G. S., Kong, Y. Y., Vongphoe, M., Bhargava, A., Wei, C., and Cao, K. (2005). "Speech recognition with amplitude and frequency modulations," *Proc. Natl. Acad. Sci. U.S.A.* **102**, 2293–2298.
- Zwicker, E. (1952). "Die Grenzen der Hörbarkeit der Amplitudenmodulation und der Frequenzmodulation eines Tones" ("The limits of audibility of amplitude modulation and frequency modulation of a pure tone"), *Acustica* **2**, 125–133.