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Speech Comprehension Difficulties in Older Adults: Cognitive Slowing or Age-Related Changes in Hearing?

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Speech comprehension declines more rapidly in older adults than in younger adults as speech rate increases. This effect is usually attributed to a slowing of brain function with age. Alternatively, this Age × Speed interaction could reflect the inability of the older adult's auditory system to cope with speed-induced stimulus degradation. When the authors speeded speech in a way that produced minimal degradation, both age groups were equally affected. However, when speech was speeded using other methods, word identification declined more in older than in younger adults. Hence, auditory decline rather than cognitive slowing may be responsible for older adults' poorer performance in speeded conditions.

Keywords: speed of processing, speech recognition, aging, hearing, sensory–cognitive interactions

One of the most prevalent theories in aging research is that a generalized slowing in brain function with age is responsible for most, if not all, of the age-related declines in problem solving, reasoning, memory, and language (Cerella, 1990; Lindenberger & Baltes, 1994; Salthouse, 1985, 1993, 1996). According to this theory, slowing in brain functioning is thought to reduce the speed at which various cognitive operations can be performed. For example, it is generally assumed that the reason why older adults often find it difficult to understand someone who is talking rapidly, or fail to follow a conversation when there are multiple speakers, is that the rate of flow of information approaches or exceeds the maximum rate that can be accommodated by the cognitive processes involved in language comprehension (Wingfield, 1996; Wingfield, Poon, Lombardi, & Lowe, 1985).

Cognitive Slowing or Perceptual Decline?

The contribution of speed of processing in language comprehension has been studied by comparing the performance of younger and older adults when speech is artificially speeded (Fitzgibbons & Gordon-Salant, 1996; Gordon-Salant & Fitzgibbons, 1993, 1999, 2001; Vaughan & Letowski, 1997; Wingfield, 1996; Wingfield et al., 1985), and the typical finding has been that comprehension declines more rapidly for older adults than for younger adults, a result that is consistent with a generalized slowing hypothesis (Wingfield, 1996; Wingfield et al., 1985). However, there is another possible explanation as to why older adults find it more difficult to handle rapid rates of speech. Speeding speech, in addition to increasing the rate of flow of information, also tends to degrade and/or distort the speech signal (Gordon-Salant & Fitzgibbons, 1999). Therefore, it is possible that the reason why older adults are more affected by speeding is that the auditory systems of older adults are less able to handle these distortions than are the auditory systems of younger adults. Age-related declines in hearing have been well documented (see Schneider, 1997; Schneider & Pichora-Fuller, 2000, for recent reviews), and it has been shown that such declines contribute substantially to older adults' poorer comprehension and memory for connected discourse when listening is difficult (Humes, 1996; Schneider, Daneman, Murphy, & Kwong-See, 2000).

Thus, although there is convincing evidence that speeding speech has a more deleterious effect on older than on younger adults, the effect could be due to age-related declines in hearing or to a generalized slowing in the cognitive and linguistic functions that are required for good speech comprehension. Because older adults are experiencing declines in a number of auditory processing abilities, the stimulus degradation produced by speeding speech might be expected to produce delays or mistakes in phoneme or word recognition that are more severe in older than in younger adults (Pichora-Fuller, Schneider, & Daneman, 1995; Schneider, Daneman, & Pichora-Fuller, 2002). These early (sensory) problems may then cascade upward and lead to poorer comprehension and/or memory for the information being conveyed. Alternatively, it could be that the degree of auditory decline with age is not severe enough to impair the reception of speeded speech but that there is a slowing in semantic and/or linguistic processing.

How then can we determine whether the Age × Speed interaction results from age-related declines in the speed of cognitive processing or from age-related declines in the ability to process auditory signals that have been distorted by speeding? First, we

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note that if older adults have a lower limit than younger adults for the rate at which information can be processed, we will always observe an Age × Speed interaction. For example, if the upper rate limit at which younger adults can process speech information without error is x units of information per second, whereas the upper limit for older adults is y units per second ($x > y$), then the performance of older adults will begin to decline when the rate of information flow exceeds y, whereas the performance of younger adults will not decline until the rate of information flow exceeds x. Thus, when speech is speeded, comprehension will begin to decline in older adults before it does in younger adults, leading to an Age × Speed interaction.

We also note that if it is more difficult for an older adult's deteriorating auditory system to compensate for the distortions introduced by speeding than it is for a younger adult's auditory system, comprehension will begin to decline at a lower rate of speed for older adults than it does for younger adults. The inability of an aging auditory system to handle speed-induced distortions means that mistakes in phoneme or word recognition would begin to occur in older adults at a lower speed than they would in younger adults. Hence, we would expect an Age × Speed interaction if there were age-related declines in the ability to process speed-distorted signals.

Because both age-related changes in cognitive processing speed and age-related changes in the ability to handle speed-induced acoustic distortion can lead to an Age × Speed interaction, it becomes difficult to determine the source(s) of this interaction. The only conditions under which we would not observe an Age × Speed interaction are when there are no age-related differences in cognitive processing speed and no age-related differences in the ability to compensate for the acoustic distortions resulting from speeding speech.

The obvious way to approach this problem is to find older adults with auditory systems equivalent to those of younger adults. However, it is very difficult, if not impossible, to do this given that there are age-related declines in virtually every auditory ability (Schneider, 1997). Hence, even when older adults are matched to younger adults with respect to hearing thresholds (e.g., Tun, 1998), they may not be matched with respect to other auditory abilities. Often, the best that can be done in comparing performances across age groups is to make it equally difficult for older and younger adults to correctly perceive individual words when these words are unsupported by context. In previous work using unspeeded materials, we (Schneider et al., 2000) have found that, when we equate younger and older adults with respect to perceptual difficulty, age-related differences in comprehension and memory for connected discourse tend to disappear. Hence, before speeding the speech material, we first made it equally difficult for younger and older adults to hear individual words in the unspeeded condition.

To equate younger and older adults with respect to perceptual difficulty in the present experiment, we presented the speech signal in a noise background whose level was adjusted to make it equally difficult for younger and older adults to identify individual words in the unspeeded condition when there was no contextual support to aid in identifying these words. The speech materials used were the sentences from three of the lists in the Revised Speech Perception In Noise (R-SPIN) Test (Bilger, Nuetzel, Rabinowitz, & Rzeczkowski, 1984). This test was chosen because it has been standardized so that performance is comparable across lists and because of its extensive use in the lab and in the clinic. Sentences, spoken by a male speaker, were presented in a background babble consisting of 12 talkers speaking simultaneously. The listeners' task was to identify the last word of each sentence immediately after they heard it. Sentences were of two types: those in which the last word was predictable from the sentence context (e.g., "The witness took a solemn oath") and those in which the last word could not be predicted from sentential context (e.g., "John hadn't thought about the oath"). There were 25 high- and 25 low-context sentences in each list. On the basis of the results of previous studies, we selected signal-to-noise ratios (SNRs) that we expected would produce approximately 80% correct identification of the low-context words in both younger and older adults when the R-SPIN sentences were unspeeded. This meant that younger adults listened to the R-SPIN sentences at an SNR that was lower than that presented to older adults.

Given that younger and older adults are equated with respect to their ability to hear individual words in the unspeeded condition, we would expect the performance of older adults to decline more rapidly than that of younger adults when the R-SPIN sentences are speeded if (a) there are age-related declines in cognitive processing speed and/or (b) if older adults are more sensitive to speed-induced acoustic distortion than are younger adults. To distinguish between these two possibilities, we explored different methods of speeding speech to produce different degrees of speed-induced distortion.

Consider first what we would expect if older adults are more sensitive than younger adults to speed-induced acoustic distortion and if their cognitive processing speed is slower than that of younger adults (Hypothesis 1). We first note that we should always observe an Age × Speed interaction because of cognitive slowing. Moreover, if we speed speech in such a way that it is much more difficult for older adults to hear the speed-distorted words than it is for younger adults, the Age × Speed interaction should be larger. If, on the other hand, we can speed speech in such a way that it is equally detrimental to both younger and older adults to hear the speed-distorted words, the differential effect of speed on the two age groups should be substantially reduced. In other words, the extent of the Age × Speed interaction should be modulated by the method of speeding.

Of course, it could be the case that the contribution of age-related sensory deficits to the speeded-speech effect are negligible and that the Age × Speed interaction is mediated primarily by cognitive slowing (Hypothesis 2). If this were the case, then changing the degree of speed-induced distortion should have a negligible effect on the Age × Speed interaction. Nevertheless we should still observe an interaction because of cognitive slowing.

A third possibility is that there are no differences in cognitive processing speed between younger and older adults and that the Age × Speed interaction is due solely to speed-induced acoustic distortion (Hypothesis 3). If this hypothesis were true and one of the methods of speeding successfully eliminated age differences in the effects of speed-induced acoustic distortion, we would expect to find younger and older adults to be equally affected by speeding. In other words, we should not observe an Age × Speed interaction. Finally, if there are no age differences in cognitive processing speed and no age differences in sensitivity to speed-induced acoustic distortion, we should not observe an Age × Speed interaction in any of the speeded conditions (Hypothesis 4).

Methods of Speeding

The first method that we used to increase speed eliminated every *n*th amplitude sample in a digitized version of the speech signal.[1] In general, speeding speech by eliminating every *n*th amplitude sample (a) shifts the energy into a higher frequency range (removing every *n*th amplitude value shortens the period of every sinusoid in the speech signal, thereby translating all frequencies upward), (b) speeds up all transitions, and (c) shortens all gaps (periods of silence or relative silence in the speech signal). These three consequences might prove to be particularly difficult for older listeners to handle given their loss of high-frequency sensitivity and their declines in temporal resolution (Fitzgibbons & Gordon-Salant, 1996; Schneider & Pichora-Fuller, 2001).

In the second method for speeding speech, we speeded the rate of flow of information by segmenting the speech signal into 10-ms segments and eliminating every third segment. Note that this method, which is the one most frequently used in the literature (Wingfield et al., 1985), increases speed without a frequency shift but removes speech segments without regard to their informational content. For example, if 10-ms segments are removed during a formant glide, discontinuities are introduced into the glide, and glide rate is increased. If segments are removed during a stop consonant, the duration of the stop is shortened. Such removals may affect which phoneme is heard.

In the third method, we increased speed by the same amount without distorting the transitional information. We did this by examining the speech signal to locate steady-state portions. These could be pauses or gaps between words or syllables, or portions of a steady-state vowel. Whenever possible, we removed or shortened pauses between words and portions of steady-state vowels. We also avoided excising material where there were transitions. However, sometimes it was necessary, after pauses and portions of steady-state vowels were removed, to shorten bursts and excise initial and terminal portions of transitions, especially at the higher speeds. In this way, transitions were by and large preserved, and there were no frequency shifts. Gordon-Salant and Fitzgibbons (1999) have argued that there is convergent evidence that “older listeners have difficulty following the rapidly changing acoustic elements in a speech sequence” (p. 301), and they have shown that older adults find it especially difficult to deal with selective time compression of consonants (Gordon-Salant & Fitzgibbons, 2001). By leaving the transitions relatively intact while speeding the speech, we thought to minimize the effects of speeding on the aging auditory system.

In Experiment 1, each listener heard one of the lists presented at normal speed, one that was speeded to one and a half times the normal rate by deleting every third amplitude value and one that was speeded to one and a half times the normal rate by deleting steady-state portions of the signal. On the basis of previous data (Pichora-Fuller et al., 1995), we selected SNRs of 3 dB for younger adults and 8 dB for older adults to equalize the performance of the younger and older participants at a value that was significantly less than perfect performance for the low-context items in the unspeeded condition. Under quiet conditions, and at normal speech rates, both younger and older adults with good hearing perform at or near ceiling. However, if there are subclinical age-related declines in auditory processing, the auditory systems of older adults may be functioning at or near capacity whereas the auditory systems of younger adults are not being stressed at all. Hence, when speech is speeded in a quiet background, the auditory systems of younger adults may have excess capacity that would allow them to handle the inevitable distortions introduced by speeding, whereas the distortions introduced by speeding may overwhelm the auditory systems of older adults. To equalize performance on the baseline (unspeeded) condition, and to place younger and older adults on an equal perceptual footing, we tested both groups in a background babble whose level was adjusted to produce equivalent performance on low-context sentences for unspeeded speech. Experiment 2 was the same as Experiment 1 except that the condition in which the speech was speeded by deleting every third amplitude sample was replaced by a condition in which the speech was speeded by deleting every third 10-ms segment of speech. In Experiment 3, each listener heard one of the lists presented at normal speed and the other two lists speeded by deleting steady-state portions of the signal to produce speeds one and a half and two times the normal rate.

Method

Participants

In each of three experiments, independent groups of 12 younger and 12 older adults, whose first language was English, were tested. The older adults were volunteers from the local community; the younger participants were recruited from students and staff at the University of Toronto at Mississauga. None of the participants had any history of hearing disorders, and none used hearing aids. All participants were paid $10 an hour for their participation and had pure-tone, air-conduction thresholds less than or equal to 25 dB HL (the dB elevation in the listener’s threshold above what is normal for healthy young adults) between 0.25 and 3.00 kHz (American National Standards Institute S3.6-1989) in the right ear (exceptions are listed in Table 1), with interaural differences less than or equal to 15 dB at each frequency. Although listeners with hearing in this range are usually referred to as having normal hearing, the hearing of older adults is by no means equivalent to that of younger adults. Older adults’ average thresholds are 8–10 dB poorer than those of younger adults for frequencies less than or equal to 2 kHz. For frequencies greater than 2 kHz, threshold differences increased and differed by as much as 40 dB at the highest frequency tested (8 kHz). This audiometric pattern is typical of older adults whose hearing is considered to be clinically normal. In general, their thresholds are significantly increased at higher frequencies, and they are suffering from a number of anomalies with respect to temporal processing (Fitzgibbons & Gordon-Salant, 1996; Schneider & Pichora-Fuller, 2001; Wingfield, 1996; Wingfield et al., 1985). The average age, years of formal education, Mill Hill Vocabulary scores (which assessed general language functioning; Raven, 1965), and number of exceptions to the hearing criteria of each of the participant groups are given in Table 1.

Apparatus and Stimuli

The unspeeded stimuli were digitized versions (sampling rate = 20 kHz) of Lists 1, 3, and 5 of the revised R-SPIN Test (Bilger et al., 1984). The average speech rate across the three lists was 216.4 words per minute. Five different versions of each list were created. Version 1 was the unadulterated list. In Version 2, each R-SPIN sentence was speeded by removing every third amplitude sample (time compression ratio of 33%, speech rate of 324.6 words per minute). To accomplish this, we first extracted digitized

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[1] This method of speeding has not been used to study how age affects the recognition of speeded speech. It is introduced here to illustrate how the differential sensitivity of younger and older adults to speed-induced distortions affects their ability to recognize words.

Table 1

Mean Age, Years of Education, Mill Hill Vocabulary Scores, and Number of Participants Who Had Hearing Levels at One Frequency Only That Were Greater Than 25 dB HL But Less Than or Equal to 35 dB HL in the Right Ear

	Age		Education		Mill Hill vocabulary scores		Hearing criterion exceptions
Experiment	*M*	Range	*M*	*SD*	*M*	*SD*	
1							
Young	20.67	19–23	15.42	1.16	14.50	1.45	0
Young SNR +8[a]	21.00	20–23	16.17	1.27	12.92	2.43	0
Old	71.17	65–79	14.33	2.50	15.17	2.12	3
2							
Young	22.00	20–24	16.67	1.87	13.50	1.83	1
Old	68.25	65–74	14.17	4.32	14.25	2.30	1
3							
Young	20.67	19–23	15.25	1.76	14.08	1.78	1
Old	72.25	65–84	13.50*	2.32	16.17**	2.04	1

Note. HL = the dB elevation in the listener's threshold above what is normal for healthy young adults.
[a] The control group of young participants in Experiment 1 tested at a signal-to-noise ratio (SNR) of +8.
* significant age difference at $p = .05$. ** significant age difference at $p = .01$.

sentences from the list. Then every third amplitude value from the digitized sentences was discarded. Before the shortened sentence was replaced in the digitized list, zero amplitude values were added to the beginning and end of the sentence (zero padding by equal amounts at both ends) to restore the extracted segment to its original length. The speeded extract was then reinserted in the R-SPIN list at the same position from which it was extracted. Note that neither the position of the speeded sentence in the list nor the time between sentence midpoints was affected.

In Version 3, the digitized sentence was divided up into adjacent 10-ms segments (10 ms = 200 amplitude samples). Then every third 10-ms segment was deleted. After zero padding, the shortened sentences were put back into the list. Again, neither the position of the sentence in the list nor the time between sentence midpoints was affected by the shortening.

In Version 4, each R-SPIN sentence was speeded by removing steady-state segments from each sentence. In constructing the Version 4 sentences, we first displayed the sound spectrogram of an extracted sentence. The technician then identified steady-state portions of the sentence. These typically were parts of the sentence where sound was absent or where there was relatively little change in the sound's spectral content. The technician then shortened these steady-state components by removing material from their centers, taking care to always make the cuts at zero crossings (points on the amplitude waveform where the amplitude switched from positive to negative or vice versa) to minimize transient effects. After removing a segment, the technician then listened to the shortened sentence to ensure that the removal had minimal effects on phoneme recognition. Approximately the same portion of sound was removed from each part of the sentence. In Version 4, as in Versions 1 and 2, the sentence was shortened by one third. After zero padding, the shortened sentences were then reinserted into the list. Again, neither the position of the sentence in the list nor the time between sentence midpoints was affected by the shortening. Version 5 was constructed in the same fashion as Version 4 but with half of the sentence removed, so that the duration of the sentence was shortened by one half (time compression ratio of 50%, speech rate = 432.8 words per minute).

The background babble that accompanied each list was also sampled at a rate of 20 kHz and was left unmodified. All versions of the list were presented at a signal-to-babble ratio of 8 dB for older adults (the standardized procedure for the administration of R-SPIN) and 3 dB for younger adults in an attempt to produce equal performance levels in the unspeeded condition with respect to the low-context words. The sentences and babble were then converted to an analog signal by means of the Tucker-Davis Technologies (Alachua, FL) A-D converter under the control of a personal computer and presented to the right ear over a Telephonics (Huntington, NY) TDH-49 headphone to the participant who was seated in a double-walled sound-attenuating chamber. The lists were presented at a level that was 50 dB above each participant's threshold for detecting speech babble. (The standard procedure in the R-SPIN Test is to present the sentences 50 dB above the listener's babble threshold to ensure equal audibility across listeners.)

Procedure

During a session, each participant read and signed the consent form, took the Mill Hill Vocabulary Test, and had their audiometric thresholds determined. Following this step, each person's babble threshold was determined using an adaptive two-interval forced-choice procedure. In this procedure, a babble segment was presented in one of two randomly chosen intervals (the other interval was empty). The two intervals, which began 1.5 s after the listener pressed a button, were each 1.5 s long and were separated by a 1.5-s silent period. Lights on the button box indicated the occurrence of each interval, and the listener's task was to identify the interval containing the babble segment by pressing one of two buttons. Immediate feedback was provided. An adaptive staircase procedure (Levitt, 1971) was used to determine babble threshold (the sound pressure level corresponding to the 79% point on the psychometric function). This babble threshold was used to determine the sound pressure level of the R-SPIN sentences.

Following a brief break, each participant listened to each of three lists in a different random order, with the order in which each participant experienced the three lists being completely counterbalanced across participants. In Experiment 1, one of the three lists was unspeeded (Version 1), one was speeded by a factor of one and a half by deleting every third amplitude value (Version 2), and one was speeded by a factor of one and a half by deleting steady-state segments (Version 4). In Experiment 2, one list was unspeeded (Version 1), one was speeded by a factor of one and a half by deleting every third 10-ms segment (Version 3), and one was speeded by a factor of one and a half by deleting steady-state segments (Version 4). In Experiment 3, one list was unspeeded (Version 1) and the other two were speeded by factors of one and a half and two by deleting steady-state segments (Versions 4 and 5, respectively).

Participants were encouraged to take a short break between lists. Occasionally, older adults asked to break the session into 2 days. When that was done, the three lists were presented in the second session. There were no observable differences in performance between those participants tested on 1 day versus over 2 days in any of the experiments. Participants were asked to identify the word immediately after hearing the sentence and specify if the last word was predictable or not from the sentence context.

Statistical Analyses

In Experiments 1 and 2, three preplanned t tests were conducted. The first evaluated whether we were successful in matching performance across age groups in the unspeeded condition. The second determined whether there was a significantly greater reduction in performance in the older than in the younger participants due to speeding by removing every third amplitude segment, whereas the third determined whether there was a greater reduction in performance in the older than in the younger participants due to speeding by deleting steady-state segments. Previous experiments (Gordon-Salant & Fitzgibbons, 1995, 1999, 2001; Stine & Wingfield, 1987; Tun, 1998; Tun, Wingfield, Stine, & Mecsas, 1992; Vaughan & Letowski, 1997; Wingfield et al., 1985; Wingfield, Tun, Koh, & Rosen, 1999) involving Age × Speed interactions indicated an average effect size[2] in the intermediate range (Cohen's $f^2 = 0.08$). Given an effect size of this magnitude, the a priori power of the t test for interaction was estimated to be .59 ($\alpha = .05$, one-tailed). Hence, given the average effect size found in previous experiments investigating Age × Speed interactions, the likelihood of detecting an age difference in the extent of the reduction due to speeding by eliminating every third amplitude value or by eliminating steady-state segments is .59. However, because Experiments 1, 2, and 3 included three independent tests of whether older adults were more susceptible than younger adults to speeding by a factor of one and a half, the power obtained by combining the results of these three experiments for this speeding condition rises to .95. Because Experiment 3 was a three-factor, completely crossed design, with speed and context as within-subject factors and age as a between-subjects factor, the data were subjected to a three-factor analysis of variance (ANOVA). Assuming an effect size of 0.08 (Cohen's f^2) for the interaction between age and speed and a Type I error of .05, the a priori power of detecting an Age × Speed interaction is .83 in this design. The probability of observing a main effect of age when Cohen's f^2 equals 0.08 is 0.89.

Experiment 1: Results and Discussion

Figure 1 (top left) shows that when the low-context sentences were presented at a normal rate of speed, younger adults performed slightly (72.33%) but not significantly worse (77.67%) than older adults, $t(22) = -1.53$, $p = .139$, two-tailed. Hence, our attempt to match the two age groups with respect to performance on low-context items by presenting the sentences to younger adults at a lower SNR (3 dB) than the same sentences presented to older adults (8 dB) can be considered as roughly successful. Figure 1 (top left) also shows that when the low-context sentences were speeded by deleting every third amplitude sample, older adults experienced a much greater drop in performance (34 percentage points) than did younger adults (18 percentage points). This was confirmed by a t test which showed that the decline in performance in older adults due to speeding was significantly greater than the decline in performance in younger adults due to speeding, $t(22) = 3.44$, $p = .001$, one-tailed.[3]

Figure 1 (bottom left) shows that both younger and older adults were correctly identifying the last word in the sentence when there was contextual support nearly 100% of the time. However, when the high-context sentences were speeded by deleting every third amplitude sample, older adults recognized significantly fewer words than younger adults. This was also confirmed by a t test which showed that the decline in performance in older adults due to speeding was significantly greater than the decline in performance for younger adults, $t(22) = 4.46$, $p < .001$, one-tailed. Hence, for both low- and high-context sentences, speeding speech by deleting every third amplitude sample has a much more deleterious effect on older than on younger adults.

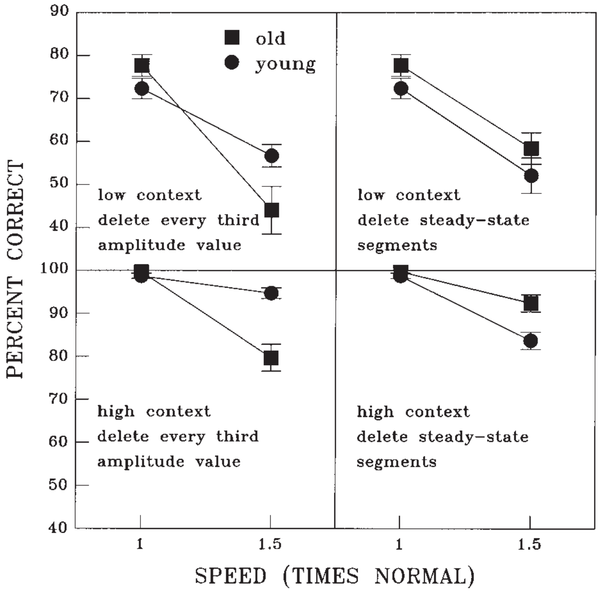

Figure 1. Percentage correct identification of the final word in a sentence as a function of the degree of speeding for younger (circles) and older (squares) adults. The sentences in the left panels were speeded by deleting every third amplitude sample. The sentences in the right panels were speeded by deleting steady-state segments. The results for low- and high-context sentences are shown in the top and bottom panels, respectively. Error bars represent standard errors.

When the speech was speeded by the same amount by removing steady-state portions of the speech signal, younger and older adults were equally affected by this method of speeding for low-context sentences (see Figure 1, top right), $t(22) = -0.17$, $p = .568$, one-tailed. However, for high-context sentences (see Figure 1, bottom right), the same method of speeding seems to have a lesser effect on older than on younger adults, $t(22) = -2.64$, $p = .015$, two-tailed.[4] Thus, although older adults find it more difficult than younger adults to process the signal when it is speeded by deleting every third amplitude sample for both low- and high-context sentences, older adults are not especially disadvantaged vis-à-vis younger adults on low-context sentences when the signal is speeded by deleting steady-state portions of the signal, and they appear to be significantly less affected by speeding when there is contextual support for identifying the sentence final word. This latter result, however, could be due to ceiling effects because both

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[2] For each experiment, Levin's (1997) method was used to estimate ω^2. These ω^2 values were then converted to Cohen's (1988) f^2 and averaged to obtain an estimate of the average effect size.

[3] A one-tailed test was used here because the research hypothesis was that the decrement in performance should be greater in older than in younger adults.

[4] A two-tailed test was used in this instance because the result is in the opposite direction to our prediction.

younger and older adults are at ceiling when high-context sentences are presented at a normal speed. Hence, when sentences are speeded by deleting steady-state portions, a procedure that preserves pitch and formant transitions, there is no evidence that older adults are more affected by speeding than younger adults.

However, before we can conclude that the Age × Speed interaction is eliminated if we speed speech by deleting steady-state portions of the sentence, we must consider a possible alternative explanation. The fact that the performance of older adults was slightly but not significantly better than that of younger adults in the normal speed condition for low-context items (see Figure 1, top left) means that older adults had a greater potential range of decline than younger adults. To see whether this factor could account, in part, for the pattern of results in Experiment 1, we tested an additional group of 12 younger adults (see Table 1) at an SNR of 8 dB. The performance of these two young groups (one tested at an SNR of 3 dB, and the other tested at SNR of 8 dB) on low-context sentences is shown in Figure 2 (top panels). Increasing the SNR by 5 dB boosted performance of younger adults by 13 percentage points in the unspeeded low-context condition, $t(22) = 4.48$, $p < .001$, two-tailed, to the point where they were outperforming the older adults who were also tested at an SNR of 8 dB, $t(22) = 2.53$, $p = .018$, two-tailed. However, there was no indication in younger adults that SNR affected the extent of decline for low-context sentences when speech was speeded by deletion of every third amplitude value, $t(22) = 0.66$, $p = .516$, two-tailed, or when it was speeded by deleting steady-state segments, $t(22) = 0.16$, $p = .874$, two-tailed. Hence, the relative position of older and younger adults in the unspeeded condition for low-context sentences had no effect on the extent of decline due to speeding.

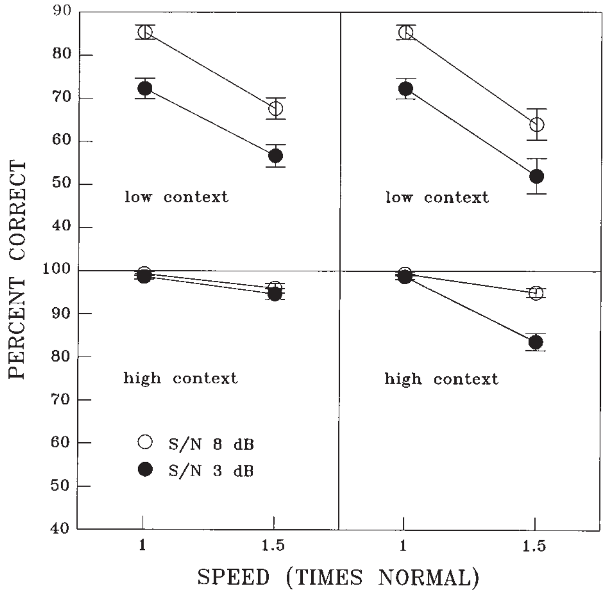

Figure 2. Percentage correct identification of the final word in a sentence as a function of the degree of speeding for younger adults tested at signal-to-noise (S/N) ratios of 3 dB (filled circles) and 8 dB (unfilled circles). The sentences in the left panels were speeded by deleting every third amplitude sample. The sentences in the right panels were speeded by deleting steady-state segments. The results for low- and high-context sentences are shown in the top and bottom panels, respectively. Error bars represent standard errors.

Figure 2 (bottom panels) also compares the performance of the two young groups on high-context sentences. Note that increasing the SNR cannot increase performance in the unspeeded condition for high-context sentences because performance is already at ceiling. However, it can and does improve performance in the two speeded conditions. The result is that the decline in performance when the sentences are speeded is smaller for both types of speeding and significantly so when speech is speeded by deleting steady-state segments, $t(22) = -4.76$, $p < .001$, two-tailed. Nevertheless, caution must be exercised in interpreting Age × Speed interactions when one of the speed levels produces asymptotic performance.

Experiment 2: Results and Discussion

Experiment 2 compared the effect of speeding speech by deleting every third 10-ms sample (the customary way that speech is speeded in the literature) with the effect of speeding speech by deleting steady-state portions of the signal. Figure 3 (top left) shows that younger adults performed less well (71.33%) than older adults (82.67%) in the unspeeded condition in Experiment 2 for low-context sentences, $t(22) = -3.32$, $p = .003$, two-tailed. Hence, the signal-to-noise difference between younger and older adults was not successful in equating the two age groups with respect to performance on low-context sentences in the unspeeded condition of Experiment 2. However, as we saw in the ancillary condition to Experiment 1 (see Figure 2), the extent of the decline in younger adults due to the speeding of low-context sentences does not appear to depend on whether they are tested at an SNR of 8 dB (where they outperform older adults for low-context items) or at an SNR of 3 dB (where older adults may outperform them).

Figure 3 (top left) shows that when the low-context sentences were speeded by deleting every third 10-ms sample, older adults experienced a greater drop in performance than did younger adults. This was confirmed by a *t* test which showed that the decline in performance in older adults due to speeding was significantly greater than the decline in performance in younger adults due to speeding, $t(22) = 1.99$, $p = .030$, one-tailed. Hence, an Age × Speed interaction is observed even when the speeding method preserves pitch. However, the size of the interaction is smaller than that in Experiment 1 when the method of speeding also produced an upward pitch shift.

Figure 3 (bottom left) shows that both younger and older adults were correctly identifying the last word in the sentence when there was contextual support nearly 100% of the time. However, when the high-context sentences were speeded by deleting every third 10-ms segment, the performance of older and younger adults declined by about the same amount, $t(22) = -1.00$, $p = .327$, two-tailed. Hence for low- but not for high-context sentences, speeding speech by deleting every third 10-ms segment had a more deleterious effect on older than on younger adults.

As in Experiment 1, when the speech was speeded by the same amount by removing steady-state portions of the speech signal, younger and older adults were equally affected by this method of speeding for low-context sentences (see Figure 3, top right), $t(22) = 1.13$, $p = .136$, one-tailed. However, for high-context sentences (see Figure 3, bottom right), this method of speeding seems to affect older adults less than it does younger adults, $t(22) = -2.00$, $p = .057$, two-tailed. Again, caution must be

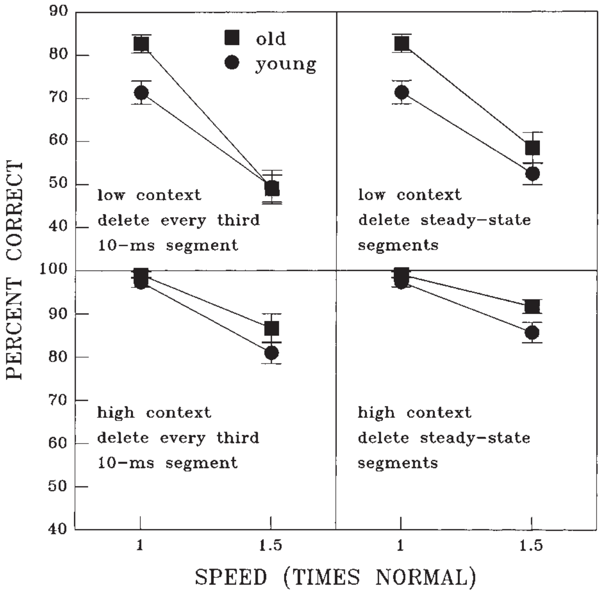

Figure 3. Percentage correct identification of the final word in a sentence as a function of the degree of speeding for younger (circles) and older (squares) adults. The sentences in the left panels were speeded by deleting every third 10-ms segment. The sentences in the right panels were speeded by deleting steady-state segments. The results for low- and high-context sentences are shown in the top and bottom panels, respectively. Error bars represent standard errors.

exercised in interpreting interaction effects in the high-context conditions because of the presence of ceiling effects.

Experiments 1 and 2 taken together show that when speech is speeded by deleting segments without regard to the critical features of the speech signal, word recognition in older adults declines more than it does in younger adults in low-context conditions. However, when speech is speeded by deleting steady-state portions of the signal, losses in comprehension are no more severe in older adults than in younger adults when SNRs are adjusted so that the performance of younger and older adults is nearly comparable in unspeeded conditions on low-context sentences.

Experiment 3: Results and Discussion

In Experiment 3, the rate of speech was increased to two times its normal value to see whether age differences would begin to show up at higher speeds when speech was speeded by deleting steady-state portions of the signal. In this experiment, performance was compared at three speeds: normal (Version 1), one and a half times normal (Version 4), and twice normal (Version 5). Figure 4 (top panel) shows that the performance of both younger and older adults did not differ on low-context sentences in the unspeeded condition (73.7% and 77.7%, respectively). Hence, testing younger and older adults at different SNRs successfully balanced the two groups with respect to perceptual listening stress in the unspeeded condition, $t(22) = 1.27$, $p = .217$, two-tailed. Figure 4 also suggests that performance for the younger and older adults did not differ at any of the three speech rates for either low- or high-context sentences, although the pattern of decline with speed appears to be dependent on sentential context. These conclusions were supported by a 2 (age) × 2 (context) × 3 (speed) ANOVA that found no effect due to age, $F(1, 22) = 0.53$, $MSE = 132.23$, $p = .476$, a significant effect of speed, $F(2, 44) = 315.35$, $MSE = 138.26$, $p < .001$, and a significant effect of context, $F(1, 22) = 225.68$, $MSE = 2049.56$, $p < .001$. However, none of the two-way interactions with age were significant: speed by age, $F(2, 44) = 0.02$, $MSE = 138.26$, $p = .985$; context by age, $F(1, 22) = 2.00$, $MSE = 93.16$, $p = .171$. The Speed × Context interaction, however, was significant, $F(2, 44) = 9.23$, $MSE = 58.77$, $p < .0001$, as was the three-way interaction between speed, age, and context, $F(2, 44) = 3.98$, $MSE = 58.77$, $p = .026$. Because there is no evidence in Experiment 3 of any performance differences for low-context sentences between younger and older adults at any of the three speeds used (see Figure 4, top), we can explore this three-way interaction by comparing the beneficial effect of contextual support when the two age groups are equated with respect to their performance on low-context items. The beneficial effect of context is calculated by subtracting at each speed and age group performance on low-context sentences from performance on high-context sentences. Figure 5 shows that the beneficial effect of context declines more rapidly as a function of speed in younger adults than it does in older adults. A 2 (age) × 3 (speed) ANOVA on the difference scores between high- and low-context items indicates a significant effect of speed, $F(2, 44) = 9.23$, $MSE = 117.54$, $p < .001$, no age effect, $F(1, 22) = 2.00$, $MSE = 186.32$, $p = .171$, but a significant Age × Speed interaction, $F(2, 44) = 3.98$, $MSE = 117.54$, $p = .026$. It appears that this interaction is due to the fact that the difference in contextual benefit between younger and older adults increases with speed. However, none of the pairwise age contrasts (contextual benefit for older adults minus contextual benefit for younger adults) reached the .05 level of significance (Newman–Kuels test). These results confirm previous findings (Pichora-Fuller et al., 1995) that older adults, who

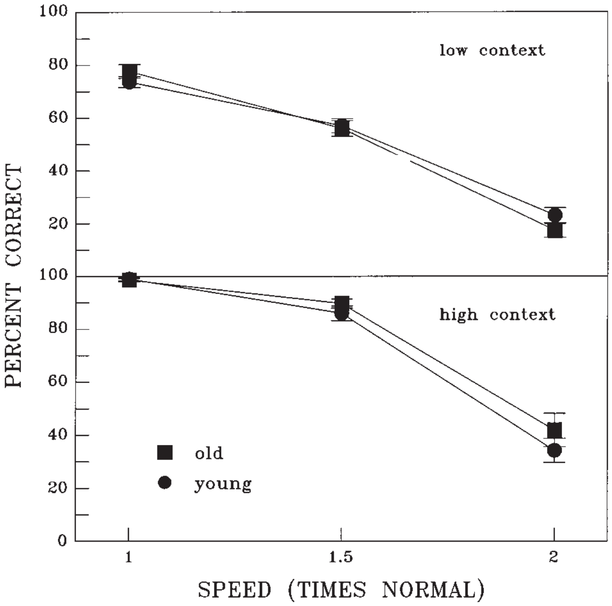

Figure 4. Percentage correct identification of the final word in a sentence as a function of the degree of speeding for younger (circles) and older (squares) adults when speech is speeded by deleting steady-state segments. The results for low- and high-context sentences are shown in the top and bottom panels, respectively. Error bars represent standard errors.

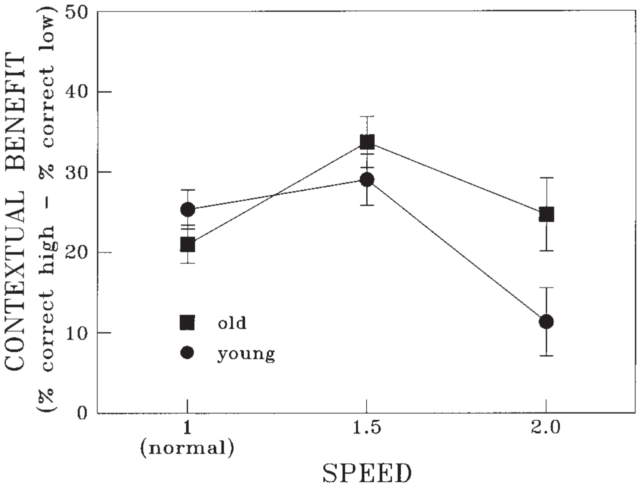

Figure 5. Contextual benefit as a function of speed in Experiment 3. Contextual benefit is obtained by subtracting percentage correct for the low-context sentences from percentage correct for the high-context sentences. Note that the contextual benefit at the highest speed is significantly greater for older adults (squares) than for younger adults (circles). Error bars represent standard errors.

may be characterized as being in the early stages of presbycusis, are better able to use context than younger adults when both are tested under difficult listening situations. This ability of older adults in the early stages of hearing loss to make better use of context may be a consequence of the fact that they are forced to depend on context more often than younger adults. Some suggestion that this might be the case comes from a study by Dubno, Ahlstrom, and Horwitz (2000) who found that older adults with exceptionally good hearing did not benefit more from context than did younger adults.

General Discussion

The results of Experiments 1–3 indicate that when listening conditions in unspeeded conditions are adjusted so that younger and older adults are approximately equally accurate in identifying individual words unsupported by context, the magnitude of the Age × Speed interaction depends on the manner in which speech is speeded. When speech is speeded by deleting every third amplitude value, the Age × Speed interaction is relatively large for both low- and high-context sentences. Speeding speech by deleting every third amplitude segment both shifts the energy in the speech signal into a higher frequency region (all frequencies are translated upward by a factor of one and a half), speeds up formant transitions, and reduces the gap in stop consonants. Experiment 2 shows that when speech is speeded by deleting every third 10-ms segment, older adults are also more affected than younger adults for low-context sentences. Speeding speech in this way, in addition to haphazardly shortening vowel duration and pauses between words, will speed up formant transitions in an uneven fashion and shorten gaps in stop consonants in an inconsistent way. However, speeding speech by deleting every third 10-ms segment does not translate frequencies upward. Hence, this type of speeding might be expected to have less of a perceptual effect on word recognition than speeding by deleting every third amplitude value.

However, when speech is speeded by deleting steady-state portions of the signal in Experiments 1–3, losses in word recognition are no more severe in older adults than in younger adults in low-context sentences, and there is some evidence that older adults are less sensitive to speeding than younger adults when listening to high-context sentences. Recall that when we speeded speech in this way, we attempted to remove speech segments in such a way that cues to phoneme recognition were preserved. Hence, there were no frequency shifts, formant transitions were left alone, and phonemically relevant gaps were by and large left unaltered. Thus, three of the factors that we know have a larger perceptual impact on older than on younger adults were essentially unaltered when the speech material was speeded. It is interesting that there was no evidence of an Age × Speed interaction in any of the three experiments when speech was speeded by deleting steady-state segments for low-context sentences.

Evaluating the Perceptual Hypothesis

The perceptual hypothesis is based on the notion that older adults find it more difficult to handle speed-induced acoustic distortions than do younger adults. A corollary of this hypothesis is that older and younger adults should be differentially sensitive to the different methods of speeding because they introduce different types of acoustic distortion. In other words, older adults should show a different pattern of responding to the three methods of speeding than will younger adults. To determine the extent to which this was true, we compared the response of younger and older adults with an increase in speed by a factor of one and a half across three different methods of speeding. Recall that in Experiment 1, speed was increased by a factor of one and a half by deleting every third amplitude value. In Experiment 2, the same increase in speed was obtained by deleting every third 10-ms segment, whereas in Experiment 3, speed was increased by the same amount by deleting steady-state segments. For each of the participants in each of these experiments, we determined the loss in percentage of word recognition due to speeding (percentage correct at normal speed minus percentage correct at one and a half times the normal speed).

To determine whether the method of speeding differentially affected younger and older adults, we computed the reduction in accuracy due to an increase in speech rate for each method of speeding. The data from Experiment 1 were used to evaluate the reduction in accuracy occasioned by deleting every third amplitude value (Method 1 speed factor = 1.5). Specifically, for each participant in Experiment 1, we subtracted the percentage of sentence-final words correctly identified when the sentences were speeded by deleting every third amplitude value from the percentage of words correctly identified when speech was unspeeded. The comparable data from Experiment 2 were used to compute the effect of speeding by deletion of every third 10-ms segment (Method 2 speed factor = 1.5), and the data from the unspeeded and one and a half times the normal speed condition of Experiment 3 were used to compute the effect of speeding by deletion of steady-state segments (Method 3, speed factor = 1.5). A 2 (age) × 2 (context) × 3 (method of speeding) ANOVA on these speed-induced accuracy decrements revealed a significant main effect of age, $F(1, 66) = 12.02$, $MSE = 150.32$, $p = .001$ (speed-induced accuracy decrements were larger, on average, in older than in younger adults), a significant main effect of context, $F(1, 66) = 52.37$, *MSE* = 89.59, $p < .001$ (the accuracy reduction was larger for low-context than for high-context sentences), but no clear main effect due to method of speeding, $F(2, 66) = 2.84$, *MSE* = 150.32, $p = .066$. However, there was a clearly significant interaction between age and method of speeding, $F(2, 66) = 6.12$, *MSE* = 150.32, $p = .004$, supporting the conclusion that the method of speeding affected the two ages differentially. Neither the interaction between context and method of speeding, $F(2, 66) = 1.14$, *MSE* = 89.59, $p = .326$, nor the three-way interaction between age, context, and method of speeding, $F(2, 66) = 1.57$, *MSE* = 89.59, $p = .217$, was significant. Hence, the differential effect of method of speeding on younger and older adults appears to be the same for both high- and low-context sentences. Finally, there was a significant interaction between age and context (a switch from low- to high-context sentences mitigated the effect of speeding on performance more in older than in younger adults), $F(1, 66) = 8.04$, *MSE* = 89.59, $p = .006$.

The significant interaction between age and method of speeding in the overall ANOVA indicates that the method of speeding has a different effect in older adults than it does in younger adults. Figure 6 plots decrements in performance due to speeding separately for younger and older adults. (In this figure, decrements in performance were averaged across high- and low-context sentences because there was no statistical justification to support the notion that the effect of method of speeding differed as a function of context). For younger adults, speeding by removal of every third amplitude sample had the least effect on word recognition, whereas speeding by deleting 10-ms segments produced the most pronounced decrement in performance. A 2 (context) × 3 (method of speeding) ANOVA on the performance decrements in young participants indicated main effects due to method of speeding, $F(2, 33) = 3.90$, *MSE* = 134.20, $p = .030$, and context, $F(1, 33) = 11.41$, *MSE* = 76.10, $p = .002$, but not for the interaction between these two factors, $F(2, 33) = 1.41$, *MSE* = 76.10, $p = .258$. Pairwise comparisons (Newman–Kuels test, $\alpha = .05$) showed that the main effect of method of speeding was primarily due to a significant difference between speeding by deleting every third amplitude segment and speeding by deleting every third 10-ms segment. That speeding by deleting every third amplitude sample produced the smallest decrement suggests that younger adults are relatively immune to the frequency shifts induced by this method. However, they do appear to be affected when the method of speeding inconsistently speeds up formant transitions and shortens phonemic gaps.

Figure 6 also shows that older adults are more susceptible to speeding when speech is speeded by deleting every third amplitude sample, or when it is speeded by deleting every third 10-ms segment, than when it is speeded by deleting steady-state segments. A 2 (context) × 3 (method of speeding) ANOVA on the performance decrements in older participants confirmed main effects due to method of speeding, $F(2, 33) = 4.94$, *MSE* = 166.44, $p = .013$, and context, $F(1, 33) = 44.08$, *MSE* = 103.09, $p < .001$, but not for the interaction between these two factors, $F(2, 33) = 1.31$, *MSE* = 103.09, $p = .284$. Pairwise comparisons (Newman–Kuels test, $\alpha = .05$) indicated that speeding by deleting every third amplitude value and speeding by deleting every third 10-ms seg-

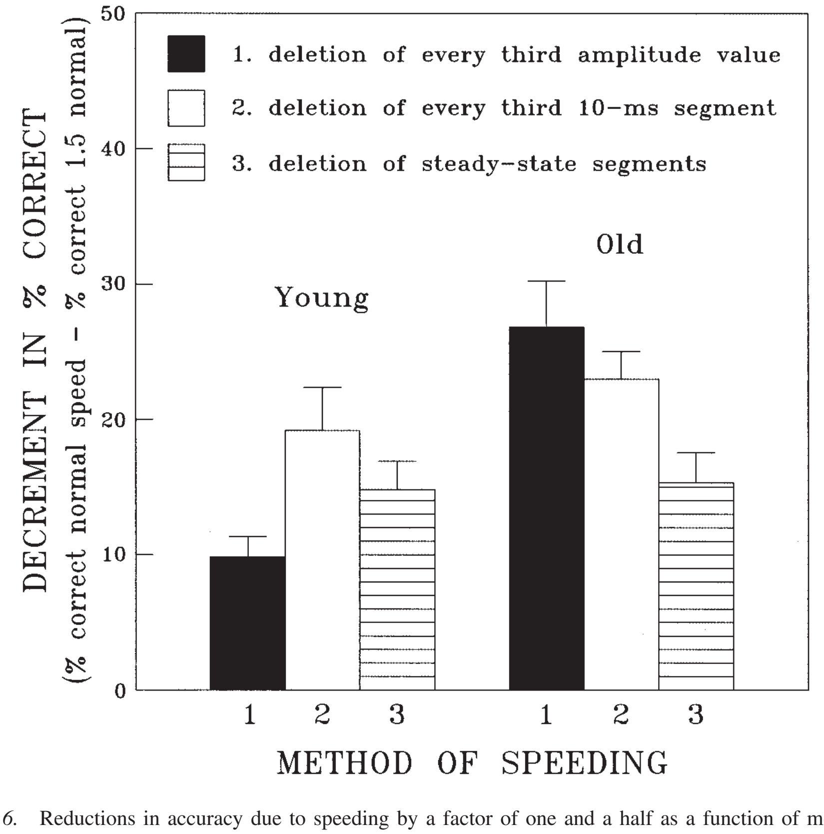

Figure 6. Reductions in accuracy due to speeding by a factor of one and a half as a function of method of speeding for younger and older adults. Error bars represent standard errors.

ment produced more of a decrement in performance than speeding by deletion of steady-state segments. That speeding by deleting every third amplitude value proved difficult for older adults is not surprising because this method of speeding translates all frequencies upward by a factor of one and a half. In addition, speeding by deleting every third 10-ms segment was nearly as difficult for older adults to process as was speeding by deletion of every third amplitude value. Apparently, both younger and older adults find it difficult to process speeded speech when the method of speeding inconsistently speeds up formant transitions and shortens phonemic gaps.

Why, then, do some methods of speeding differentially affect older adults more than they do younger adults? Recent studies by Gordon-Salant and Fitzgibbons (1993, 2001) suggested that older adults find it difficult to handle the spectral distortion and time compression of consonants that often occur when speech is speeded. Further evidence that older adults might be more sensitive to speed-induced acoustic distortions comes from a study by Wingfield et al. (1999) in which spoken passages were speeded by deleting steady-state segments without regard to their location. After speeding these passages, these investigators also created a condition in which the passages were restored to their normal length by inserting pauses at syntactic boundaries. This latter manipulation preserves speed-induced acoustic distortions but restores the time available for cognitive processing of the material to what was available before the passages were speeded. Restoring processing time for the speeded materials eliminated all speeding effects for younger adults, suggesting that reduced processing time was responsible for the speeded speech effect in younger adults. However, restoring processing time for older adults only partially reduced the effects of speeding, even when the inserted pauses increased the time available for processing the speeded material beyond what was available when the unspeeded passages were presented. These results are consistent with the hypothesis that the acoustic distortions induced by this method of speeding have a greater effect on older adults than on younger adults.

Evaluating the Cognitive Hypothesis

Of course the task used here (identification of sentence-final words) is much less difficult than comprehending speech in everyday situations. One might be tempted to argue that cognitive processes were insufficiently engaged because the task involved only word recognition. Two factors mitigate against this explanation. First, sentence-final words were more readily recognized when they were supported by context. This would not happen if participants were processing only the sentence-final word rather than the entire sentence. Second, all participants were asked to indicate, after they reported the word, whether the last word could or could not be predicted from sentential context. Over all conditions, younger participants were 89.5% accurate in identifying high- and low-context sentences, and older participants were 82.7% accurate in judging whether a sentence was high or low context. In order to benefit from context, and in order to correctly identify high- and low-context sentences, the participants had to be engaging in linguistic and semantic processing. Hence, the data support the hypothesis that when isolated sentences are involved, an Age × Speed interaction, if observed, is likely due to perceptual processing deficits in older adults rather than to a slowing of the cognitive mechanisms involved in sentence processing.

However, one cannot rule out the possibility that age-related cognitive differences might account for a larger portion of the speeded-speech effect in more cognitively complex listening situations. If, for example, younger and older adults were required to answer questions about a story they just heard (a task that is more cognitively complex than identifying the last word of a sentence), age-related cognitive declines might make older adults more susceptible to speeding than younger adults even when speech is speeded by deleting steady-state segments. If this were to happen, then we would be forced to conclude that age-related differences in linguistic and cognitive processing were also contributing to Age × Speed interactions. The answer to this question awaits further experimentation.

Finally, one could also argue that our failure to find an Age × Speed interaction when speech is speeded by deleting steady-state segments was due to a lack of power. To investigate this possibility, we performed two additional analyses on the low-context sentences where we can be sure that the ability to measure an Age × Speed interaction is not compromised by ceiling effects. First, we conducted an ANOVA across all three experiments for sentences presented at a normal rate and for sentences speeded to one and a half times the normal rate by deleting steady-state segments. A 3 (experiment) × 2 (age) × 2 (speed) ANOVA found no effect of experiment, $F(2, 66) < 1$, a significant age effect, $F(1, 66) = 8.48$, $MSE = 120.69$, $p = .005$, a significant speed effect, $F(1, 66) = 195.16$, $MSE = 75.43$, $p < .001$, but with none of the two- and three-way interactions approaching significance (all ps $>$ .25). Thus, there is no evidence across experiments of any Age × Speed interaction when low-context sentences are speeded by a method that minimizes stimulus degradation. Second, a power analysis for the low-context sentences[5] in Experiment 3 showed that the proportion of variance accounted for by the Age × Speed interaction was only $\eta^2 = .01$, with Cohen's f for this interaction term being 0.08, an effect size that Cohen (1988) considered small ($f = 0.10$). By way of contrast, the effect size for speed ($\eta^2 = .88$, Cohen's $f = 2.67$) was much larger than an effect size that Cohen considered large ($\eta^2 = .14$, Cohen's $f = 0.40$) and 137 times larger than the effect due to the interaction between age and speed. A sample of over 500 observers would be needed in order to have a 0.80 probability of detecting an interaction of the size found in this experiment (power = .80). Given that the amount of variance accounted for by the interaction is so inconsequential, we argue that it is reasonable to treat it as nonexistent. Thus, when low-context sentences are speeded by deleting steady-state portions, there is no evidence for a speeded-speech effect.

The present results also raise the possibility that performance on other cognitive tasks may be adversely affected by the perceptual status of older adults. Because the proper functioning of higher order cognitive processes can be highly dependent on the integrity of the information supplied by the sensory systems, it is not unreasonable to expect that cognitive functions dependent on sensory input might be adversely affected by sensory declines.

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[5] We did not conduct a similar power analysis on the results from the high-context condition because, as the data in Figure 4 show, older adults were less sensitive to speeding than were younger adults when high-context sentences were used. A power analysis of this interaction would establish how many participants would be required to show that speeding has less of an effect on older than on younger participants.

Indeed, it has been shown that when listening is difficult, age-related declines in hearing contributed substantially to older adults' poorer comprehension of and memory for connected discourse (Humes, 1996; Schneider et al., 2000) and that some of the memory deficits exhibited by older adults when attempting to remember word pairs in quiet can be simulated in younger adults by simply asking them to listen to the word pairs in noise (Murphy, Craik, Li, & Schneider, 2000). In other words, it is possible that many cognitive declines are a consequence of inadequate signal processing by aging sensory systems.

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