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Masking Period Patterns & Forward Masking for Speech-Shaped Noise: Age-related effects

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Abstract

Objective—The purpose of this study was to assess age-related changes in temporal resolution in listeners with relatively normal audiograms. The hypothesis was that increased susceptibility to non-simultaneous masking contributes to the hearing difficulties experienced by older listeners in complex fluctuating backgrounds.

Design—Participants included younger (n = 11), middle-aged (n = 12), and older (n = 11) listeners with relatively normal audiograms. The first phase of the study measured masking period patterns for speech-shaped noise maskers and signals. From these data, temporal window shapes were derived. The second phase measured forward-masking functions, and assessed how well the temporal window fits accounted for these data.

Results—The masking period patterns demonstrated increased susceptibility to backward masking in the older listeners, compatible with a more symmetric temporal window in this group. The forward-masking functions exhibited an age-related decline in recovery to baseline thresholds, and there was also an increase in the variability of the temporal window fits to these data.

Conclusions—This study demonstrated an age-related increase in susceptibility to non-simultaneous masking, supporting the hypothesis that exacerbated non-simultaneous masking contributes to age-related difficulties understanding speech in fluctuating noise. Further support for this hypothesis comes from limited speech-in-noise data suggesting an association between susceptibility to forward masking and speech understanding in modulated noise.

Introduction

It has long been observed that speech recognition thresholds are usually lower in a fluctuating masker than in a steady masker for listeners with normal hearing (Miller et al. 1950). This benefit of listening in a modulated masker can be quantified as a masking release; i.e., the difference in recognition thresholds between the steady and fluctuating maskers. Older listeners – even those with relatively normal audiograms – usually show less

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masking release than young, normal-hearing adults, and this reduced benefit is associated primarily with poorer thresholds in the modulated masker rather than altered thresholds in the steady masker (e.g., Dubno et al. 2002; Grose et al. 2009; Stuart et al. 1996; Takahashi et al. 1992). One account for this reduced ability to take advantage of the favorable speech-to-masker ratio during the masker minima is that the older listeners are more susceptible to temporal masking. That is, the minima of the masker are less resolved because of exacerbated forward and backward masking by the surrounding masker peaks. This hypothesis has received support from Gifford and colleagues (2005; 2007) who found both higher speech thresholds in modulated maskers and increased susceptibility to forward masking in older listeners who were otherwise matched with younger listeners in terms of audiometric profile. Dubno et al. (2003) also found an inverse association between speech recognition in an interrupted masker and the forward-masked threshold for a brief tonal signal in a study of older and younger listeners with normal audiometric hearing. In similar vein, Gehr and Sommers (1999) found elevated backward masking in older listeners, despite relatively normal audiometric hearing, and suggested that this may contribute to poorer speech perception in older listeners. Finally, in the domain of cochlear implant hearing, Lee et al. (2012) found slower recovery from forward masking in older listeners, and an association between recovery rate and speech perception performance.

The purpose of this study was to further pursue the hypothesis of age-related susceptibility to temporal masking by measuring both forward and backward masking, and quantifying the response patterns in terms of a temporal window. The concept of a temporal window has proved useful in summarizing performance across a variety of temporal tasks. It is essentially a “leaky integrator” that weights the contribution of sound power across time relative to some arbitrary temporal reference point. In one of its simpler forms, the temporal window can be portrayed as a pair of exponential functions that describe the attenuation across time before and after some arbitrary point in time (Moore et al. 1988). These two functions are typically asymmetric, reflecting greater forward masking than backward masking.

A paradigm that lends itself to temporal window estimation is the masking period pattern (MPP). This procedure was introduced by Zwicker (1976) and makes use of a brief signal to ‘map out’ the resolution of the masker envelope. That is, signal detection threshold is measured as a function of the temporal position of the signal relative to the modulation cycle of the masker. The purpose of this study was to use the MPP paradigm to derive temporal window shapes for groups of adult listeners of different ages. The goal was to determine whether changes in temporal window shape with age might contribute to an understanding of the reduced ability of older listeners to benefit from a fluctuating background when listening to speech in noise. The study proceeded in two phases. In the first phase, the MPP for a brief signal in a modulated masker was measured and, from these data, the temporal window estimated. In the second phase, a forward masking function was measured across a longer time interval, and the accuracy with which the MPP-derived temporal window accounted for the forward masking data was assessed. Whereas most MPP studies use a brief tonal pip as a signal (e.g., Buss et al. 2013; Wojtczak et al. 2003), in this study both the masker and the brief signal were speech-shaped noises (SSN). The rationale for using a SSN as the signal was to employ a target sound that had a similar spectral complexity to speech in order to enhance the ecological relevance of the task in the context of 'glimpsing' a brief complex signal in a fluctuating masker.

In summary, the purpose of this experiment was to derive temporal window estimates for different age groups of normal-hearing adults in order to determine whether age-related changes in the temporal window could account for reduced masking release in a modulated masker with age. Participation was restricted to listeners with relatively normal audiometric hearing since it is known that cochlear impairment can affect MPP performance (Zwicker et al. 1982).

Materials and Method

Subjects

Three age groups of listeners participated: Younger (20 – 33 years, mean = 23.9 years; n = 11; 9 female); Mid-Age (41 – 59 years, mean = 50.6 years; n = 12, 9 female); and Older (65 – 80 years, mean = 69.2 years; n = 11, 6 female). All had relatively normal audiograms, with audiometric thresholds ≤ 20 dB HL for the octave frequencies 250 – 4000 Hz. Whereas thresholds at 8000 Hz remained ≤ 20 dB HL for the Younger and Mid-Age listeners, they ranged between 5 – 55 dB HL in the Older group. Group mean thresholds for the test ear are shown in Fig. 1. The default test ear was the left ear unless thresholds in the right were better; this was the case for eight of the Older group. The Older group, in addition, was required to pass a cognitive screening test (Montreal Cognitive Assessment [MoCA]; (Nasreddine et al. 2005)) as an inclusion criterion. The purpose of this screener was to minimize the likelihood that age-related cognitive deficits would contribute to differences in performance. This study was approved by the Institutional Review Board of the University of North Carolina at Chapel Hill; all subjects provided written consent and were paid for their participation.

Stimuli

Masker—The masker consisted of a SSN with a spectral profile based on the generic long-term average spectrum of speech (LTASS) computed by Byrne et al. (1994). For the MPP phase of the study, this masker was presented continuously under 3 conditions: (1) *Steady High*, where the SSN was output at a constant overall level of 65 dB SPL; (2) *Steady Low*, where the SSN was output at a constant overall level of 30 dB SPL: and (3) 5-Hz *Modulated*, where the SSN alternated between 65 dB SPL and 30 dB SPL at a modulation rate of 5 Hz. These levels were chosen to coincide with those of a separate speech-in-noise study being undertaken in our laboratory, and were based on Desloge et al. (2010). The modulation pattern was approximately square wave with the transitions between the high and low segments of the modulation cycle shaped by a raised-cosine gate having a rise/fall time of 1 ms. For the forward masking phase of the study, a 400-ms segment of the SSN masker was presented at 65 dB SPL, at which point it dropped to a baseline level of 30 dB SPL. This transition was also shaped by a 1-ms, raised-cosine gate.

Signal—The signal consisted of an independent SSN with identical spectral parameters to the masker. For each signal presentation, a 30-ms segment of the SSN was extracted at a random starting point from within a 10.7-sec pre-computed sample. This 30-ms segment was shaped with a 15-ms cosine rise/fall ramp (no steady-state portion). For signal presentation in the *Modulated* masker in the MPP phase of the study, 6 temporal positions of the signal relative to the falling transition of the modulation cycle were tested; in these 6 conditions, the onset of the signal relative to the falling transition occurred at -65, -30, 0, 35, 70, and 100 ms. For signal presentation in the forward masking phase of the study, the onset of the signal relative to the offset of the masker was fixed at 4 intervals: 4, 16, 64, and 128 ms.

The stimuli were generated using a digital signal processing platform (RP6, Tucker-Davis Technologies, Alachua, FL) in conjunction with custom scripts written in MATLAB (MathWorks, Natick, MA). Stimuli were presented monaurally using a Sennheiser HD580 headphone (SEC, Old Lyme, CT).

Procedure

Signal threshold in both the MPP and forward masking phases was measured in a three-alternative, forced-choice task incorporating a 2-down, 1-up adaptive rule that estimated the 70.7% correct point on the psychometric function (Levitt 1971). Signal level was initially adjusted in steps of 4 dB, and this was halved after 2 reversals in signal level direction to the final step size of 2 dB. A threshold estimation track was terminated after 8 reversals, and the mean of the final 6 reversal levels was taken as the threshold estimate for that track. Threshold estimation tracks where the standard deviation (SD) of the final 6 reversal points exceeded 4 dB were rejected and replaced with additional tracks. Three threshold estimates within a range of 3 dB were collected for each condition, with a fourth collected if the range of thresholds exceeded 3 dB. The average of all estimates was taken as the threshold value for that condition. Most subjects completed the study in about 3 listening sessions, each lasting about 1 hour.

Temporal window fits

The temporal window shape was defined by a pair of exponential functions, each function forming one side of the window and having the expression:

$$W(t)=\left(1+\frac{2t}{T_p}\right)\exp\left(\frac{-2t}{T_p}\right) \quad (1)$$

Here, the time-weighted function, $W(t)$, is defined by the time interval t(ms) to the center of the window and the time constant, T_p, that defines the steepness of the function (i.e., window skirt). Each side of the temporal window has a separate time constant, designated T_{p_a} and T_{p_b} respectively. The Matlab function *fminsearch* was used to estimate these free parameters.

Results

MPP

Results for the MPP phase of the study are shown in Fig. 2 which plots mean signal threshold (± 1 SD) for the three age groups: Younger (circles), Mid-Age (triangles), and Older (squares). Signal threshold is plotted as a function of the temporal position of the signal relative to the masker modulation phase, with group symbols slightly offset for visual clarity. For reference, a schematic of the masker modulation cycle is shown as a solid black line. Thresholds for the *Steady High* and *Steady Low* masker conditions are plotted on the left side of the figure aligned with the abscissa break. These baseline thresholds will be discussed first.

Steady maskers—Mean signal thresholds in the *Steady High* masker differed by less than 1 dB across the three age groups (64.2 – 65.0 dB SPL), and were approximately equivalent to the masker level; i.e., the signal-to-masker ratio at threshold was about 0 dB. In the *Steady Low* masker, mean thresholds differed by more than 2 dB (33.5 – 36.1 dB SPL), with the signal-to-masker ratio exceeding 3 dB. The signal thresholds were submitted to a repeated-measures analysis of variance (ANOVA) with one within-subjects factor (*masker level*: High, Low) and one between-subjects factor (*age group*: Younger, Mid-Age, Older). The results indicated main effects of *masker level* ($F[1,31] = 8388.01$; $p < 0.001$) and *age group* ($F(2,31) = 6.95$; $p = 0.003$), and no interaction between these factors ($F[2,31] = 2.82$; $p = 0.075$). Thus, even in the baseline steady masker conditions, there was an age effect wherein thresholds were higher in the older age group than in the younger groups.

Modulated masker—Signal thresholds in the modulated masker varied with the temporal position of the signal, and corresponded to the general shape of the masker envelope; that is, they were higher when the signal was positioned in the peak of the masker and lower when the signal was positioned within a masker minimum as would be expected for MPPs. However, even the lowest thresholds in the modulated masker, associated with the condition where the signal was positioned 35 ms after the modulation offset, were elevated with respect to the baseline *Steady Low* thresholds for all listeners ($t[33] = 20.18$; $p <0.001$). This indicates effective non-simultaneous masking. The MPP thresholds were submitted to a repeated-measures ANOVA with one within-subjects factor (*signal temporal position*: -65, -30, 0, 35, 70, and 100 ms) and one between-subjects factor (*age group*: Younger, Mid-Age, Older). A preliminary assessment of the data with Mauchly's test of sphericity indicated that the variances of the differences between all possible pairs of the within-subjects factor were unlikely to be equal ($p < 0.001$); therefore Greenhouse-Geisser adjustments to the degrees of freedom were incorporated in interpreting the ANOVA. The analysis indicated main effects of *signal temporal position* ($F[2.81, 87.15] = 240.21$; $p < 0.001$) and *age group* ($F[2,31] = 6.71$; $p = 0.004$), and a significant interaction between these two factors ($F[5.62, 87.15] = 4.97$; $p < 0.001$). Planned pair-wise comparisons indicated that the Younger and Older age groups differed significantly at the signal temporal positions of 0 and 70 ms ($p \leq 0.017$), and that the Mid-Age and Older groups differed significantly at the signal temporal position of 70 ms ($p = 0.003$). The Younger and Mid-Age groups did not differ at any signal temporal position. This data pattern indicates that when the brief signal was placed immediately after the offset of the masker, the older listeners were more susceptible to forward masking than the younger listeners. When the signal was positioned such that its offset abutted the onset of a masker peak (signal temporal position = 70 ms), the older listeners were particularly susceptible to backward masking.

Of secondary note, it is evident that thresholds for signals placed in the peak of the masker (signal temporal positions of -65, -30, and 100 ms) were somewhat elevated relative to the *Steady High* baseline even though all of these conditions represent simultaneous masking. This observation was confirmed with a repeated-measures ANOVA that compared these four conditions across the three age groups (within-subjects factor: *signal condition*; between-subjects factor: *age group*). There was a main effect of condition ($F[3,93] = 160.75$; $p < 0.001$), but not of age group ($F[1,31] = 0.63$; $p = 0.54$), and no interaction between these factors ($F[6,93] = 0.30$; $p = 0.93$). Within-subjects contrasts indicated that thresholds in the baseline *Steady High* condition were lower than those for any of the peak-placement conditions ($p < 0.001$). This data pattern suggests that signal detection cues are more salient in a steady masker than in a dynamically fluctuating masker.

Forward Masking

Results of the forward masking phase of the study are shown in Fig. 3 which plots mean signal threshold as a function of the interval between masker offset and signal onset (signal-masker interval). For reference, thresholds in the baseline *Steady High* masker are shown aligned with the left abscissa break, and thresholds in the *Steady Low* masker are shown aligned with the right abscissa break. Plotted on a log time scale, thresholds recover in a relatively linear fashion as the masker-signal interval increases, although the rate of recovery appears to vary across age groups. The forward-masked thresholds were submitted to a repeated-measures ANOVA with one within-subjects factor (*signal-masker interval*: 4, 16, 64, and 128 ms) and one between-subjects factor (*age group*: Younger, Mid-Age, Older). Results indicated main effects of *signal-masker interval* ($F[3, 93] =362.26$; $p < 0.001$) and *age group* ($F[2,31] = 5.61$; $p = 0.008$), and a significant interaction between these two factors ($F[6, 93] = 5.66$; $p < 0.001$). Planned pair-wise comparisons indicated that the Younger age group differed significantly from both the Mid-Age and Older age groups at the signal-masker intervals of 64 and 128 ms ($p < 0.05$), and that the Mid-Age and Older age groups differed at the signal temporal position of 128 ms ($p = 0.005$). This pattern of results suggests an age-related difference in the threshold recovery function, with the younger listeners showing the most rapid recovery function. To capture these recovery functions, a linear regression was fitted to the threshold data of each subject, and the slope of this line (dB/log[ms]) was taken as the estimate of rate of recovery. The fits of these lines were generally good, with the percent variance accounted being, on average, 97% (SD = 4%), 94% (SD = 6%), and 89% (SD = 14%) for the Younger, Mid-Age, and Older age groups, respectively. The mean slope values were -13.0 (SD = 1.58), -12.6 (SD = 2.51), and -8.7 (SD = 3.01) for the Younger, Mid-Age, and Older age groups, respectively. An ANOVA indicated a main effect of *age group* ($F(2,33) = 10.42$; $p <0.001$), and post-hoc testing using the Tukey honest significant difference (HSD) test indicated that the slopes of the Older group were significantly shallower ($p \leq 0.001$) than the slopes of the Younger and Mid-Age groups; those of the latter two groups did not differ.

Temporal window fits

In order to summarize the temporal resolution inherent in the MPPs, the individual data were fitted with temporal windows as described earlier. By way of example, Fig. 4 shows the fits to the average data of the Younger group (left column) and Older group (right column). The upper row re-plots the mean data from Fig. 3 superimposed on a schematized masker envelope shown by a dashed line. The arrows on the left of the plot indicate mean thresholds in the *Steady High* and *Steady Low* maskers. The solid black lines indicate the fit to these data generated by the derived temporal window. The variance accounted for is noted in the upper right corner of each panel. The temporal windows themselves are shown in the middle pair of panels. Each temporal window is summarized by two parameters: (1) the equivalent rectangular duration (ERD), and (2) the fraction, a, that represents the ratio of the slope of the left-side skirt of the window (T_{pa}) to the slope of the right-side skirt (T_{pb})). The ERD is the duration of a boxcar window having the same area as that contained under the curve of the temporal window. The parameter a captures the symmetry of the temporal window, with unity indicating perfect symmetry (i.e., equivalent forward and backward masking) and values less than unity indicating a shallower forward masking function relative to the backward masking function. In the group average temporal windows shown in the middle panels of Fig. 4, the ERD is longer for the Older listeners than the Younger listeners and a is closer to unity in the Older group indicating a more symmetric mean window for the Older group. The distributions of individual ERD and a values for the three age groups are displayed in the upper and lower panels of Fig. 5, respectively. Each rectangle extends from the 25th to 75th percentile, with the horizontal line indicating the median; each vertical line extends from the lowest to the highest individual value.

The individual ERDs were submitted to an ANOVA which indicated a main effect of age group ($F[2, 31] = 4.9$; $p = 0.014$). Post-hoc analysis using Tukey HSD revealed that only the ERDs of the Younger and Older age groups differed; the ERDs of the Mid-Age group did not differ from either the Younger or Older groups. An ANOVA on the a values generated a similar result: There was a main effect of age group ($F[2, 31] = 5.09$; $p = 0.012$), and post-hoc analysis using Tukey HSD revealed that only the Younger and Older age groups differed in temporal window asymmetry.

Temporal windows and forward masking

Recall that the temporal windows were derived from the MPP data. It was of interest to gauge how well an individual's temporal window predicted her/his forward masking function. This exercise provided an indication of the extent to which the temporal window summarized a listener's temporal resolution in general. By way of example, the lower panels of Fig. 4 show this analysis for the mean data of the Younger group (left panel) and Older group (right panel). The group mean forward masking data are re-plotted from Fig. 3, and the solid line shows the fit generated by the respective temporal window shown in the middle panels. The variance accounted for by this fit is shown in the upper right corner of each panel. It can be seen in this example that the average temporal window of the Younger group better predicts their forward masking performance than does the average temporal window of the Older group. This exercise was undertaken for each subject, and the results are summarized in Fig. 6 which shows the distributions of variance accounted for by the temporal windows for the MPP fits (upper panel) and the forward masking fits (lower panel) for the three age groups. Each rectangle extends from the 25th to 75th percentile, with the horizontal line indicating the median; each vertical line extends from the lowest to the highest individual value. Dealing first with the MPP fits, it can be seen that the individual fits of the temporal windows to the MPP data from which they were derived were uniformly good across age groups. However, the ability of those temporal windows to predict the forward masking data was more variable. For the Younger group, the fits were generally above 80%, and were generally above 70% for the Mid-Age group; the fits for the Older age group tended to be lower, with one listener in particular showing an extremely poor fit.

Discussion

The purpose of this study was to examine age-related changes in temporal resolution, independent of elevated audiometric thresholds, which shed light on the nature of the difficulties experienced by older persons listening in complex fluctuating backgrounds. The goal was to obtain a measure of the temporal window to capture aspects of both simultaneous and non-simultaneous masking. One main finding was that older listeners appear to exhibit greater susceptibility to backward masking relative to younger or middle-aged listeners. This finding is suggested by the particularly elevated thresholds in the older group for the MPP condition where the signal occurred immediately prior to the masker transition from low to high levels in the modulated masker (signal onset re. modulation offset = 70 ms, see Fig. 2). This elevated threshold resulted in a more symmetric temporal window in the older listeners compared to the younger listeners. The finding of pronounced backward masking is supported by earlier work that measured backward masking functions in older listeners with normal audiometric hearing (Cobb et al. 1993; Gehr and Sommers 1999). These studies found elevated masked thresholds relative to young adults at all signal-masker intervals and, importantly, also found that the recovery function was shallower in the older listeners. Enhanced backward masking is of interest because it is often interpreted as reflecting factors other than the temporal encoding capabilities of the auditory system, per se (Hill et al. 2004). For example, susceptibility to backward masking is thought to reflect an inability to perceptually segregate the (brief) signal from the ensuing masker. Evidence in support of this notion comes from the observation that the magnitude of backward masking diminishes when the onset of the masker is cued, facilitating the perceptual distinction between signal and masker (Puleo et al. 1980; Zhang et al. 2007). The suggestion that backward masking reflects higher-level confusion effects is also supported by the observation that backward-masked thresholds are amenable to training; that is, masked signal detection thresholds can be reduced with training (Buss et al. 1999). It is interesting to note that analogous age-related effects in MPP performance have been noted at the other end of the age spectrum. Specifically, Buss et al. (2013) measured MPPs for tonal signals in children of different ages and found that children, particularly those less than about 6.5 years of age, were more susceptible to backward masking than young adults. This similarity in susceptibility to backward masking in children and older adults suggests that at both ends of the age range, diminished perceptual segregation skills contribute to poorer performance in acoustically dynamic environments. If older listeners are indeed more susceptible to backward masking, and this is due to a perceptual confusion effect, then performance should be amenable to training. This is an area for future investigation.

Another main finding was that the rate of recovery from forward masking declines with age. As the masker-signal interval increased, older listeners converged on their baseline thresholds less rapidly than did younger and middle-aged listeners, and this was particularly evident at the longer intervals. The more prolonged forward masking effect in older listeners has been reported previously in electric hearing (Lee et al. 2012). Other studies of acoustic hearing have also reported increased susceptibility to forward masking in older listeners (Gifford and Bacon 2005; Gifford et al. 2007). Dubno et al. (2003) found that older listeners with normal audiograms had elevated forward-masked thresholds compared to younger listeners but that there was no age-related difference in the amount of forward masking. At the longer signal-masker intervals, the middle-aged listeners also performed more poorly than the younger listeners. This supports other studies that have demonstrated that some aspects of temporal processing deficits emerge relatively early in the aging process (e.g., Grose et al. 2006; Grose et al. 2012; Ross et al. 2007; Ruggles et al. 2012).

Although both the forward masking data and the MPP data exhibited an age effect, and the MPP data generated well fitting temporal window functions, the success with which those temporal windows predicted the individual forward masking functions was somewhat variable, particularly in the older group. This has bearing on the question of the degree to which age-related differences in forward masking recovery functions contributed to the exacerbated backward masking observed in older listeners in the MPP task. Specifically, in the MPP condition most affected by backward masking (i.e., the 70-ms signal position) the age-related spread in signal threshold was similar to that seen for the 64-ms signal-masker interval in the forward masking task. This raises the possibility that the signal thresholds for this MPP condition reflect an *age-independent* constant magnitude of backward masking combined with an *age-dependent* magnitude of forward masking. However, it is evident from Oxenham and Moore (1994, 1995) that the additivity of non-simultaneous masking is in most cases not linear, at least in the (young) normal system. In addition, Gehr and Sommers (1999) show a clear age dependence in backward masking recovery functions. The weight of evidence therefore advocates for caution in interpreting the similar spread in signal thresholds noted above as indicating age-independence of backward masking. In any case, the well fitting temporal windows derived from the MPP data capture the contributions of both forward and backward masking and clearly show a dependence of window symmetry on listener age. Thus, the parsimonious conclusion is that for signal detection in an on-going modulated masker, there is an age-related increase in susceptibility to backward masking.

The finding of prolonged forward masking in older listeners has led to the hypothesis that the reduced benefit exhibited by older listeners for recognizing speech in a fluctuating masker is due in part to the increased forward masking of the speech snippets that occur during the masker minima. Indeed, Dubno et al. (2003) found an inverse association between speech recognition in an interrupted masker and the forward-masked threshold for a brief tonal signal, and Gifford et al. (2007) found both higher speech thresholds in modulated maskers and increased susceptibility to forward masking in older listeners. Although speech recognition was not measured in the present study, the older listeners (but not the younger or middle-aged listeners) had participated in another study that included speech-in-noise testing; specifically, they had been tested with the Hearing In Noise Test (HINT) administered in both a steady and a 10-Hz modulated SSN masker.[1] To determine whether there was an association between performance in the forward-masking task and the speech-in-noise results, a series of four Pearson product moment correlations were computed between the four forward-masked thresholds and the speech recognition threshold in the modulated masker. In line with Dubno et al. (2003), the expectation was that older listeners who exhibited lower forward-masked thresholds would exhibit lower speech recognition thresholds in the modulated masker. The one-tailed correlations were significant for the 4-, 64-, and 128-ms intervals ($r = 0.56$, $p = 0.036$; $r = 0.64$, $p = 0.018$; and $r = 0.56$, $p = 0.037$, respectively), but not for the 16-ms interval ($r = 0.44$, $p = 0.087$). Thus, the findings of the present study generally support the notion that the reduced benefit that older listeners receive from listening in a modulated masker is likely due, in part, to an increased susceptibility to forward masking. Given the exacerbated backward masking also observed in this study for the older listeners, it might be expected that an association should exist as well between speech recognition in modulated noise and the MPP threshold most reflective of backward masking (i.e., the 70-ms signal position, see Fig. 2). However, no such association was found ($r = -0.10$; $p = 0.767$). One possible explanation for this lack of an association centers on the role of perceptual confusion as the basis of backward masking. The exacerbated backward masking effect observed in the MPP task might be driven by the close perceptual similarity between the SSN signal and the SSN masker that may have been particularly problematic for the older listeners. In the speech-in-noise task, on the other hand, the speech signal might be sufficiently distinct perceptually from the SSN masker that the older listeners were less prone to signal-masker confusions, with the result that backward masking played less of a role in this task.

In summary, this study demonstrates that older listeners are more susceptible to non-simultaneous masking than younger and middle-aged listeners, particularly to backward masking. As a result, the derived temporal windows of the older listeners are more symmetric than those of younger adults. In terms of forward masking, older listeners show prolonged recovery functions relative to younger adults. For these older adults, it was possible to demonstrate an association between forward-masked thresholds and speech recognition in a modulated masker. Therefore, this study supports the hypothesis that increased susceptibility to non-simultaneous masking in older listeners reduces their ability to benefit from the momentary improvements in signal-to-masker ratio associated with masker minima, thereby contributing to their difficulties understanding speech in fluctuating backgrounds.

[1]The older listeners had participated in a study, to be reported separately, that included the measurement of masked speech recognition using HINT sentences. The SSN masker was either held steady at 65 dB SPL or was square-wave modulated between 65- and 30- dB SPL at a rate of 10 Hz. Presentation was monaural using Sennheiser HD 580 headphones. For each masker condition, the level of the target sentences were adaptively varied using a 2-down, 1-up stepping rule to determine a 71% correct threshold estimate. At least three estimates of threshold were collected for each listener and masker condition, with a fourth collected if the range of the first three exceeded 3 dB. The final threshold value was the average of all estimates.

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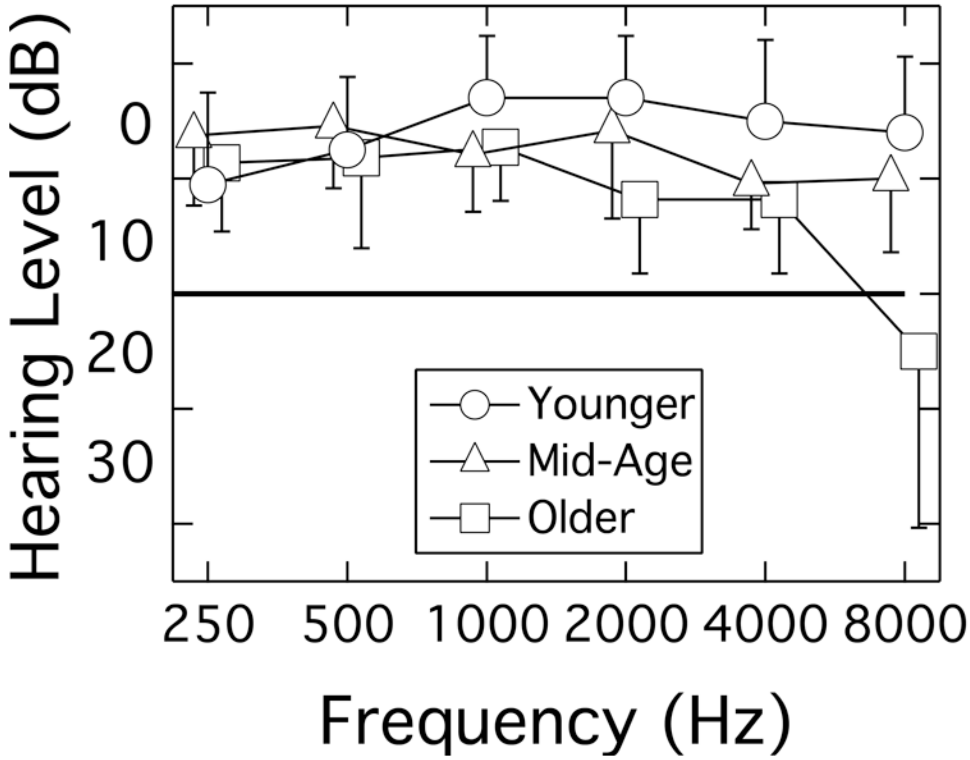

Fig. 1.

Group mean audiometric thresholds (dB HL) in the test ear for Younger (circles), Mid-Age (triangles), and Older (squares) listeners. Symbols have been offset horizontally for visual clarity. Error bars are 1 standard deviation (SD). The horizontal line at 20 dB HL demarcates the limit for clinically normal thresholds.

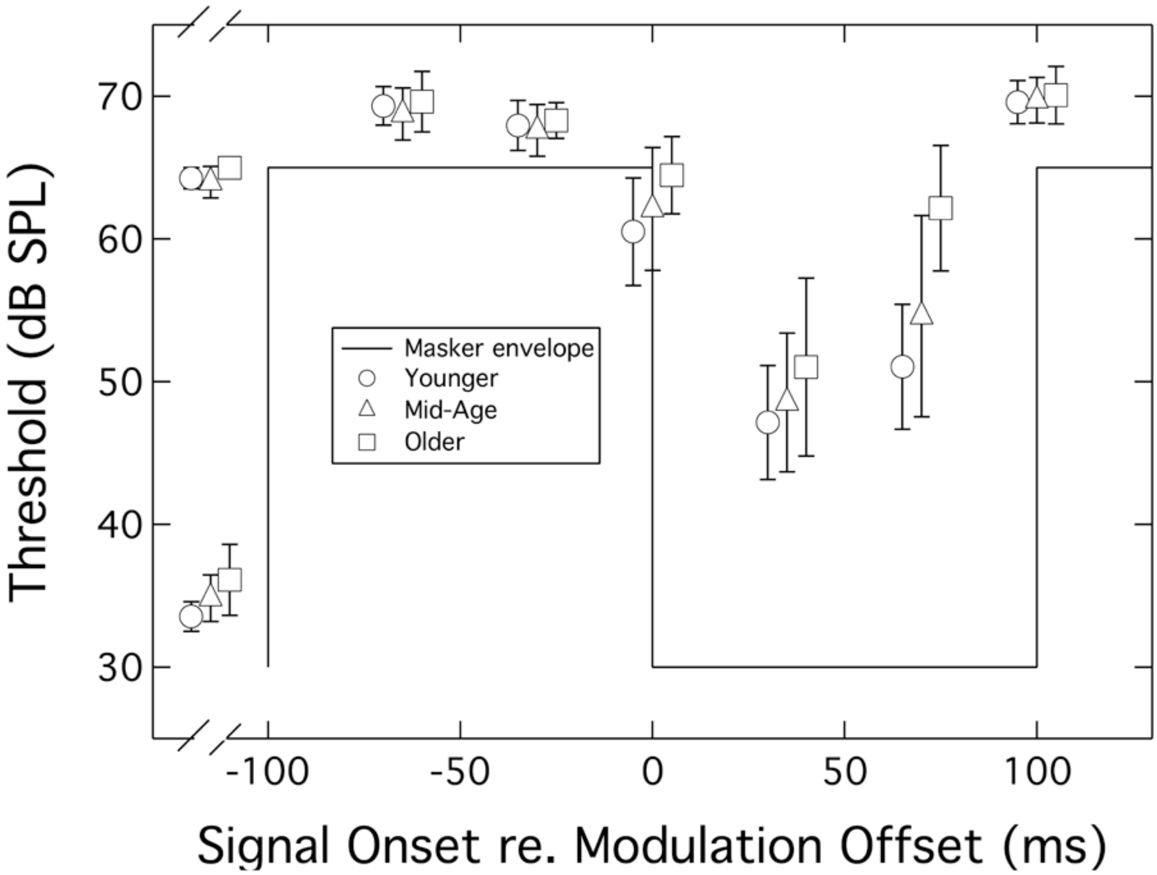

Fig. 2.

Group mean masked thresholds as a function of signal temporal position relative to the offset of a masker modulation cycle for Younger (circles), Mid-Age (triangles), and Older (squares) listeners. Baseline masked thresholds in the *Steady High* and *Steady Low* maskers are shown on the left aligned with the abscissa break. Symbols have been offset horizontally for visual clarity. Error bars are ±1 SD. The square-wave masker envelope is shown schematically as a solid line.

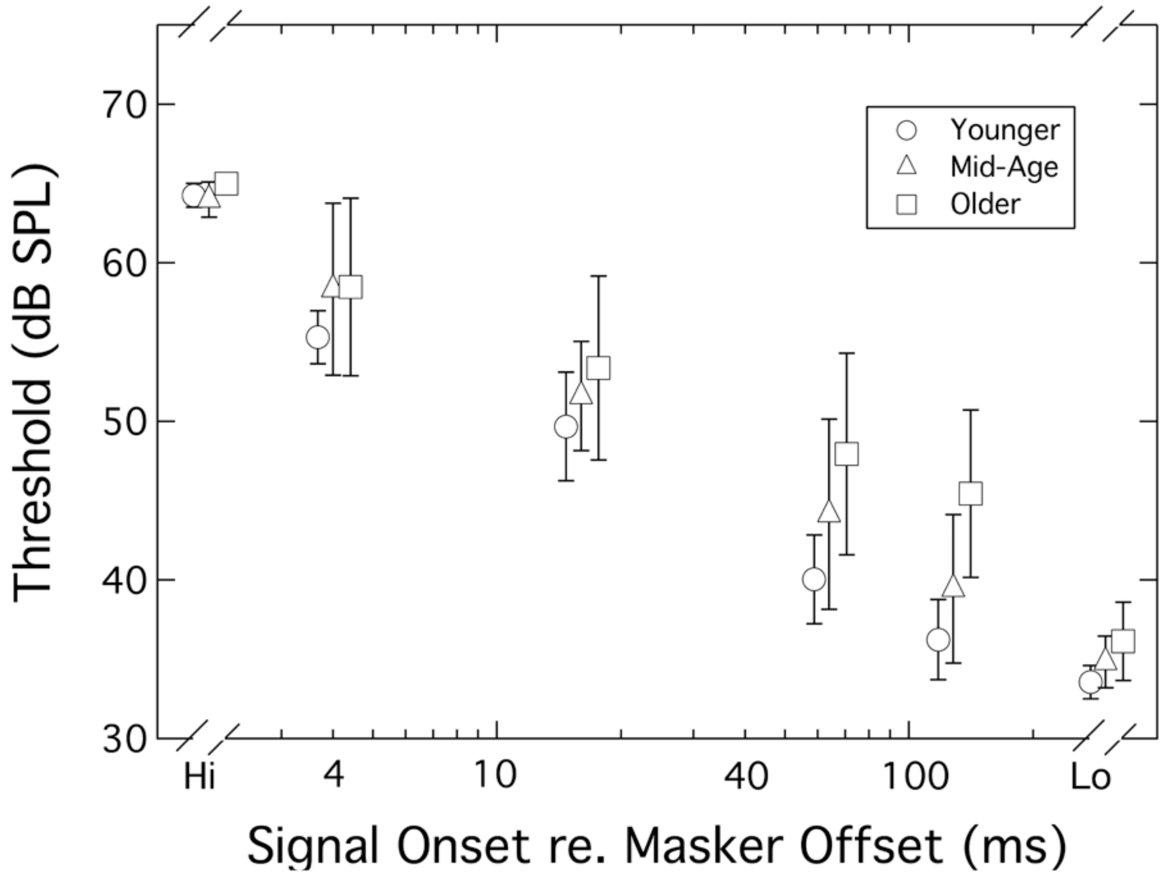

Fig. 3.

Group mean forward-masked thresholds as a function of the signal-masker interval for Younger (circles), Mid-Age (triangles), and Older (squares) listeners. Baseline masked thresholds in the *Steady High* masker are shown aligned with the left abscissa break; baseline thresholds in the *Steady Low* masker are shown aligned with the right abscissa break. Symbols have been offset horizontally for visual clarity. Error bars are ±1 SD.

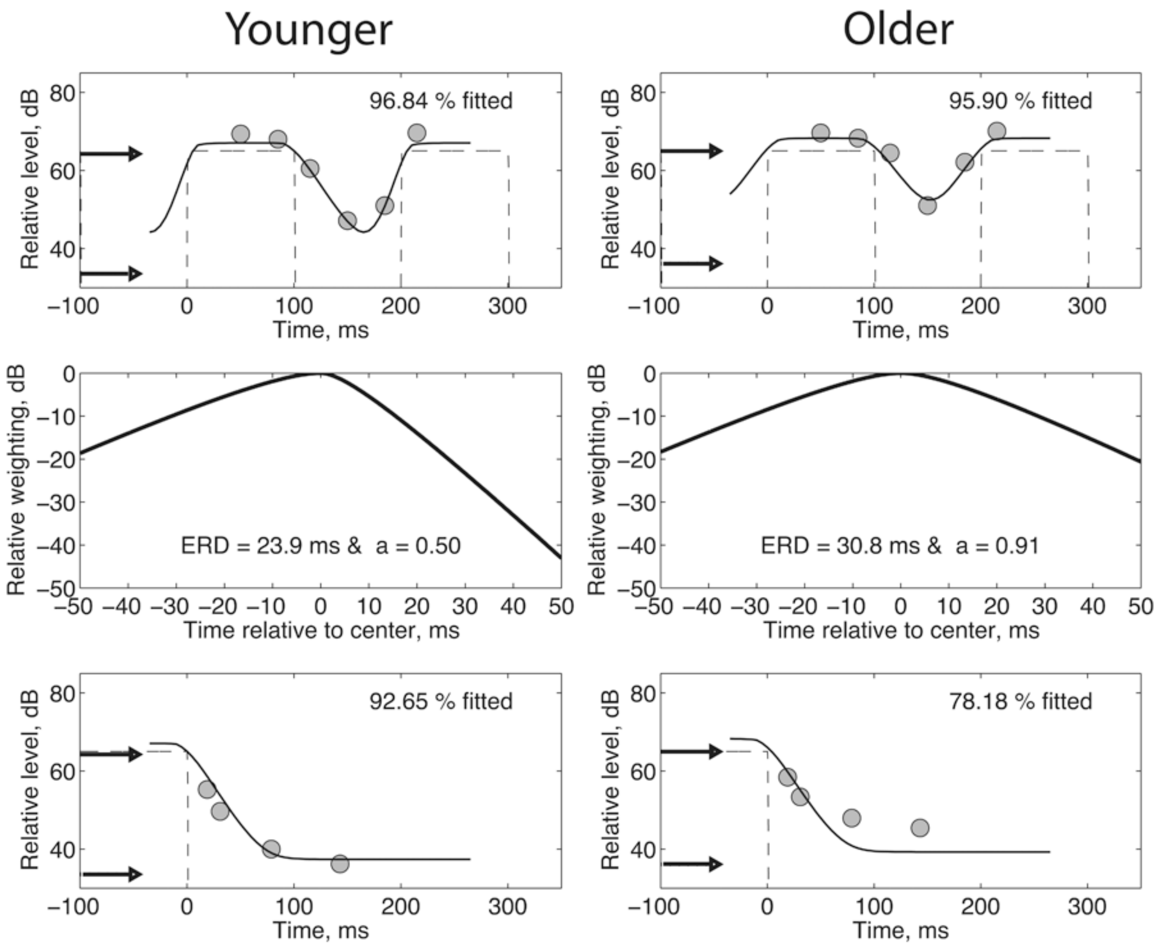

Fig. 4.

Temporal window fits for the average data of the Younger (left column) and Older (right column) groups. The upper row shows the mean masking period pattern (MPP) data (gray circles) relative to a schematic of the modulation cycle of the masker (dashed line). Arrows to the left indicate masked thresholds in the steady maskers. The solid line shows the fit to the data generated by the derived temporal window, and the percent variance accounted for is shown in the upper right corner. The middle row shows the actual temporal windows. The summary parameters of equivalent rectangular duration (ERD) and the slope ratio *a* are shown in each panel. The lower row shows the mean forward masking data (gray circles) relative to the offset of the masker (dashed line). The solid line shows the fit to the data generated by the derived temporal window, and the percent variance accounted for is shown in the upper right corner.

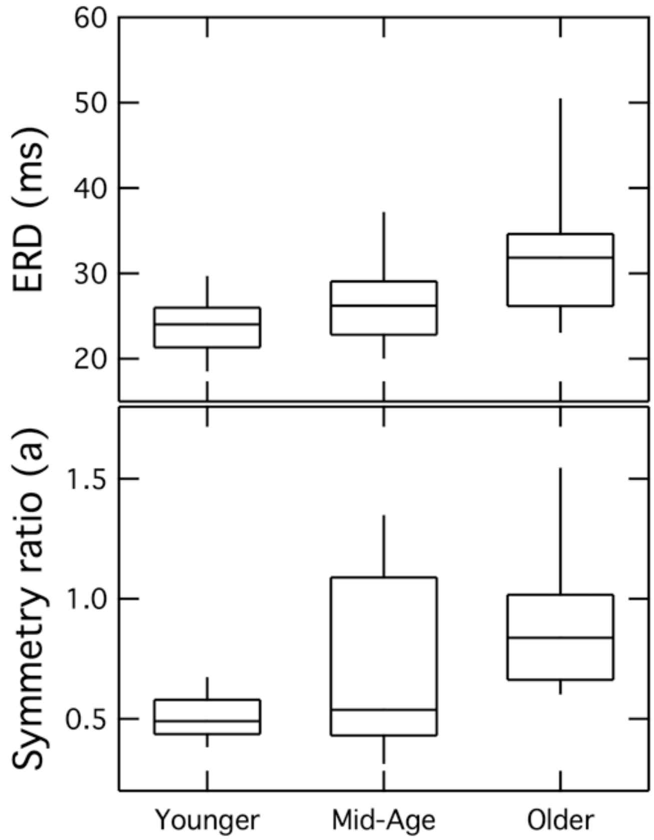

Fig. 5.
Distribution of ERD values (upper panel) and *a* values (lower panel) for the three age groups. Each rectangle extends from the 25th to 75th percentile, with the horizontal line indicating the median; each vertical line extends from the lowest to the highest individual value.

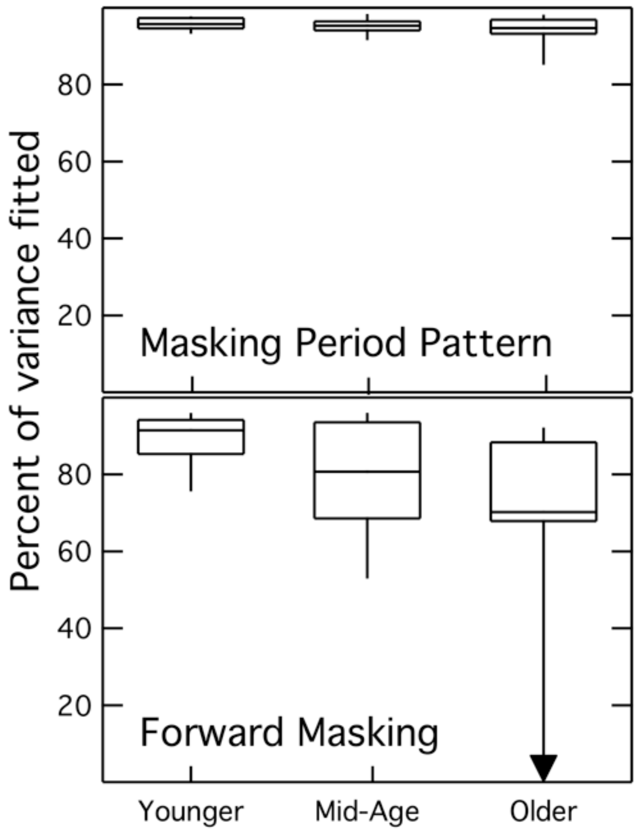

Fig. 6.

Distribution of variances accounted for by the temporal window fits for the MPP data (upper panel) and forward masking data (lower panel) for the three age groups. Each rectangle extends from the 25th to 75th percentile, with the horizontal line indicating the median; each vertical line extends from the lowest to the highest individual value, with the downward arrow indicating the extremely poor fit of one listener.