Age-related differences in the temporal modulation transfer function with pure-tone carriers

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Detection of amplitude modulation (AM) in 500 and 4000 Hz tonal carriers was measured as a function of modulation frequency from younger and older adults with normal hearing through 4000 Hz. The modulation frequency above which sensitivity to AM increased ("transition frequency") was similar for both groups. Temporal modulation transfer function shapes showed significant age-related differences. For younger subjects, AM detection thresholds were generally constant for low modulation frequencies. For a higher carrier frequency, AM detection thresholds then increased as modulation frequency further increased until the transition frequency. In contrast, AM detection for older subjects continuously increased with increasing modulation frequency, indicating an age-related decline in temporal resolution for faster envelope fluctuations. Significant age-related differences were observed whenever AM detection was dependent on temporal cues. For modulation frequencies above the transition frequency, age-related differences were larger for the lower frequency carrier (where both temporal and spectral cues were available) than for the higher frequency carrier (where AM detection was primarily dependent on spectral cues). These results are consistent with a general age-related decline in the synchronization of neural responses to both the carrier waveform and envelope fluctuation.
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I. INTRODUCTION

Amplitude modulation (AM) is one of the elementary features of natural sounds, including many communication signals. For example, a vowel can be modeled as a periodic carrier (vocal fold production) modulated by specific vocal-tract characteristics, which result in amplitude fluctuations in the speech waveform. This temporal envelope carries important information relevant to speech perception (Drullman, 1995; Shannon *et al.*, 1995).

The auditory system is highly sensitive to small amplitude fluctuations. Sinusoidal amplitude modulation (SAM), one of the basic forms of AM, consists of a carrier (tone or noise), which periodically varies in amplitude in the same manner as the modulating sinusoid. The modulation depth (m) is defined by the amplitude of the modulating signal, which is a proportion (between 0 and 1) of the carrier amplitude.

Typical neural responses to AM tones are locked to the stimulus envelopes (envelope locking), in addition to phase locking to the carrier frequencies. In a comprehensive study examining cues for AM detection and discrimination, Nelson and Carney (2007) found at the inferior colliculus of awake rabbits that the synchronization of neural responses was phase locked to stimuli with modulation depths as low as −30 dB, which is comparable to AM detection thresholds measured behaviorally. In addition, when modulation depths were above modulation detection thresholds, rate-depth functions were steep enough to predict modulation-depth discrimination measured behaviorally. Envelope information is well preserved and even enhanced in neural responses at all levels of the auditory system, which has led to a hypothesis of a specialized neural mechanism to extract AM information [for a review, see Joris *et al.* (2004)].

The function relating SAM detection thresholds to modulation frequency is called the temporal modulation transfer function (TMTF). Starting from low modulation frequencies (4–5 Hz), AM detection thresholds either stay constant or increase slightly (become worse) as the modulation frequency increases until a transition frequency is reached. Below the transition frequency, AM detection thresholds are dependent primarily on temporal cues [e.g., see Kohlrausch *et al.* (2000)]. Above this frequency region, the TMTF pattern is dependent on the type of carrier. That is, as the modulation frequency increases, AM thresholds either rapidly increase with a broadband-noise carrier (Viemeister, 1979) or even more rapidly decrease (improve) with a tonal carrier (Zwicker and Fastl, 1990). The discrepancy between carrier types is an indication of the involvement of spectral side components in the case of tonal carriers (Moore and Glasberg, 2001). As the modulation frequency increases above the transition frequency, the spectral side components surrounding the carrier frequency gradually move out of the critical bandwidth centered at the carrier frequency, providing additional cues for AM detection. Such spectral cues are not available with broadband-noise carriers. For tonal carriers, the transition frequency is a function of carrier frequency and is about 1/2 of the critical bandwidth associated with the carrier frequency (Zwicker and Fastl, 1990).

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In a systematic study of AM detection (Kohlrausch *et al.*, 2000), the effects of carrier frequency and level on the shape of the tonal TMTF were examined. With the exception of very low carrier levels (30 dB SPL), for carrier frequencies above 2000 Hz, a general pattern was observed. Below the transition frequency, AM detection thresholds remained constant for modulation frequencies up to 100–130 Hz, above which AM thresholds increased with modulation frequency until the transition frequency was reached. It was suggested that this increase in AM thresholds reflects a limit of the auditory system to follow fast envelope fluctuations. Below the transition frequency, TMTFs were likely limited by modulation filtering, which was modeled by Kohlrausch *et al.* (2000) as a low-pass filter with a cutoff frequency of ~150 Hz and was independent of peripheral auditory filtering associated with the carrier frequency. At modulation frequencies above the transition frequency, where AM detection for tonal carriers improved dramatically with increasing modulation frequency, peripheral auditory filtering most likely contributed to the shape of the tonal TMTF, as both temporal and spectral cues (side components) were available. The contribution of spectral cues was dependent on the bandwidth of the auditory filter associated with the carrier frequency. For carrier frequencies below 2000 Hz, the auditory filter bandwidth is narrower than that of the hypothetical modulation filter, which may allow spectral cues to be involved. In this way, the tonal TMTF may reveal the contribution of low-pass modulation filtering and peripheral filtering, depending on carrier frequency.

Studies of masking and interference of AM stimuli reveal another important feature of AM detection. AM detection is not susceptible to the negative effects of simultaneously or nonsimultaneously presented stimuli unless the competing stimuli are modulated at a similar rate (Bacon and Grantham, 1989; Yost and Sheft, 1989; Bacon and Opie, 2002; Dau *et al.*, 1997a, 1997b; Ewert and Dau, 2000; Wojtczak and Viemeister, 2005). This is consistent with the hypothesis of a "modulation-specific mechanism" for AM processing (Joris *et al.*, 2004). The hypothesis was further conceptualized in a modulation filter bank model (Dau *et al.*, 1997a, 1997b; Dau *et al.*, 1999; Ewert and Dau, 2000; Nelson *et al.*, 2004), which states that for each peripheral auditory filter there is a bank of modulation filters. AM detection improves with increasing carrier bandwidth and stimulus duration, suggesting that AM information is integrated across frequency and time (Dau *et al.*, 1997b). Furthermore, the shape of the TMTF and the associated time constant do not change with carrier frequency (Eddins, 1993; Dau *et al.*, 1997b; Kohlrausch *et al.*, 2000). Thus, temporal resolution of the auditory system reflects analyses from two domains. One is the audio-frequency domain at the periphery, including basilar membrane filtering, which broadens with increases in center frequency. The other is the temporal modulation domain for detecting envelope fluctuations with constant temporal resolution across audio frequency (Dau *et al.*, 1999). Because time constants for peripheral auditory filters are generally inversely related to filter bandwidth, temporal resolution would be expected to increase with an increase in modulation frequency if peripheral filtering was the limiting factor. Given that AM thresholds progressively increase at higher modulation frequencies, the modulation filtering process in the temporal modulation domain is likely to occur at more central levels of the auditory system.

In general, AM detection by listeners with hearing loss differs with audiometric configuration. AM detection is poorer than normal for listeners with high-frequency hearing loss with both broadband-noise carriers (Bacon and Viemeister, 1985) and tonal carriers (Moore and Glasberg, 2001) but similar to normal for listeners with flat hearing loss [e.g., see Bacon and Opie (2002) for broadband-noise carriers and Bacon and Gleitman (1992) for tonal carriers]. For broadband carriers, the difference may reflect the importance of carrier bandwidth, which would be narrower than normal for listeners with high-frequency hearing loss. These observations are consistent with the modulation filter bank model (Dau *et al.*, 1997a, 1997b), which assumes that the output of modulation filters can be integrated across auditory filters. In many studies of AM detection by adults with hearing loss, there were considerable differences in age between normal-hearing and hearing-impaired subjects [e.g., see Bacon and Viemeister (1985) and Moore and Glasberg (2001)]. However, the aging effect was not systematically assessed, possibly due to the robust AM detection observed from hearing-impaired listeners. Thus, the effect of age on AM detection is largely unknown.

Takahashi and Bacon (1992) measured AM detection and AM masking using a broadband-noise carrier in a younger group and in three older groups (50, 60, and 70 year olds) with normal hearing. The TMTFs for the four groups were similar in shape. Although AM detection thresholds were generally poorer for the three older groups than for the younger group, age-related differences were not statistically significant, similar to results for Purcell *et al.* (2004) for envelope following responses. In contrast, a study of auditory steady-state evoked responses to AM tones (Leigh-Paffenroth and Fowler, 2006) reported that the number of phase-locked responses was larger at a 40 Hz modulation frequency than at lower (20 Hz) and higher (90 Hz) modulation frequencies; there were also significant age-related differences at the 500 Hz carrier frequency but not at the 2000 Hz carrier frequency. Given the auditory system's specialized neural mechanism to process AM information (Joris *et al.*, 2004) and high sensitivity to AM (Viemeister, 1979; Kohlrausch *et al.*, 2000), AM information integrated across frequency channels with a broadband-noise carrier and presented at suprathreshold levels [as in Takahashi and Bacon (1992)] may carry redundant cues and may not reveal subtle age-related differences in detection. With redundancy reduced by using shorter stimulus durations, lower stimulus levels, and tonal carriers, age-related differences may be more easily revealed. For example, as reported by Takahashi and Bacon (1992), differences between the younger group and the three older groups were larger than the group variances at very low (2 Hz) or very high modulation frequencies. Indeed, for the 2 Hz modulation frequency, the 500 ms stimulus contained only one modulation cycle, which was difficult to detect. At high modulation frequencies, the increased need to follow fast envelope fluctuations may have affected detection more for older subjects than for younger subjects. In both situations, therefore, age-related differences were more likely to be observed.

The finding of a frequency-dependent aging effect on steady-state evoked responses to AM tones (Leigh-Paffenroth and Fowler, 2006) was consistent with psychophysical studies of intensity discrimination, frequency discrimination (He *et al.*, 1998), and frequency modulation detection (He *et al.*, 2007), where age-related differences were larger at lower carrier frequencies and decreased as frequency increased. This frequency-dependent aging effect could not be explained in terms of hearing sensitivity because thresholds of younger and older subjects in these studies were closely matched, especially at lower frequencies. An alternate explanation was based on the involvement of temporal cues, which may degrade with increasing age. According to the modulation filter bank model (Dau *et al.*, 1997a, 1997b; Kohlrausch *et al.*, 2000), AM detection is determined by the temporal resolution of the auditory system, which is limited by the characteristics of both modulation filters and peripheral auditory filters, especially for tonal AM detection. If temporal resolution degrades with increasing age, aging should affect the tonal TMTF differently at modulation frequencies below and above the transition frequency. More specifically, below the transition frequency where AM detection is mainly determined by temporal cues (or by modulation filter bank characteristics), more age-related differences are expected. In contrast, above the transition frequency where AM detection also involves spectral cues, less age-related differences may be observed because peripheral filtering is generally unaffected by aging when there are no confounding effects of hearing loss (Sommers and Humes, 1993; Peters and Hall, 1994; Gifford and Bacon, 2005). To test these hypotheses, AM detection was measured from younger and older subjects with normal hearing using tonal carriers. TMTFs were measured at carrier frequencies of 500 and 4000 Hz to maximize any frequency-dependent aging effect.

II. METHODS

A. Amplitude-modulated signals

The mathematical description of a sinusoidal AM waveform with a pure-tone carrier is given by

$$x(t) = [1 + m\cos(f_m t + \phi)]\sin(f_c t). \quad (1)$$

Here, m is the modulation depth ($0 < m \leq 1$), ϕ is the modulation phase (ϕ=0 in this study), and f_m and f_c are the modulation and carrier frequencies, respectively. AM signals were digitally generated with custom LABVIEW software (LABVIEW 6.1, National Instruments) and converted to analog using a 16 bit digital-to-analog converter (National Instruments, model 6052E) with a sampling rate of 50 kHz. The signal was gated with a duration of 600 ms (including 30 ms $\cos^2$ rise-fall ramps), which consisted of at least three modulation cycles. The modulated waveform was normalized in amplitude after stimulus generation to prevent possible cues for detection due to the increase in rms amplitude after modulation (Yost *et al.*, 1989). The generated AM signals were low-pass filtered (TDT PF1) at a cutoff frequency of 10 kHz, attenuated (TDT PA4), and then passed through a headphone buffer (TDT HB5) to an insert earphone (Etymotic Research, ER2). The frequency response of the earphone was flat from 100 to 7000 Hz as measured in an ear simulator (Brüel & Kjær, model 4157).

B. Procedures

Given the large amount of data collected from each subject, an efficient adaptive procedure, the maximum-likelihood method, was used to measure AM detection thresholds. The maximum-likelihood method has been described elsewhere (Green, 1993; Gu and Green, 1994; Leek *et al.*, 2000); it has been successfully applied to the measurement of frequency and intensity discrimination (He *et al.*, 1998) and gap detection (Florentine *et al.*, 2001). Briefly, thresholds for AM detection were measured using a single-interval (yes-no) maximum-likelihood procedure. The slope factor (k) was 1.0 with modulation depth converted to logarithmic units ($20 \log m$) based on the results of a pilot study of psychometric functions for AM detection (see the Appendix). Each threshold was determined from 30 trials, including eight randomly inserted catch trials. In five of the catch trials, the minimum modulation depth (m=0.001, −60 dB in $20 \log m$) was presented. In the remaining three catch trials, the maximum modulation depth was presented, which was adjusted individually for each subject and condition and ranged from m=0.5 (−6 dB) to m=0.8 (−2 dB). In the maximum-likelihood procedure, modulation depth was varied adaptively, gradually converging to a threshold value with a minimum step size of 0.5 dB. The threshold was defined as the "sweet point" (Green, 1993), which was calculated based on the estimated midpoint (m) of the psychometric function and the false alarm rate (α) after 30 trials.

Each stimulus presentation trial contained two signals separated by 500 ms of silence; the first signal was always unmodulated and the second signal varied in modulation depth. Subjects were instructed to press the "yes" button on a vote box (TDT RBOX) if they detected AM in the second signal or the "no" button if they did not. No correct-answer feedback was given.

TMTFs were measured with the tonal signal presented at 75 dB SPL. The carrier frequencies were 500 and 4000 Hz. Modulation frequencies were 5, 40, 80, 100, 200, and 250 Hz for the 500 Hz carrier and 5, 40, 80, 100, 200, 400, 500, and 1000 Hz for the 4000 Hz carrier. Each threshold was the average of two measurements, except when the two thresholds differed by more than 2 dB. In that case, two additional measurements were obtained, and the average of four measures was taken as the final threshold. Additional measures were necessary in ~2% of the cases for older subjects and in ~1% of the cases for younger subjects.

C. Subjects

Eight younger subjects (mean age of 20.5 years, age range of 18–26 years) and eight older subjects (mean age of 70.6 years, age range of 60–80 years) participated. All subjects had absolute thresholds of ≤20 dB HL (ANSI, 1996)

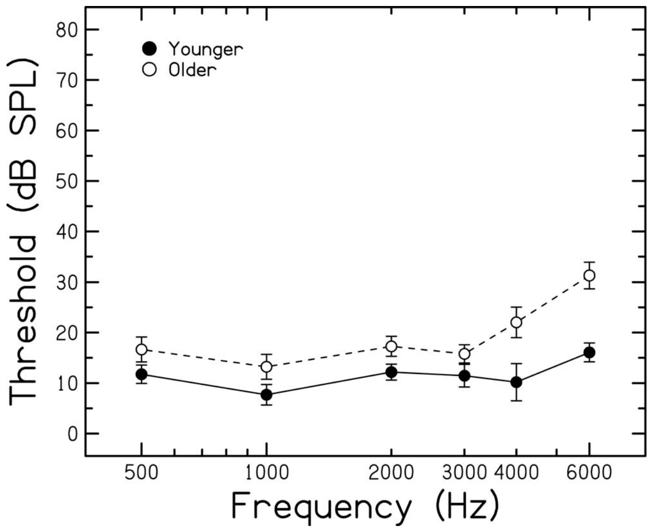

FIG. 1. Group means and standard errors of absolute thresholds (in dB SPL) for pure tones for younger subjects (filled) and older subjects (open).

through 4000 Hz. Figure 1 shows pure-tone thresholds in dB SPL for the younger subjects (filled symbols) and the older subjects (open symbols). Subjects had no prior experience with the listening task. Thus, training was provided prior to data collection to familiarize subjects with the test procedures and stimuli. During training, subjects were tested at both carrier frequencies at a modulation rate of 5 Hz using a constant stimulus procedure with a small number of repetitions (5). Training was terminated when sigmoidal shapes of psychometric functions for AM detection were consistently obtained. This was accomplished in approximately 1 h for the younger subjects and in approximately 2 h for the older subjects.

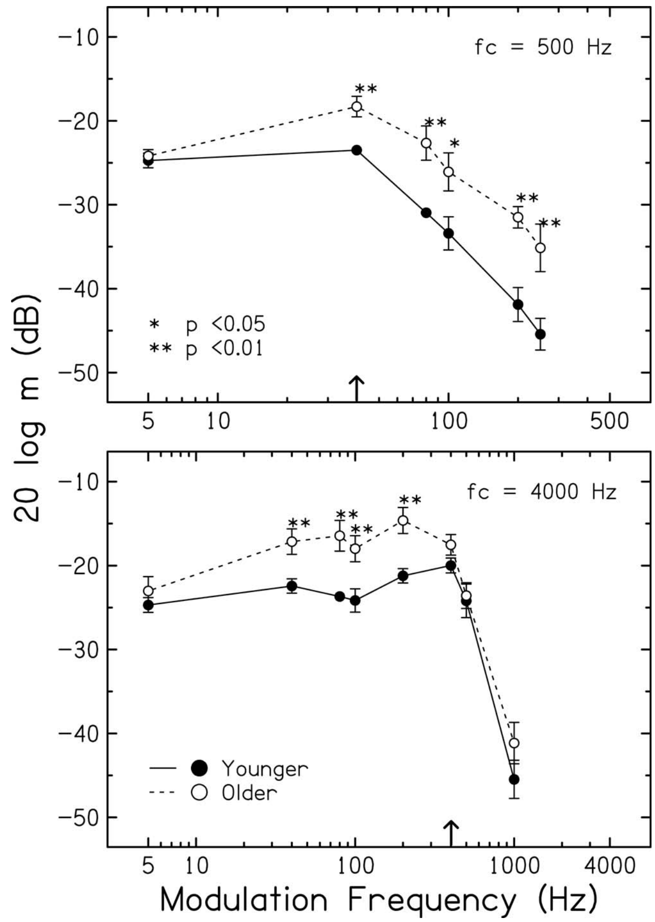

FIG. 2. Group means and standard errors of AM detection thresholds as a function of modulation frequency for younger subjects (filled) and older subjects (open). Temporal modulation transfer functions (TMTFs) for 500 and 4000 Hz carrier frequencies are presented in the top and bottom panels, respectively. The single asterisk indicates a significant difference at $p < 0.05$, and double asterisks at $p < 0.01$ based on *t*-tests. The arrows denote the approximate transition frequency for each carrier frequency.

III. RESULTS

Figure 2 shows group means and standard errors for AM detection thresholds ($d' = 1$) as a function of modulation frequency for younger subjects (filled) and older subjects (open). TMTFs for the 500 Hz carrier are plotted in the top panel, and TMTFs for the 4000 Hz carrier are plotted in the bottom panel. The general patterns were consistent with previous studies of AM detection (Zwicker, 1952; Kohlrausch *et al.*, 2000; Moore and Glasberg, 2001). For younger subjects, the transition frequency was about 10% of the carrier frequency for both carriers. Although the precise values of the transition frequencies could not be defined given the limited number of data points, the approximate values were similar to those reported by Kohlrausch *et al.* (2000), i.e., ~40 Hz for the 500 Hz carrier and ~400 Hz for the 4000 Hz carrier. AM thresholds at modulation frequencies at and below the transition frequency remained generally constant for the 500 Hz carrier. For the 4000 Hz carrier, AM thresholds were generally constant (i.e., the standard deviation was less than 1 dB across modulation frequency) to 100 Hz, then increased (worsened) as modulation frequency further increased to the transition frequency. Above the transition frequency, thresholds decreased (improved) at a fast rate as modulation frequency further increased. The rate of improvement in AM detection for modulation frequencies higher than the transition frequency differed between the low and high carrier frequencies (averaging 8.1 dB/octave for the 500 Hz carrier and 19.6 dB/octave for the 4000 Hz carrier).

Similar to results for younger subjects, TMTFs for older subjects were characterized by segments that differed in direction and rate of change in AM thresholds. Although transition frequencies were similar to those for the younger subjects, the shapes of the TMTFs differed. Below the transition frequency, older subjects' AM detection thresholds continuously increased for both carrier frequencies as modulation frequency increased from 5 Hz, suggesting an age-related decline in temporal resolution for faster envelope fluctuations. Although age-related differences were observed at both carrier frequencies, differences were seen at modulation frequencies below and above the transition frequency for the 500 Hz carrier but were restricted to modulation frequencies below the transition frequency for the 4000 Hz carrier. Above the transition frequency, slopes of TMTFs for older subjects averaged 6.3 dB/octave for the 500 Hz carrier and 17.9 dB/octave for the 4000 Hz carrier. These values were smaller than the slopes for younger subjects, but age-related differences were not statistically significant, as confirmed by a repeated-measure analysis of variance (ANOVA). For both younger and older subjects, slopes were significantly steeper for the 4000 Hz carrier frequency than for the 500 Hz carrier frequency [$F(1,11)=104.72$, $p<0.0001$], with a nonsignificant age by carrier frequency interaction.

Differences in TMTF shapes were confirmed by a repeated-measure ANOVA on AM thresholds, with age as the grouping factor and carrier frequency and modulation frequency as the repeated measures, for modulation frequencies from 5 to 200 Hz. Beyond 200 Hz, modulation frequencies were not matched for the 500 and 4000 Hz carriers. Note that modulation frequencies of 5–200 Hz spanned a range below and above the transition frequency for the 500 Hz carrier but were below the transition frequency for the 4000 Hz carrier. Results from two younger subjects were not included in the analysis due to missing data. Results revealed significant main effects of age [$F(1,12)=10.55$, $p=0.007$], carrier frequency [$F(1,12)=87.59$, $p<0.0001$], and modulation frequency [$F(4,48)=24.26$, $p<0.0001$]; no significant interaction between age and carrier frequency was observed. Thus, over this range of modulation frequencies (5–200 Hz), age-related differences were observed for both carriers. Furthermore, a significant age by modulation frequency interaction [$F(4,48)=7.84$, $p<0.0001$] confirmed that the age effect differed with modulation frequency; i.e., age-related differences increased with increasing modulation frequency.

Post hoc tests focused on the shapes of the TMTF for the 4000 Hz carrier for modulation frequencies below the transition frequency. More specifically, the question was whether AM thresholds remained constant for lower modulation frequencies and then increased, as reported by Kohlrausch *et al.* (2000). First, AM detection thresholds increased linearly as the modulation frequency increased from 5 to 100 Hz, but for older subjects only [$F(1,12)=15.19$, $p=0.002$]. Second, AM thresholds at 200 Hz were significantly higher than AM thresholds at modulation frequencies of 5, 40, 80, and 100 Hz for younger subjects [$F(1,12)=5.15$, $p=0.042$] and older subjects [$F(1,12)=19.30$, $p=0.001$]. Thus, results for older subjects suggested a continuous trend of increasing AM detection thresholds as the modulation frequency increased from 5 to 200 Hz. In contrast, AM detection for younger subjects remained constant through 100 Hz followed by an increase in AM thresholds, consistent with the TMTF pattern described by Kohlrausch *et al.* (2000).

To further assess age-related differences in AM detection, group means were evaluated by *t*-tests at each modulation frequency. These revealed significant differences between younger and older groups for the 500 Hz carrier at modulation frequencies of 40–250 Hz (at and above the transition frequency). In contrast, for the 4000 Hz carrier, significant age-related differences were observed only at modulation frequencies below the transition frequency (Fig. 2, single asterisk indicating a significant difference at $p<0.05$ and double asterisks indicating $p<0.01$).

IV. DISCUSSION

A. AM detection by younger subjects

TMTFs obtained from younger subjects were consistent with those described in the literature. For modulation frequencies lower than transition frequencies, the lowest AM detection thresholds averaged approximately −25 dB for both 500 and 4000 Hz carriers, thresholds that were similar to results from Viemeister (1979) but slightly higher than those reported by Kohlrausch *et al.* (2000). Discrepancies may be due to the effect of stimulus duration [800 ms used by Kohlrausch *et al.* (2000) compared to 600 ms in the current study]. The shape of the TMTF for the 500 Hz carrier was relatively flat for modulation frequencies below the transition frequency, consistent with the data of Kohlrausch *et al.* (2000) for carrier frequencies ⩽2000 Hz. For the 4000 Hz carrier, constant AM thresholds were followed by increasing AM thresholds as the modulation frequency increased from 5 Hz to the transition frequency, similar to the data of Kohlrausch *et al.* (2000) for higher carrier frequencies. Thresholds began to increase at about 100 Hz, which was numerically similar to the previous study (100–130 Hz). The transition frequency was about 10% of the carrier frequency for both low and high carrier frequencies.

B. Age-related differences in AM detection

AM detection thresholds were poorer for older than younger subjects at some modulation frequencies. TMTF shapes also differed between the two age groups. As predicted, for modulation frequencies below the transition frequency (where AM detection was based primarily on temporal cues), age-related differences increased with increasing modulation frequency, with a similar trend for both lower and higher carrier frequencies. In contrast to results from younger subjects, AM thresholds for older subjects showed a steady increase as the modulation frequency approached the transition frequency, which suggested a decline in temporal resolution for faster envelope fluctuations.

For modulation frequencies above the transition frequency (where spectral cues may also be involved in AM detection), age-related differences in AM thresholds were larger for the 500 Hz carrier than for the 4000 Hz carrier. This frequency-dependent aging effect suggested a difference in the availability of temporal information between lower and higher carrier frequencies and a difference in the use of this information by younger and older subjects. Given the reciprocal nature of the relationship between temporal resolution and filter bandwidth, temporal resolution would be expected to be better at higher than lower center frequencies. However, temporal resolution as measured by gap detection does not vary greatly with frequency, except for very low and very high frequencies (Florentine *et al.*, 1999). In addition, auditory filtering, as suggested by critical band analysis, does not reflect the fact that neural firings are synchronized to the period of the signal (phase locking); neural phase locking is strong at low frequencies and decreases as the frequency increases (Rose *et al.*, 1967). Thus, phase locking cues may compensate for the poorer temporal resolution imposed by peripheral auditory filtering for low-frequency signals. Moreover, spectral and intensity information may also be carried by the temporal patterns of neural responses (Joris *et al.*, 2004). For older subjects, such temporal cues may deteriorate, consistent with their increasing difficulty following envelope fluctuations near the transition frequency (Fig. 2). If the use of temporal cues declines with age, larger age-related differences in AM detection would be expected at the lower frequency carrier than at the higher frequency carrier for modulation frequencies above each carrier's transition frequency. That is, for the lower frequency carrier, the transition occurs in a region where temporal cues are still available. For the higher frequency carrier, AM detection above the transition relies primarily on spectral cues. This difference would result in higher AM thresholds above the transition for the older group than for the younger group, but for the lower frequency carrier only, consistent with the pattern of results in Fig. 2.

A similar frequency-dependent aging effect on AM detection was reported in a previous study of steady-state evoked responses to AM tones (Leigh-Paffenroth and Fowler, 2006), wherein the number of phase-locked responses to AM tones was larger for younger subjects than for older subjects for the 500 Hz carrier frequency but not for the 2000 Hz carrier frequency. More specifically, significant age-related differences were observed at a higher modulation frequency (90 Hz) but not at lower modulation frequencies (20 and 40 Hz), which was consistent with results of the current study for the 500 Hz carrier. The lack of a significant aging effect at 2000 Hz in the evoked potential study may be due to the use of signals with large modulation depths ($m = 0.2-1.0$), which are associated with a high probability of detection and may result in robust evoked responses for both younger and older subjects (see psychometric functions for AM detection in Fig. 3).

A relevant question was whether the observed aging effect on AM detection was due to age-related differences in sensation levels. As shown in Fig. 1, significant age-related differences in absolute thresholds were observed [$F(1,14) = 0.40$, $p = 0.0061$]. However, a correlation analysis revealed no systematic relationship between absolute and AM thresholds. For older subjects, no significant correlations were observed between absolute thresholds at 500 Hz and AM detection thresholds for the 500 Hz carrier; absolute thresholds at 4000 Hz were significantly correlated with AM detection thresholds for the 4000 Hz carrier for the 5 Hz modulation frequency only.

A correlation analysis further revealed that for the 500 Hz carrier, except for the 5 Hz modulation frequency, AM detection thresholds below and above the transition frequency were significantly correlated with each other. In contrast, for the 4000 Hz carrier, significant correlations were clustered and distributed at low ($\leqslant 100$ Hz) and high ($\geqslant 400$ Hz) modulation frequencies, coincident with parts of the TMTF determined by different cues. That is, AM thresholds based on temporal cues were significantly correlated with each other and AM thresholds based primarily on spectral cues were significantly correlated with each other, but temporally based and spectrally based AM thresholds were not correlated.

The frequency-dependent trend of age-related differences in AM detection was consistent with age-related differences in frequency and intensity discrimination (He *et al.*, 1998) and in frequency modulation detection (He *et al.*, 2007), where age-related differences were largest at low standard or carrier frequencies and decreased as frequency increased. The similarity among these different measures suggests some common underlying mechanism such as the use of temporal cues, which may decline with age. For example, Fitzgibbons and Gordon-Salant (1995) reported that duration discrimination was poorer for older than for younger adults and that the age-related deficit increased with increasing stimulus complexity. Gap detection was also poorer for older than for younger adults, especially when the gap was placed near the stimulus onset or offset (Snell, 1997; Strouse *et al.*, 1998; He *et al.*, 1999; Snell and Hu, 1999). In a comprehensive study of both monaural and binaural temporal processing, Strouse *et al.* (1998) measured gap detection, voice onset time, interaural time difference, and masking level differences from groups of younger and older subjects with well-matched normal audiograms and observed significant age-related differences for all measures.

Although declines in temporal processing with age are well documented, the underlying mechanism for these declines remains unclear. Walton *et al.* (2002) measured single unit responses to a SAM noise carrier from inferior colliculus neurons of young and old CBA mice and observed an age-related degradation in cycle-by-cycle coding of SAM. This was confirmed by a later study (Allen *et al.*, 2006) using a prepulse procedure to measure the ability of mice to trace the onset and ongoing AM cycles of a continuous broadband noise; age-related differences were observed in the perception of ongoing, but not onset, AM cycles. In addition, Walton *et al.* (2002) found significant age-related decreases in the coding of high-rate envelope modulations, consistent with the trend observed in the current study that age-related differences increased as modulation frequency increased.

In summary, tonal TMTFs measured at 75 dB SPL showed significant age-related differences, although transition frequencies were similar for younger and older adults. For younger subjects, AM detection thresholds were generally constant for modulation frequencies below the transition frequency. For a higher carrier frequency, AM detection thresholds remained constant for modulation frequencies up to 100 Hz and then increased as modulation frequency further increased until the transition frequency. For older subjects, AM detection continuously increased (became worse) with increasing modulation frequency, indicating an age-related decline in temporal resolution for faster envelope fluctuations. Significant age-related differences were observed whenever AM detection was dependent on temporal cues. For modulation frequencies below the transition frequency, age-related differences in AM detection were similar for lower and higher carrier frequencies, consistent with the modulation filter bank model wherein temporal resolution is constant across carrier frequency (Dau *et al.*, 1997a, 1997b). In contrast, for modulation frequencies above the transition frequency, age-related differences were larger for the lower frequency carrier (where both temporal and spectral cues

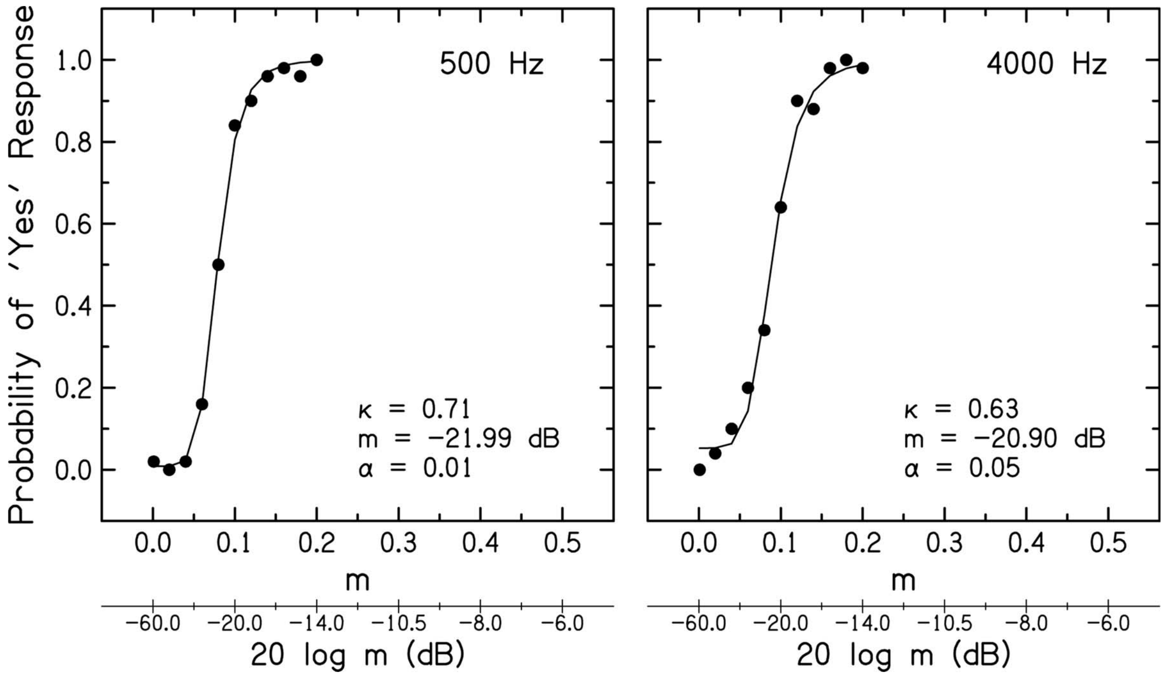

FIG. 3. Examples of measured (symbols) and fitted (lines) psychometric functions for AM detection obtained from one younger subject. The modulation frequency was 5 Hz, and the stimulus duration was 600 ms. Data for 500 and 4000 Hz carrier frequencies are presented in the left and right panels, respectively. Data were collected in a two-tone paradigm, whereby the first signal was always unmodulated and the second signal varied in modulation depth.

were available) than for the higher frequency carrier (where AM detection was primarily dependent on spectral cues). This frequency-dependent aging effect on AM detection was consistent with other measurements, such as frequency and intensity discrimination (He *et al.*, 1998) and frequency modulation detection (He *et al.*, 2007), suggesting that a common mechanism, such as the use of temporal cues, is involved in these measurements and deteriorates with age. The results of this behavioral study are consistent with a general age-related decline in the synchronization of neural responses to both the carrier waveform (phase locking) and envelope fluctuation (envelope locking).

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APPENDIX: PSYCHOMETRIC FUNCTIONS FOR AM DETECTION WITH A YES-NO PROCEDURE

In order to apply the maximum-likelihood method (Green, 1993) to the measurement of AM detection in the main study, it was necessary to establish a working psychometric function for tonal AM detection and to determine the effects of modulation frequency, carrier frequency, stimulus duration, and stimulus paradigm on its slope. Data were collected from four younger subjects (mean age of 20 years, age range of 18–22) whose absolute thresholds were ⩽20 dB HL (ANSI, 1996) through 4000 Hz.

Signal generation was the same as described in Sec. II. Signals were 60 dB SPL and had $\cos^2$ rise/fall ramps of 5 ms for durations ⩽50 ms and 30 ms for durations ⩾400 ms. The method of constant stimuli with a yes-no task was used; for each psychometric function, 11 evenly spaced m values were employed, where the minimum m was always zero (i.e., no modulation) and the maximum m ranged from 0.2 to 0.5, depending on the carrier frequency, stimulus duration, and individual subject. Each m value was presented 50 times in random order. Thus, each psychometric function was the result of 550 trials. To minimize subjects' fatigue due to the large number of trials, the total number of trials was divided into ten blocks with 55 trials in each block.

For each subject, psychometric functions were measured for two carrier frequencies (500 and 4000 Hz) and two modulation frequencies (5 and 80 Hz) with three stimulus durations corresponding to 4, 3, and 2 modulation cycles, respectively. In a majority of the measurements, a "one-tone" stimulus paradigm was used, where a single signal was presented in each trial and the subject determined whether the signal was modulated or not. Psychometric functions were also measured with a "two-tone" paradigm for 500 and 4000 Hz carrier frequencies with a 5 Hz modulation frequency and a 600 ms duration. In the two-tone paradigm as used in the main study, each trial contained two signals separated by 500 ms silence; the first signal was always unmodulated, and the second one varied in modulation depth (as described in the Sec. II). Each measured psychometric function was fitted with a logistic function adapted from Green (1993), which was described in He *et al.* (1998).

Figure 3 shows representative results from a younger subject for measured (symbols) and fitted (lines) psychometric functions for AM detection with a 600 ms signal duration at carrier frequencies of 500 Hz (left panel) and 4000 Hz (right panel). The functions were obtained using the two-tone paradigm and a 5 Hz modulation frequency. Data were plotted on a linear scale (m), but corresponding logarithmic values were also given. Generally, the psychometric functions for AM detection featured steep slopes, which were somewhat steeper for the 500 Hz carrier than for the 4000 Hz carrier.

AM detection thresholds ($d'=1$) and slopes of the psychometric functions (k) at both carrier frequencies did not differ significantly for one-tone and two-tone paradigms (threshold: $p=0.11$; slope: $p=0.28$). A significant main effect of duration on AM detection thresholds was observed for both 5 Hz $[F(1,3)=9.28,\ p=0.0146]$ and 80 Hz $[F(1,3)=337.54,\ p<0.0001]$ modulators. That is, AM detection thresholds improved with increasing stimulus duration for both carrier frequencies, consistent with previous studies (Viemeister, 1979; Yost and Sheft, 1990; Lee and Bacon, 1997; Dau *et al.*, 1997b). However, the slope (k) of the psychometric function was independent of signal duration. A significant effect of carrier frequency was observed only at the 80 Hz modulation frequency for AM thresholds $[F(1,3)=11.20,\ p=0.0442]$ and at the 5 Hz modulation frequency for slope $[F(1,3)=29.73,\ p=0.0121]$. For the 600 ms stimulus duration, modulation frequency had no significant effect on AM detection thresholds ($d'=1$) and on the slope of the psychometric function (threshold: $p=0.28$; slope: $p=0.07$).

To summarize, when the modulation depth, m, was expressed on a logarithmic scale, $20\log(m)$, the psychometric function for AM detection had a steep slope, which was constant across most experimental conditions, i.e., one-tone versus two-tone stimulus paradigms, stimulus durations, and modulation frequencies. Some differences in AM threshold and psychometric function slope were related to carrier frequencies, but differences were not systematic. The k value averaged across stimulus duration and modulation frequency was 0.94 (s.d.$=0.14$) for the 500 Hz carrier and 0.69 (s.d.$=0.16$) for the 4000 Hz carrier, with a grand average of 0.82. As a result, the slope (k) parameter was set to 1.0 in the maximum-likelihood method used to measure AM detection in the main study.

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