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An Examination of Speech Recognition in a Modulated Background and of Forward Masking in Younger and Older Listeners

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Abstract

Purpose—To compare speech intelligibility in the presence of a 10-Hz square-wave noise masker in younger and older listeners and to relate performance to recovery from forward masking.

Method—The signal-to-noise ratio required to achieve 50% sentence identification in the presence of a 10-Hz square-wave noise masker was obtained for each of the 8 younger/older listener pairs. Listeners were matched according to their quiet thresholds for frequencies from 600 to 4800 Hz in octave steps. Forward masking was also measured in 2 younger/older threshold-matched groups for signal delays of 2–40 ms.

Results—Older listeners typically required a significantly higher signal-to-noise ratio than younger listeners to achieve 50% correct sentence recognition. This effect may be understood in terms of increased forward-masked thresholds throughout the range of signal delays corresponding to the silent intervals in the modulated noise (e.g., <50 ms).

Conclusions—Significant differences were observed between older and younger listeners on measures of both speech intelligibility in a modulated background and forward masking over a range of signal delays (0–40 ms). Age-related susceptibility to forward masking at relatively short delays may reflect a deficit in processing at a fairly central level (e.g., broader temporal windows or less efficient processing).

Keywords

forward masking; effects of age; modulated noise; speech recognition

The National Institute on Deafness and Other Communication Disorders (NIDCD) reported that approximately one third of individuals over 60 years of age and over half of all individuals over 75 years live with a clinically significant hearing loss (NIDCD, 2001). Given those statistics, it is not surprising that a common complaint expressed by older individuals is difficulty understanding speech, particularly in a noisy background. However, recent research has shown that even those older listeners who have normal hearing sensitivity exhibit significant performance deficits on measures of speech recognition (Dubno, Horwitz, & Ahlstrom, 2002, 2003). Beyond the effects of reduced audibility, speech understanding is likely affected by an age-related impairment in temporal resolution (e.g., Gordon-Salant & Fitzgibbons, 1993, 1999; Humes & Christopherson, 1991; Schneider, Pichora-Fuller, Kowalchuk, & Lamb, 1994; Snell, 1997; Strouse, Ashmead, Ohde, & Grantham, 1998).

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One way to conceptualize temporal resolution is in the context of a temporal window model (e.g., Moore, Glasberg, Plack, & Biswas, 1988; Oxenham, 2001). The model incorporates bandpass filtering, level-dependent compression, a temporal window centered over the signal presentation, and a decision device. Cochlear hearing loss can influence temporal resolution, particularly by affecting the compression stage. Independent of hearing loss, however, age does not appear to affect this stage of processing. Gifford and Bacon (2005) examined several psychophysical measures thought to reflect nonlinear cochlear processing in younger and older listeners with matched audiograms. Measures of auditory filter shapes at low signal levels, suppression, and estimates of compression based on forward masking were not significantly affected by age. The authors did, however, report that older listeners with normal hearing consistently exhibited higher forward-masked thresholds than their younger counterparts. Given that the older listeners exhibited normal filtering and compression, Gifford and Bacon concluded that the origin of the age differences in forward masking was likely located at a central level of auditory processing. There are many studies detailing significant effects of age on measures of temporal processing (e.g., Fitzgibbons & Gordon-Salant, 1995, 1998, 2001; Gordon-Salant & Fitzgibbons, 1999; Strouse et al., 1998).

It is well known that speech understanding for listeners with normal hearing may be better in a temporally fluctuating masker than in a steady-state masker. This difference is reduced or absent in listeners with even mild forms of sensorineural hearing loss (e.g., Bacon, Opie, & Montoya, 1998; Festen & Plomp, 1990). A number of studies have examined the effects of age on speech intelligibility performance in a modulated noise masker (e.g., Dubno et al., 2002, 2003; Souza & Turner, 1994; Stuart & Phillips, 1996; Takahashi & Bacon, 1992). Takahashi and Bacon reported no effect of age once the effects of audibility were factored out statistically. Souza and Turner (1994) also reported no effect of age; however, the fluctuating masker that they used (multitalker babble) tends to produce smaller amounts of improvement relative to steady-state noise, thus it may not be as sensitive to potential effects of age. Stuart and Phillips (1996) and Dubno et al. (2002, 2003) reported a significant effect of age on speech recognition performance in a fluctuating background. The older listeners in these studies had higher quiet thresholds than the younger listeners (particularly for frequencies >2 kHz), raising the possibility that audibility differences may have influenced the results. To address this, Dubno et al. (2002, 2003) presented a low-level noise in older and younger listeners to equate audibility across participants. Although it is possible to equate audibility, this approach does not necessarily equate performance for tasks involving suprathreshold processing such as frequency selectivity (e.g., Dubno & Schaefer, 1991; Leek & Summers, 1993; Moore, Vickers, Glasberg, & Baer, 1997) and temporal resolution (e.g., Bacon et al., 1998; Henry & Grantham, 2000). Thus, any underlying pathology that may have contributed to differences in absolute thresholds between the younger and older listeners in Dubno et al. (2002, 2003) could have contributed to differences in speech recognition. In other words, the threshold-matching noise may control for audibility, but not necessarily for other effects of hearing loss.

There is thus some discrepancy in the literature regarding the effect of age (independent of audibility) on speech recognition in a temporally fluctuating background. On the one hand, Takahashi and Bacon (1992) found no effect of age once audibility was factored out statistically using partial correlations. On the other hand, Dubno and colleagues (2002, 2003) found an effect of age once audibility was controlled via noise masking. It is unclear whether the discrepancy is related to differences in the way in which audibility was controlled for in these studies or to some other methodological difference. In any event, it seems most reasonable to control for audibility by having younger and older participants with identical absolute thresholds. Moreover, to avoid potentially different underlying pathologies in younger and older hearing-impaired listeners, it could be argued that the best approach is to test younger and older listeners with normal absolute thresholds, effectively equating groups in terms of audibility and hearing loss. This was the approach used here to evaluate whether there is an effect of age on the ability to recognize speech in a modulated background.

Experiment 1A: Speech Recognition in a Modulated Masker

Participants

The younger and older participants with normal hearing in Gifford and Bacon (2005) also participated in the current study. All participants received a hearing evaluation including both air-conduction and bone-conduction pure-tone audiometry. Eight participants were assigned to each group. The mean age of the younger group was 25.6 years, with a range of 19–30 years. The mean age of the older group was 63.8 years, with a range of 60 to 75 years. All participants were native speakers of American English, and received an hourly wage for their participation. The criterion for inclusion was hearing thresholds ≤15 dB HL at audiometric test frequencies from 250 to 6000 Hz. Individuals from the two age groups were matched according to their quiet thresholds for 200-ms pure tones obtained in a two-interval forced-choice (2IFC) adaptive procedure with a 3-down, 1-up stepping rule to track 79.4% correct (Levitt, 1971). Pairs of younger and older participants were matched such that thresholds were within 5 dB of each other for 3 out of 4 frequencies in the range of 600–4800 Hz (in octave steps). The match was achieved at 1200 and 2400 Hz and at one of the adjacent octave frequencies (600 or 4800 Hz); thresholds were matched within 9 dB at the other adjacent octave frequency. Individual and mean quiet thresholds for all participants enrolled in the study are shown in Figure 1.

Stimuli, Conditions, and Procedure

Speech recognition was measured using the sentences from the Hearing in Noise Test (HINT; Nilsson, Soli, & Sullivan, 1994). The sentences were recorded from CD and played back on one channel of a digital audiotape (DAT) player (Sony 59ES). The DAT output was amplified (Crown D-75), attenuated (Wilsonics PATT), and routed monaurally to one channel of Sony MDR stereo headphones via a headphone buffer (TDT HB6). The sentences were presented in a broadband noise that was shaped to match the long-term spectrum of the HINT sentences (the same noise that is provided for use with the HINT). Sentence Lists 24 and 25 were combined to form a 20-sentence list that was used for all participants except Y8, the first author. This participant was well acquainted with these lists, so a separate researcher presented unfamiliar lists (Lists 16 and 17) to this participant.

The broadband noise was modulated with a 10-Hz square wave (modulation depth of 100%). The background noise was recorded and played on the second channel of the DAT player. The noise was fixed at an overall level of 70 dB sound pressure (SPL), and the level of the HINT sentences was varied adaptively to achieve 50% correct using a one-down/one-up stepping rule. Recognition of all key words for a given sentence constituted a correct response. The initial step size of 4 dB was decreased to 2 dB after the fifth sentence. The signal-to-noise ratio (SNR) corresponding to 50% correct was calculated as the mean of the last six presentation levels.[1]

Results and Discussion

The results for the older (unfilled bars) and younger (filled bars) listeners are shown in Figure 2. Except for Participant Pair 4, in which there was essentially no difference in the speech reception threshold (SRT) for the two listeners, the older listeners consistently required a more

[1]The repeatability of this method for obtaining a speech threshold in dB SNR was assessed in three newly recruited listeners with normal hearing. All three listeners were administered the HINT adaptively using the same 24 lists with the steady-state, speech-shaped noise provided with the test (using the same method as in Experiment 1A). For each of the three listeners, the 12 estimates of the speech reception threshold were extremely consistent. The standard deviations of the mean of these estimates ranged from 0.6 to 0.9 dB.

favorable SNR than their younger counterparts to achieve the same level of performance. On average, this difference was 5.5 dB. A one-way analysis of variance revealed a highly significant effect of age, $F(1,14) = 19.6$, $p < .001$. It is important to note that these same older listeners demonstrated essentially identical processing as their younger, threshold-matched listeners on measures of frequency selectivity, suppression, and psychophysical estimates of compression (Gifford & Bacon, 2005).

The higher SNR required for the older listeners in the present study suggests that age affects the amount of benefit one can derive from the momentary increases in the SNR that are present in the valleys of the modulated masker. This conclusion is based on the likelihood that these listeners would have performed similarly to one another in the presence of a steady-state masker. Although an SRT was not obtained in such a background, the majority of data has shown that speech recognition in the presence of a steady-state masker is essentially identical for younger and older listeners with similar hearing thresholds (Bacon et al., 1998; Dubno et al., 2002; Takahashi & Bacon, 1992).

The results reported here are consistent with those of Dubno et al. (2002, 2003), in which significant age-related differences on measures of speech recognition in the presence of a modulated masker were observed.

Experiment 1B: Forward Masking

Rationale

The 10-Hz square wave masker in Experiment 1A was modulated at 100%, suggesting that the masking of the speech in the valley or brief “off time” of the masker was likely governed by forward masking (e.g., Bacon & Lee, 1997; Gregan, Bacon, & Lee, 1998). The higher SNR in the older listeners is consistent with these listeners’ greater susceptibility to forward masking as shown in Gifford and Bacon (2005). In that study, forward masking was measured at only one short (5-ms) delay between masker offset and signal onset. Others (e.g., Dubno et al., 2002; Sommers & Gehr, 1998) have observed a similar effect. It is of interest to determine whether the greater susceptibility to forward masking exists throughout the silent interval of the modulated masker. Dubno et al. (2003) found higher forward-masked thresholds in older listeners at delays ranging from 10 to 100 ms. The quiet thresholds of their younger and older listeners were not, however, equated in their forward-masking experiment (i.e., the threshold-matching noise was not present), and indeed the authors concluded that the elevated forward-masked thresholds in the older listeners could be attributed to their elevated quiet thresholds. It is thus unclear whether older listeners with normal hearing will show elevated forward-masked thresholds at a range of delays following masker offset.

For a 10-Hz square wave, the silent period is 50 ms (one half the period). Thus, in the present experiment, forward masking was measured for delays from 2 to 40 ms. A delay closer to 50 ms was not used because it was assumed that at those delays, masking by a square-wave modulated masker might consist of a combination of forward and backward masking.

Participants

Two of the older listeners from Experiment 1A with normal hearing participated (O4 and O8). These listeners were chosen based upon their availability.[2] Fortunately, these two provide an interesting comparison, because O4 was the only older listener in Experiment 1A who performed as well as their younger counterpart (see Figure 2). Moreover, only O4 performed

[2]Every attempt was made to include all older listeners in Experiment 1B from Experiment 1A. Unfortunately, all but two of the participants were unavailable for follow up (reasons included moving out of state, death, and being “fed up” with laboratory testing).

as well as the younger listeners in general (compare O4's results with the average results from the younger listeners). Each older listener was paired with two younger listeners with whom they were matched according to their quiet thresholds for 200-ms signals—measured in a 2IFC adaptive procedure (as in Experiment 1A)—such that thresholds were within 5 dB for the masker (1675 Hz) and signal (2400 Hz) frequencies. Listener O8's younger match from Experiment 1A also participated. The rationale for matching two younger listeners to each older listener was to help control for individual differences, which are not uncommon in forward masking. Table 1 displays quiet thresholds for the two older listeners and their younger, threshold-matched counterparts. Thresholds for the 20-ms signals used in forward masking are also displayed in Table 1. The mean age of the younger participant group was 24.1 years, with a range of 18–30 years. The mean age of the older participant group was 64.5 years, with a range of 62–67 years. With the exception of Listener O4, who was male, all other participants in Experiment 1B were female.

Stimuli and Conditions

All stimuli were generated digitally using a digital array processor (TDTAP2) and output at a sampling rate of 50 kHz. The masker and signal were output through separate channels of a 16-bit digital-to-analog converter (DAC). The output of each channel was low-pass filtered at 8 kHz (TDT FT6-2), attenuated by separate programmable attenuators (TDT PA4), summed (TDT SM3), and routed monaurally to one channel of Sennheiser HD250 stereo headphones via a headphone buffer (TDT HB6).

Forward masking was measured for tonal maskers and signals. The signal frequency was 2400 Hz, and the masker frequency was 1675 Hz. The masker was thus three equivalent rectangular bandwidths (Glasberg & Moore, 1990) below the signal. The masker and signal frequencies were chosen to be consistent with the stimuli used by Gifford and Bacon (2005) in one of their forward-masking experiments. To some extent, these stimuli are roughly analogous to a self-masking situation in speech in which a lower frequency vowel can mask a higher frequency consonant. The masker level was fixed at 90 dB SPL, and the signal level was varied adaptively. The masker duration was 300 ms, and the signal duration was 20 ms, including 10-ms $\cos^2$ rise/fall times. Masker-signal delays (masker offset to signal onset) were 2, 5, 10, 20, and 40 ms. The order of testing across signal delays was quasi-random. Quiet thresholds for the 20-ms, 2400-Hz signal were also obtained (see Table 1).

Procedure

Participants were tested in a single-walled, sound-attenuating booth situated within an acoustically treated room equipped with an acoustically sealed, double-doorentry.[3] A 2IFC paradigm was used with a 3-down/1-up stepping rule to track 79.4% correct (Levitt, 1971). The observation intervals were indicated by lights on a response box. The tonal signal was presented randomly in one of two intervals. Participants responded by pressing the button on the response box corresponding to what they believed to be the signal interval. Visual feedback was provided indicating whether the response was correct or incorrect. A run consisted of 10 reversals; the threshold estimate was taken as the mean of the last 8 reversals. The initial step size of 5 dB was decreased to 2 dB after the second reversal. On the rare occasion that an estimate had a standard deviation greater than 5 dB, that run was discarded. All reported thresholds represent the mean of at least three estimates. If the standard deviation of the mean of those estimates was greater than 3 dB, one additional run was completed and averaged. This

[3]This testing environment was sufficiently quiet to allow threshold testing. For several normal-hearing participants tested in the Psychoacoustics Laboratory, there were no significant differences in quiet threshold obtained in this single-walled booth and those measured in a double-walled booth.

occurred for 8 out of the 90 thresholds obtained. Of those 90 thresholds, 86 (95.5%) had standard deviations less than 3 dB, and 67 (74.4%) had standard deviations less than 2 dB.

Results and Discussion

Forward-masked thresholds and the quiet thresholds for the 20-ms signal are shown in Figure 3. The filled and unfilled symbols represent the younger and older listeners, respectively. The two younger listeners matched to each older listener are denoted by separate symbols in each panel. First consider the results in the right panel. Listener O8 was the older listener whose SRT was worse than the matched younger listener in Experiment 1A. In general, O8's forward-masked thresholds were higher than those of the two younger listeners, except at the longest delay. Now consider the results from O4 (left panel). This was the listener whose SRT was comparable to their matched younger listener and, moreover, essentially equal to the average SRT across all younger listeners. The forward-masked thresholds for O4 were equal to those of one of the younger listeners. The other younger listener, however, had thresholds that were considerably lower. Indeed, that participant's forward-masked thresholds were lower than those of all other participants tested here. This may have been due to the fact that this participant had extensive experience with forward masking (>30 hr) from participating in other studies. Although the older listeners had also been participants in a previous study involving forward masking, they typically had <10 hr of listening experience in forward masking (Gifford & Bacon, 2005). Although there are only limited data here, the results suggest that the greater difficulty older listeners often have understanding speech in the presence of a time-varying background is associated with a greater susceptibility to forward masking.

General Discussion

As noted in the introduction, there is a discrepancy in the literature regarding the effects of age on speech recognition in modulated backgrounds. Takahashi and Bacon (1992) concluded that age did not have an effect, once audibility was taken into account. Dubno et al. (2002, 2003), on the other hand, reported that it did. Given that efforts to control differences in audibility may not control for differences in suprathreshold processing associated with various degrees of hearing loss, the present study chose to test younger and older listeners with normal hearing. They were paired based on thresholds that were within 5 dB of one another. The results showed that older listeners consistently required a more favorable SNR than the younger listeners to achieve 50% correct speech recognition in the presence of a modulated background. These results are thus more consistent with those of Dubno et al. (2002, 2003) than of Takahashi and Bacon (1992). It is not clear whether the differences across studies were due to the masker type (Dubno and colleagues used a square-wave modulated masker, as used here, whereas Takahashi and Bacon used a sine-wave modulated masker), the way in which audibility was controlled, or some other factor.

Given the temporal characteristics of the square-wave modulated masker used here, the speech recognition results are consistent with the fact that these and other older listeners tend to be more susceptible to forward masking (Dubno et al., 2002, 2003; Gifford & Bacon, 2005; Sommers & Gehr, 1998). Furthermore, Experiment 1B showed that an older listener who had an elevated SRT in Experiment 1A also had elevated forward-masked thresholds. It also showed that the one listener who had an SRT like that of the younger listeners tended not to have elevated forward-masked thresholds. Although limited, the data provide additional evidence for a connection between forward masking and speech recognition in temporally complex backgrounds, and thus are broadly consistent with previous results (Dubno et al., 2002, 2003).

In the context of the temporal window model, forward masking is believed to be influenced by nonlinear cochlear processing (e.g., Plack & Oxenham, 1998). Previous research with this group of older listeners, however, revealed no age-related difference in psychophysical measures thought to reflect nonlinear cochlear processing (Gifford & Bacon, 2005). Consequently, a more central level of processing is a more likely cause of the deficit. One possibility is a wider temporal window. Another possibility is that the higher masked thresholds in the older listeners reflect poorer auditory processing efficiency. This would result in a higher internal SNR needed to achieve masked threshold. Auditory processing efficiency is thought to be influenced not only by auditory processing but also by general cognitive factors such as attention, memory, and learning (Hartley & Moore, 2002; Patterson, Nimmo-Smith, Weber, & Milroy, 1982). Research on the effects of age on processing efficiency has been mixed. Moore, Peters, and Glasberg (1992) found processing efficiency to be affected by age in listeners with both normal and impaired hearing. Sommers and Gehr (1998) found processing efficiency to be affected by age in simultaneous masking, but not in forward masking.

Greater susceptibility to forward masking may help explain the difficulties experienced by older listeners in everyday communication situations. In the real world, the speech signal rarely exists in the absence of some type of background noise. Many environmental noises are intermittent in nature (e.g., speech from a single talker) and could be considered as both simultaneous and forward maskers. Even target speech from a single source could be capable of producing forward masking (i.e., a lower amplitude consonant being masked by a preceding higher amplitude vowel). Given that older listeners are particularly troubled by forward masking, virtually any communication environment can potentially become a difficult listening situation for an older listener—even one with normal hearing.

Summary and Conclusions

The primary goal of this study was to investigate the effects of age on speech recognition in a modulated masker (speech-shaped noise modulated by a 10-Hz square wave) and to relate those findings to forward masking. Significant differences between the age groups were observed in the SNR required to achieve 50% correct sentence intelligibility. The age-related deficit in the SRT appears to be related to a greater susceptibility to forward masking. Based on previous research with these older listeners, the greater susceptibility to forward masking probably does not reflect processing in the auditory periphery, but more likely reflects a change in central processing.

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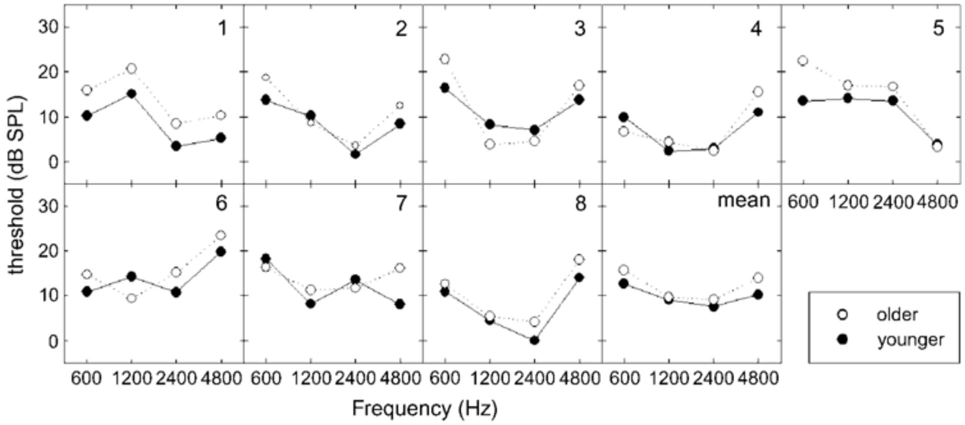

Figure 1.
Individual and mean quiet thresholds for a 200-ms signal for the younger (filled symbols) and older (unfilled symbols) listeners.

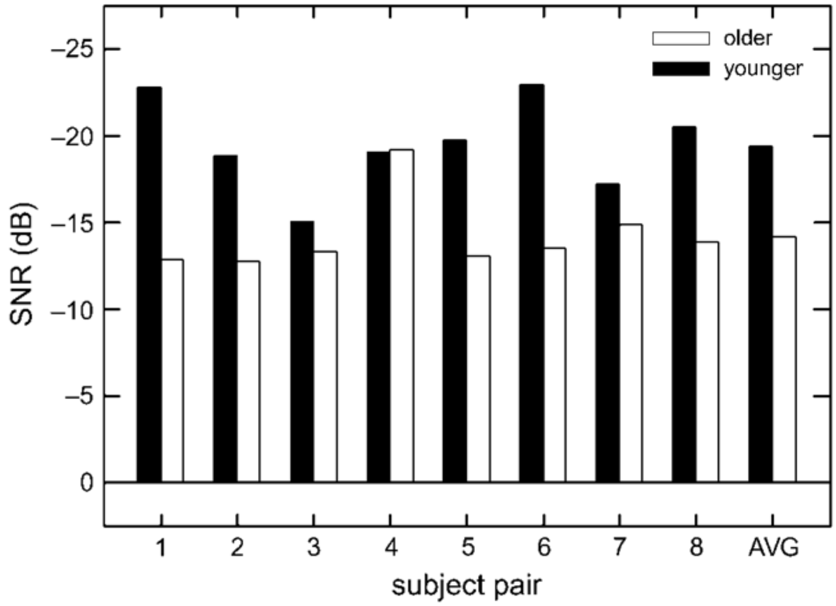

Figure 2.
Signal-to-noise ratio (SNR) required for 50% speech recognition performance in the presence of the 10-Hz square-wave modulated masker (100% modulation) for the younger (filled bars) and older (unfilled bars) listeners.

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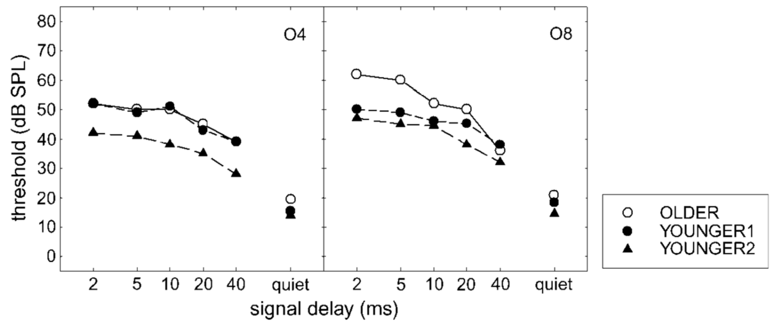

Figure 3.

Forward-masked thresholds for the two older (unfilled symbols) listeners and their two younger (filled symbols), threshold-matched counterparts. O=older.

Table 1

Quiet thresholds for the two older listeners and their younger, threshold-matched counterparts.

	Quiet Thresholds (dB SPL)		
Participant	**1675 Hz (200 ms)**	**2400 Hz (200 ms)**	**2400 Hz (20 ms)**
O4	10.1	6.2	19.5
Y1&Y4	12.1	5.1	15.3
Y2&Y4	15.1	1.8	13.9
O9	12.1	11.6	20.8
Y1&Y9	10.3	11.7	18.3
Y2&Y9	12.3	9.7	14.5
Older			
M	11.1	8.9	20.2
SD	1.4	3.8	0.9
Younger			
M	12.5	7.1	15.5
SD	2.0	4.5	2.0

Note. Quiet thresholds were obtained for 200-ms stimuli for both the signal (2400 Hz) and the masker (1675 Hz) frequencies. In addition, quiet thresholds for the 20-ms signal used in forward masking are shown in the last column. SPL = sound pressure level; O = older; Y = younger.