Listening in Aging Adults: From Discourse Comprehension to Psychoacoustics

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Abstract Older adults, whether or not they have clinically significant hearing loss, have more trouble than their younger counterparts understanding speech in everyday life. These age-related difficulties in speech understanding may be attributed to changes in higher-level cognitive processes such as language comprehension, memory, attention, and cognitive slowing, or to lower-level sensory and perceptual processes. A complicating factor in determining how these sources might contribute to age-related declines in speech understanding is that they are highly correlated. Experimenters have typically focused either on cognitive declines or sensory declines in artificially optimized test conditions. In contrast, our approach focuses on the complex interactions between age-related changes in cognitive and perceptual factors that affect spoken language comprehension, especially in nonideal, realistic conditions. In this article, we describe our attempts to systematically investigate sensory-cognitive interactions in controlled experimental situations. We begin by looking at experimental conditions that closely approximate everyday listening, and show that older adults do indeed experience deficits in spoken language comprehension relative to younger adults in these conditions. We then review further experiments designed to isolate more precisely the cognitive and perceptual sources of these age-related differences and how they vary with listening condition. In large part, we find that age-related changes in speech understanding are a consequence of auditory declines.

As many as one-third of seniors find that it is difficult to understand conversations in everyday listening situations (Hamilton-Wentworth District Health Council, 1988; see also CHABA, 1988). Among the more common complaints are that talkers seem to mumble or talk too fast and that it is hard to hear when it is noisy. In general, it is especially difficult for older adults to follow a conversation when there are multiple talkers, or when talkers or topics change. Because they miss parts of what is said and lack confidence in the accuracy of their understanding of the parts they do hear, older communicators are prone to anxiety or frustration, and may avoid or be excluded from social interactions.

The speech understanding difficulties of older listeners may arise from a number of possible sources. The difficulties could be in higher-level cognitive processes such as language comprehension, memory, attention, and cognitive slowing, or they could be in lower-level sensory and perceptual processes. A complicating factor in determining how these sources might contribute to age-related declines in speech understanding is that they are highly correlated. Perceptual declines in older adults are highly associated with declines in cognition (e.g., Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994; Uhlmann, Larson, Rees, Koepsell, & Duckert, 1989). In turn, both perceptual and cognitive declines are linked to emotional and social problems and even to mortality (e.g., Appolonia, Carabellese, Frattola, & Trabucchi, 1996; Cacciapuoti, Napoli, Abete, Marciano, Triassi, & Rengo, 1999; Naramura, Nakanishi, Tatara, Ishiyama, Shiraishi, & Yamamoto, 1999; Seniors Research Group, 1999). Thus, it is very important to understand how the interplay of perceptual and cognitive factors contributes to the speech understanding difficulties of older listeners so that they can be remediad.

The need to consider each of these levels and how they inter-relate has received increasing recognition over the last decade (e.g., Baltes & Lindenberger, 1994; CHABA, 1988). Furthermore, the need to determine how older adults perform in naturalistic, as opposed to laboratory, conditions has also been highlighted (e.g., Stern & Carstensen, 2000; WHO, 2001). Nevertheless, up until now, experimenters have typically focused either on cognitive declines or sensory declines in artificially optimized test conditions. In contrast, our approach focuses on the complex interactions between age-related changes in cognitive and perceptual factors that affect spoken language comprehension, especially in...
nonideal, realistic conditions. In this article, we describe our attempts to systematically investigate sensory-cognitive interactions in controlled experimental situations. We begin by looking at experimental conditions that closely approximate everyday listening, and show that older adults do indeed experience deficits in spoken language comprehension relative to younger adults in these conditions. We then review further experiments designed to isolate more precisely the sources of these age-related differences and how they vary with listening condition. Our research focuses primarily on participants whose hearing and cognitive status is considered to be clinically normal, although it should not be forgotten that there are large numbers of older adults who do have clinically significant impairments in one or both domains (see Schneider & Pichora-Fuller, 2000).

**Comprehending and Remembering Complex Discourse**

We approximated naturalistic listening conditions in the laboratory with an investigation of how younger and older adults comprehend and remember complex spoken discourse in both quiet and noisy listening situations (Schneider, Daneman, Murphy, & Kwong See, 2000). To establish that there was a negative age difference on our task, we tested younger and older adults under identical stimulus conditions, which is the typical approach in cognitive aging research. Younger adults (<30 years of age) and older adults (>65 years of age) with good hearing (audiometric thresholds <30 dB HL for frequencies up to 3 kHz) listened to passages read by a professional actor either in quiet or in a background of multitalker babble noise. The passages were excerpts from previously published works and were from 1,050 to 1,866 words in length. After listening to a passage, participants were asked to answer a set of questions based on information presented in the passage. There were two types of questions: detail and integrative. Detail questions asked for a specific item of information that was presented explicitly once during the story or lecture. Integrative questions required listeners to identify or infer the overall gist of the passage.

The passages were presented at the same sound pressure level (dB SPL) to all participants, and the babble noise, when present, was the same for all participants. Figure 1 plots the average number of correct answers (out of a total of 10) for younger and older listeners and for detail and integrative questions. The number of both kinds of questions answered correctly decreased in the presence of noise for both age groups, and the integrative questions proved to be more difficult for both younger and older participants. There was also a strong age effect: Older listeners answered fewer questions correctly than younger listeners, with the extent of this difference being larger for detail than for integrative questions. However, the extent of any age difference in noise for "gist" questions may have been limited by a floor effect (chance responding in these experiments was 2.5 questions correct).

These results indicate that, independent of whether the passages are presented in quiet or are embedded in a background of babble noise, older adults are unable to recall as much detail as younger adults, and may not be able to answer as many integrative questions as younger adults. This finding would not surprise cognitive aging researchers who have proposed that cognitive factors such as generalized slowing, declines in working memory capacity, and/or deficits in inhibitory processes should adversely affect the comprehension and recall of spoken or written material (e.g., Cohen, 1987; Hasher & Zacks, 1988; Kwong See & Ryan, 1996; Wingfield, 1996; Wingfield & Stine-Morrow, 2000; Wingfield & Tun, 2001). In other words, the negative age effect could easily be attributed to one or more aspects of cognitive aging.

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1. Our elderly participants are volunteers from the local community. A questionnaire is used to screen participants for general health, hearing, vision, and cognitive status. Only participants who report that they are in good health, and have no history of serious pathology (e.g., stroke, head injury, neurological disease, seizures, etc.) are included. Typically, our older participants have equivalent or greater levels of education than our younger participants and they outperform them on vocabulary tests.
Another possibility is that this negative aging effect could be attributed to subclinical auditory declines in older adults. If, for example, older listeners did not hear 10% of the words because of auditory processing problems, then they would miss some of the details and could fail to arrive at the correct gist of the passage. It is also possible that to compensate for not hearing words, older listeners might re-allocate cognitive resources to determine the meaning of the words from context, thereby leaving fewer resources for integrating the meaning of words and phrases into sentences, and extracting and storing information from the passage for later recall. To investigate this possibility, in a second experiment we presented the passages after adjusting the listening situation to make it equally difficult for both young and old adults to identify individual words.

When sounds are presented at a fixed level to individuals with varying degrees of hearing sensitivity, the sounds may be well above threshold for some, but near threshold for others. Because performance on an auditory test is often influenced by proximity of the stimulus to the listener’s threshold, it is a common practice to present stimuli in auditory experiments at a fixed number of dB above threshold (at a fixed sensation level, SL) to make it equally audible to all participants. Hence, in the second experiment the passages were presented at 50 dB SL to all listeners.

When sounds are presented in a background noise, their audibility depends not only on the level of the signal, but also on the signal-to-noise ratio (SNR), the ratio of the level of the target signal to that of the background noise. We adjusted the SNR by determining the level of background noise that would result in each individual having the same degree of difficulty in identifying individual words when these words were unsupported by context (see Schneider et al., 2000, for details). Figure 2 plots the number of correct answers for both detail and integrative questions for younger and older adults listening to passages in quiet and in two SNR conditions. A comparison of Figures 1 and 2 shows that when listeners are tested at equivalent levels of perceptual stress (Figure 2), the age differences in performance seen previously (Figure 1), for the most part, disappear. Performance still decreases as background noise increases, and integrative questions are still more difficult to answer than detail questions. However, with the possible exception of detail questions at the highest noise level, there are no age differences in performance. Hence, when tested under equivalent levels of perceptual stress, older adults are able to answer as many questions as their younger counterparts.

Natural listening situations can be considerably more complex than listening to a single talker in a noisy background. Often the listener must perform some other task while listening. The literature suggests that older adults may be more susceptible to distractions than younger adults (e.g., Craik, 1977; McDowd & Craik, 1988; Park, Smith, Dudley, & Lafronza, 1989; Rabbitt, 1965; Salthouse, Rogan, & Prell, 1984; Tsang & Shaner, 1998), and that they may find it more difficult to divide their attention between two concurrent tasks (for a review see McDowd & Shaw, 2000). To determine whether or not the addition of a secondary task would produce a negative age effect for discourse comprehension, we added a sentence verification task to the discourse experiment. Specifically, while listening to connected discourse, listeners performed a sentence-reading task in which they had to monitor for the appearance of a written sentence on a computer screen, and when it appeared, they had to read the sentence silently to themselves and then verify whether it was true or false. The addition of the distractor had the effect of decreasing performance on the questions, but did so equally for both younger and older listeners (see Schneider et al., 2000). Thus, when perceptual stress is equivalent for all participants, older adults are no more susceptible to distraction than are younger adults.

These results suggest that many of the comprehension difficulties experienced by older adults in everyday listening situations have a sensory origin. The evidence for this so far is that when we alter the listening
conditions for younger adults to make it as difficult for them to identify individual words as it is for older adults, negative age effects on discourse comprehension disappear. Presumably, sensory declines in older adults result in inadequate or error-prone representations of external events. These inadequacies and errors at the perceptual level then cascade upwards and lead to errors in comprehension.

**Comprehending and Remembering Simple Words and Sentences**

Even though our discourse experiments indicate that sensory factors might play a large role in accounting for the comprehension difficulties experienced by older listeners in everyday settings, we cannot assume that younger and older listeners are equally skilled on all other components of comprehension. Discourse comprehension draws on many component skills and resources, and it is quite possible that older listeners are less skilled than younger listeners on some of these components and more skilled on others (for a review see Wingfield & Stine-Morrow, 2000). For example, there is evidence to suggest that older adults have deficits in working memory capacity (for a review see Carpenter, Miyaki, & Just, 1994), and so they may be at a disadvantage relative to younger adults when required to integrate newly heard information with information heard earlier in the discourse because they will have less capacity to keep the earlier heard information active in temporary storage. Similarly, there is evidence to suggest that older adults have problems with the long-term retention of information (for a review see Burke & Light, 1981), and so even if they understand the discourse when first encountering it, they may be at a disadvantage relative to younger adults in retrieving that information at test. In contrast, it has been suggested that older adults have well-preserved or even better “crystallized knowledge” (e.g., world knowledge, vocabulary knowledge) than do younger adults (e.g., Wingfield & Tun, 2001), and so they may be at an advantage relative to younger adults when required to draw on contextual knowledge to aid comprehension. If the detrimental effects of reduced working memory resources and long-term retention were to cancel out the facilitative effect of greater contextual skills, the lack of cognitive age differences on our discourse comprehension task would be more apparent than real. To investigate the relations of sensory factors to individual cognitive components of language comprehension (e.g., working memory, long-term memory, use of context), we conducted a number of experiments using simpler listening comprehension and memory tasks.

We tested the effect of sentence context on word identification and recall in younger and older listeners using the Revised Speech Perception in Noise Test (SPIN-R; Bilger, Nuetzel, Rabinowitz, & Rzeczkwoski, 1984). In the SPIN-R test, participants are presented with simple sentences and asked to repeat the last word of the sentence immediately after hearing it. In some of the sentences, the last word is predictable from the context (e.g., *Stir your coffee with a spoon*), and in others it is not (e.g., *Jane was thinking about the spoon*). We varied the SNR by adjusting the level of the background babble that accompanies the sentences, and constructed psychometric functions relating percent correct word identification to SNR (Pichora-Fuller, Schneider, & Daneman, 1995). As expected, percent correct word identification increases with increasing SNR for all listeners. Results for a typical younger adult, an older good-hearing adult, and a presbycusic individual are shown in Figure 3. Moreover, the function for low-context sentences is displaced to the right relative to that for high-context sentences; that is, all listeners need a higher SNR to hear a word with a given degree of accuracy when the word is not supported by context than when it is supported by context. Note that younger adults maintain good performance in SNR conditions at which performance declines for older adults with good hearing thresholds, who in turn perform better than those with presbycusic high-frequency threshold elevations.
The degree of contextual benefit experienced by a person varies with SNR and can be estimated by computing the extent of the difference between the high- and low-context psychometric functions. Note that the range of SNRs tested corresponds to conditions that are likely to be encountered in everyday life; for example, in a quiet living room where listening is easy, the average SNR is between +9 and +14 dB, whereas in a subway or aircraft, where listening is challenging, the average SNR is -2 dB (for a review see CHABA, 1988). In general, speech intelligibility shifts from being nearly perfect to impossible over a relatively narrow SNR range and in the middle of this range a difference of 1 dB SNR can result in as much as a 20% change in speech intelligibility (Duquesnoy, 1983). For all three listeners shown in Figure 3, the degree of contextual benefit first increases and then decreases as SNR increases. Note, however, that the low-context psychometric function of the presbycusic individual asymptotes at about 65%. This means that this individual will miss approximately 35% of the low-context sentence-final words even when these sentences are presented in quiet. Furthermore, the perceptual problem experienced by this individual would not be evident in everyday situations where there is good contextual support because he or she can identify 100% of the words so long as the SNR is greater than 10 dB. By way of contrast, the younger adult can identify 100% of the words even without contextual support when the SNR is greater than 10 dB. Thus, at favourable SNRs, younger adults are not perceptually stressed when listening to sentences, whereas presbycusic individuals are operating under considerable perceptual stress, and must depend on context to identify individual words. Older adults with good hearing perform between these two extremes in terms of how perceptual stress is experienced as SNR is varied. Given that SNRs greater than 10 dB exist only in the most quiet situations encountered in the modern world, older listeners are more often likely to find themselves in environments that are perceptually stressful to them as compared to their younger counterparts.

Given that older listeners must use contextual cues more often than younger adults, it is possible that they become more skilled in the use of context. One way to evaluate this hypothesis is to find the SNR for each individual that results in the same identification accuracy for low-context sentence-final words, so that each individual can be evaluated under equivalent levels of perceptual stress. The horizontal lines intersecting the low-context psychometric functions identify the SNRs for the individual listeners that result in an identification accuracy of 20%. The length of the vertical lines between the low- and high-context conditions at the identified SNRs specify the degree of benefit from context in the selected condition of perceptual stress. In Figure 3, it is clear that for this level of perceptual stress, both older listeners are much more adept at using context than the younger individual. Figure 4 plots the advantage afforded by context for younger and older listeners as a function of the percentage of words correctly identified in the low-context situation. Note that even when the percentage of words correctly identified is very low (high degree of perceptual stress), older adults appear to be better able to use context to disambiguate words. As the percentage of words correctly identified increases, so does the degree of benefit from context, with maximum benefit being reached when around 20-40% of the words are correctly identified. Over most of the range, older adults show a higher contextual advantage than younger adults, a result also reported by Sommers and Danielson (1999).

Although use of context may rescue word identification when the SNR is adverse, this route to word identification seems likely to increase cognitive effort, with a possible consequence being the reallocation of processing resources to word identification and away from other cognitive operations such as storage of the heard information. Using the SPIN-R test materials in a working memory span procedure (following Daneman & Carpenter, 1980), we tested the effect of perceptual stress on working memory span in younger and older listeners (Pichora-Fuller et al., 1995). In addition to repeating each sentence-final word, as was done in the word identification test procedure, participants were...
required to remember the words until recall was prompted. The number of sentences in the recall set was varied from 2 to 8, with a full SPIN-R list being used for each SNR and recall set size condition. The listening working memory spans measured in the older listeners were smaller than those of the younger listeners, even though the age groups had not differed in their performance on a comparable reading working memory span test. When the SNR was challenging, the number of words recalled dropped significantly for both age groups, but with correctly and incorrectly perceived words being recalled equally well (credit was given for recalling the word that was identified even if it had been misperceived). These findings suggest that increased effort during word identification does result in the reallocation of cognitive resources from storage to perception. It is interesting that similar findings of decreases in storage have been reported when stress is introduced by introducing obstacles during motor tasks such as walking (Li, Lindenberger, Freund, & Baltes, 2001).

If the poorer scores on word identification in low-context sentences for older adults are a consequence of auditory processing deficits, then we should be able to produce equivalent deficits in younger adults by simulating them. If such a simulation is successful, then word identification scores for younger adults in simulated conditions should be equivalent to those of older adults, and the working-memory spans measured in younger adults should be similarly reduced to those of older adults. In a recent study (Pichora-Fuller, Schneider, Pass, & Brown, under review), we simulated auditory aging by temporally jittering the low-frequency components of the SPIN-R sentences. As we will show below, older adults may be experiencing auditory temporal processing difficulties, including loss of neural synchrony, which can be simulated by jittering the low-frequency components of a speech signal. Qualitatively, the jittered speech resembles speech spoken by a talker with a mild case of laryngitis. When these jittered sentences were presented to younger adults, word identification performance for low-context sentences shifted to become equivalent to the performance that we had observed earlier for older adults with good hearing thresholds (Figure 5). Furthermore, the recall of younger listeners for the jittered words in sentences was equivalent to the recall performance that we had observed earlier for older adults (Figure 6). Thus, disrupting auditory processing in younger adults has a negative impact on word identification and also on memory. This finding prompts the question of the extent to which memory losses in older adults are due to...
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to perceptual processing deficits.

To investigate this question, Murphy, Craik, Li, and Schneider (2000) tested younger and older adults in a paired-associates memory task modelled on Madigan and McCabe’s (1971) study of serial position effects. In this task, listeners heard sets of five paired associates. After each set, the first member of one of the paired associates was presented to the listener, who was asked to supply the other word in the pair. When the paired associate tested was the last from the set of five, performance was very good. However, when paired associates from earlier in the set were presented, listeners often failed to recall the second member of the pair, giving rise to a serial position effect. Figure 7 (left panel) plots the percentage of items correctly recalled as a function of their serial position in the set for younger and older adults tested in quiet. Note that the performance of younger and older adults in quiet is equivalent for serial positions 4 and 5. However, at the earlier serial positions, older adults perform more poorly than younger adults, giving rise to an age-by-serial position interaction.

The perceptual representations of these paired associates may be degraded in older adults but not in younger adults. Therefore, it is theoretically possible that poorer perceptual representation of these words in older adults prevents the words from being efficiently encoded into long-term storage. If so, then degrading the perceptual representation in younger adults should have an equivalent effect on their performance. To test this, we added background babble (from the SPIN-R test) and replicated the experiment with another group of younger listeners. Figure 7 (right panel) plots the data from the younger adults tested in noise and the data of the older adults tested in quiet. Importantly, the performance of younger adults in noise is equivalent to that of older adults in quiet.

The data presented in Figure 7 are consistent with the notion that a degraded perceptual representation impedes the encoding of remote items into long-term storage. When we obtained these results, we did not know whether the degree of degradation that occurs in the perceptual representation when the young adults hear the words in noise is equivalent to that experienced by older adults in quiet. To resolve this question, it was necessary to test both younger and older adults under equal degrees of perceptual stress. Therefore, we determined a noise level for older adults that resulted in the same percentage of misheard words (9%) as that found for younger adults when these words were presented singly in background babble. As in the previous experiment, older adults required a higher SNR than younger adults to obtain the same percent correct word identification (91%). When younger and older adults were tested at SNRs producing equivalent levels of word identification, younger adults performed better than older adults at all serial positions. Thus, equating both younger and older adults in terms of perceptual stress did not eliminate the negative age difference. However, it did eliminate the age by serial position interaction. Apparently, degrading the stimulus representation (by adding babble noise to the speech) removed the relative advantage enjoyed by younger adults at the temporally-remote serial positions.

The results of the serial position experiment suggest that noise and consequent perceptual degradation can interfere with memory, and that the degree of interference depends on the serial position of the word to be recalled. It is not too difficult to imagine that, in older adults, accumulated errors in sensory processing increase internal noise. If so, adding external noise when presenting words to young adults might simulate, at least to a first approximation, the effects of increased internal noise in older adults. Why the effect of either external or internal noise is stronger for words presented in the earlier serial positions remains to be determined and is now being investigated.

In general, the results of these experiments are consistent with the more complex discourse experiments in suggesting that perceptual degradation impedes comprehension and recall of linguistic material, and that the typically observed age-related declines in comprehension, working memory, and long-term memory processes can be substantially reduced when younger
and older listeners are equated for perceptual stress. However, even when equated for perceptual stress, older adults have poorer intermediate and long-term recall than younger adults for single words unsupported by context, but they are better at using the linguistic context to identify a degraded stimulus.

**Auditory Aging**

So far we have been arguing that deterioration in auditory processing is a major factor contributing to the difficulties experienced by the older adults in understanding spoken language. In this section, we consider the nature of the age-related changes in auditory processing. The effects of age-related declines in hearing thresholds on speech perception have been extensively studied and the finding is that high-frequency threshold hearing loss provides a good account of losses of phonemic information and word identification in quiet listening conditions (e.g., Humes, 1996; van Rooij & Plomp, 1992). In addition to these more well-known consequences of presbycusis, research in the last decade has provided new insights into the effects of other age-related declines in auditory processing on listening in older adults (for reviews, see Willott, 1991, 1996).

Even when older listeners have little difficulty detecting the presence of speech in quiet, there is no guarantee that all individual speech sounds or words are easily identifiable, or that conversations are effortless, especially when there is background noise or competing signals. A consideration of the listening conditions in which age-related differences are most pronounced points to the kinds of changes in auditory processing that seem most likely to be involved. There is extensive evidence that fast speech rate and the presence of background noise or reverberation (room echo) disrupts word identification more for older than younger adults (for reviews see Gordon-Salant & Fitzgibbons, 1993; Gordon-Salant & Fitzgibbons, 1996; Schneider & Pichora-Fuller, 2000) and binaural processing (for reviews see Grose, 1996; Koehnke & Besing, 2001).

Importantly, the traditional view of hearing loss in terms of reduced audibility for spectrally characterized sounds is inadequate to account for these particular difficulties of older listeners (for reviews see Divenyi & Simon, 1999; Schneider & Pichora-Fuller, 2000). In search of other possible explanations, over the last decade, researchers have devoted increasing effort to the investigation of the contribution and nature of behavioural and physiological declines in auditory temporal processing with age (e.g., Fitzgibbons & Gordon-Salant, 1996; Frisina & Frisina, 1997; Frisina, Frisina, Snell, Burkard, Walton, & Ison, 2001; Schneider & Pichora-Fuller, 2000). Given the variety and the importance of different temporal cues for particular aspects of speech processing (Greenberg, 1996; Phillips, 1995), diminished abilities in this domain may explain many of the problems that older listeners experience in the acoustically challenging conditions of everyday communication. We find it useful to frame recent research on auditory temporal processing in aging by distinguishing temporal cues according to their relevance to speech intelligibility at three main levels: At the supra-segmental or prosodic level, the rate and rhythm of speech influences lexical and syntactic processing; at the segmental level, gap and duration cues influence phoneme identification; and at the subsegmental level, periodicity or synchrony cues influence voice pitch, quality, and clarity (Schneider & Pichora-Fuller, 2001). Supra-segmental and segmental information is conveyed by the temporal envelope of the sound wave, whereas voice properties are conveyed by its temporal fine structure. Although older adults have greater difficulty than younger adults when the rate of speech is more rapid, use of prosody remains largely unaffected by age (Wingfield, Lindfield, & Goodglass, 2000; Wingfield & Tun, 2001). In contrast, age-related differences at the segmental level may be related to difficulty in word identification and age-related differences in synchrony coding may be related to difficulty segregating voices. Our own research has focused on age-related differences at these last two levels of auditory temporal processing: gap detection and synchrony coding.

A number of studies of gap detection using tonal signals have demonstrated that older adults do not detect a gap in the signal until the size of the gap is about twice as large as the smallest gap detectable by younger adults (approximately 6 vs. 3 ms), with gap detection thresholds not being predictable from pure-tone hearing thresholds in listeners with good audiograms (e.g., Gordon-Salant & Fitzgibbons, 1993;
Schneider, Pichora-Fuller, Kowalchuk, & Lamb, 1994; Snell, 1997; Strouse et al., 1998). In particular, older adults have significantly larger gap detection thresholds when the surrounding marker signal is short (e.g., 5 ms), but not when it is longer (e.g., 500 ms) (Moore, Peters, & Glasberg, 1992; Schneider & Hamstra, 1999; Snell & Hu, 1999).

Gaps in speech provide segmental information, such as marking the presence of stop consonants; for example, *spoon* differs from *soon* because of the presence of the stop consonant [p], which corresponds to a gap in the speech time waveform. Gap detection deficits are a probable source of certain speech perception difficulties and some studies have found significant correlations between measures of gap detection and speech perception in noise (e.g., Tyler, Summerfield, Wood, & Fernandes, 1982). Nevertheless, a clear link between nonspeech gap detection ability and specific speech perception abilities in old age has been difficult to establish (e.g., Snell & Frisina, 2000; Strouse, Ashmead, Ohde, & Grantham, 1998). It may be that a relationship between nonspeech gap detection ability and speech perception does exist, but that the stimuli used did not sufficiently tax this aspect of temporal processing for the relationship to be demonstrated. Gap detection ability is more taxed when nonspeech marker duration is shorter (Schneider & Hamstra, 1999), or when speech rate is faster (Price & Simon, 1984). We tested younger and older listeners over a range of nonspeech marker durations and in both fast and slow speech rate conditions using word-pair continua constructed by varying the duration of an inserted silent interval (catch-catch, dish-ditch, soon-spoon, slit-split; Haubert & Pichora-Fuller, 1999). As we anticipated, older adults had significantly greater difficulty than younger adults identifying speech contrasts when a gap was the differentiating cue, especially for fast speech (see Figure 8). Stimulus duration/rate had comparable effects on gap detection in nonspeech and speech stimuli, and a significant correlation was found between nonspeech and speech measures for the older group for some words in fast speech.

Synchrony coding is another aspect of auditory processing that may alter older listeners’ abilities to perceive speech in challenging everyday listening conditions. It is well known that the response of auditory neurons is phase-locked to the signal’s frequency (Rose, Hind, Anderson, & Brugge, 1971; see also Pickles, 1988). To illustrate, for a sinusoidal signal of 500 Hz, the interspike intervals (time between neural impulses) for primary auditory afferents are almost precisely integer multiples of the period of the wave form, namely 2 ms. Thus, the interspike interval provides a potentially powerful cue for frequency coding. Physiological studies have yielded converging evidence suggesting that there is age-related loss of neural temporal synchrony at various levels of the auditory system (for reviews see Frisina et al., 2001; Schneider, 1997). Such a loss of synchrony has been implicated in age-related changes on a number of nonspeech and speech perception abilities dependent on the extraction of temporal fine structure cues. Monaurally, loss of synchrony could explain why age-related increases in frequency difference limens (DL) are greater for low frequencies than for high frequencies (e.g., Abel, Krever, & Alberti, 1990; He, Horwitz, Dubno, & Mills, 1998; Moore & Peters, 1992). Because frequency DL is thought to depend on phase-locking at low frequencies, a loss of synchrony would differentially affect DLs for low-frequency signals. Such an explanation would also be consistent with the finding of age differences in detection of mistuned harmonics in complex sounds (Alain, McDonald, Ostroff, & Schneider, 2001). Binaurally, age-related changes in masking-level differences have also been observed for both nonspeech and speech signals (Grose, 1996; Pichora-Fuller & Schneider, 1991, 1992, 1998), and have been attributed to an age-related increase in temporal jitter or a loss of temporal synchrony (Pichora-Fuller & Schneider, 1992).

One important contribution of synchrony coding is that it enables a listener to extract voice properties such as the fundamental frequency and harmonic structure. These voice properties are important because they may be used by listeners to attend to a target speech source.

Figure 8. Mean percentage of responses and standard error bars as a function of speech-gap duration for the “catch”-“cash” word pair in quiet at fast- and slow-speaking rates. Adapted from Haubert and Pichora-Fuller (1999).
when there are competing speech or noise sources, especially when such competing sources are spectrally similar to the target signal. For example, monaurally presented concurrent vowels with identical formant characteristics, such as might be produced by two talkers speaking at once, are segregated when they differ minimally (less than a semitone) in fundamental frequency and harmonic structure (e.g., Culling & Darwin, 1994). Age-related declines in ability to segregate concurrent vowels suggest that loss of synchrony affects monaural speech identification when there is a competing speech signal (Summers & Leek, 1998). As described above, when we jittered speech to simulate age-related loss of synchrony coding, both word identification and recall in younger listeners mimicked the performance of older listeners who heard intact speech.

These results provide evidence of specific subclinical changes in auditory processing that result in greater perceptual stress for older as compared to younger adults when listening conditions are challenging.

**Conclusions**

In an information-processing approach there are no clear lines of demarcation between sensation, perception, and cognition. Cognitive processing is seen as a continuation and elaboration of perceptual processing. Therefore, all levels of processing, including sensory, may be sensitive to task demands. For example, whether or not a person will hear a low-intensity tone whose frequency is 950 Hz will depend on whether or not he or she expects the tone to be at this frequency or to be at 1 kHz (Dai, Scharf, & Buus, 1991; Hafer & Schlauch, 1991). This suggests that the participant can “tune” his or her hearing to a particular frequency. In more general terms, sensory systems should not be considered as passive bottom-up processors of information, but rather as “information seekers” under central control, capable of searching for a required piece of information in a complex world. Indeed, in the auditory realm this central control over information-seeking may extend all the way down to the level of the basilar membrane.

Clearly, age-related declines in sensory functions have the potential to disrupt the normal flow of information. We have seen that with age, in addition to the progressive audiometric hearing losses that render some speech cues inaudible, there are also age-related deficits in temporal processing that undermine the perception of supra-threshold cues. Loss of numerous cues may interfere with the smooth upward flow of information. In the absence of sensory declines or in favourable listening situations, there would be little need to exert selective top-down control over peripheral information gathering. Thus, younger adults listening to discourse in a quiet environment should be able to process heard information in a more or less effortless fashion. However, as the situation becomes noisier and/or age-related sensory deficits occur, it will become necessary to actively tune the system to pick up the information that is being lost due to noise or to faulty sensory processing. If the extent of executive control is limited, the tuning requirement may reduce the capacity of the system to exercise control elsewhere. In such a model, a sufficient increase in the amount of noise should produce performance decrements in higher-order tasks because more processing resources are required for controlling and improving lower-level functions. Accordingly, we would expect performance decrements in working memory span (Pichora-Fuller et al., 1995, Speranza, Daneman, & Schneider, 2000), memory for connected discourse (Schneider et al., 2000), and paired-associate memory (Murphy et al., 2000).

Age-related declines in speech understanding could also be due to declines in the cognitive processes required for speech understanding. A number of studies have found age-related declines in working memory, as well as in long-term memory. Indeed, when younger and older listeners are equated for perceptual stress, recall is poorer in older than in younger listeners. Therefore, in any task involving a recall component, we would expect older adults to be disadvantaged relative to younger adults. Then why did we not find a negative age effect in our discourse experiment where we presumably had equated for perceptual stress?

Of course, memory is not the only cognitive factor contributing to discourse comprehension. Clearly, the ability to relate the incoming stream to past knowledge is important to comprehension. The more extensive that knowledge is, the richer is the listening context. A number of studies have shown that comprehension is improved when the listener is familiar with the context. At the sentence level, older adults are more skilled than younger adults at using context to identify heard words (Pichora-Fuller et al., 1995). If world knowledge was greater for older than younger listeners, and/or older listeners, through experience, had become more skilled than younger listeners at using context based on this knowledge, then their knowledge or contextual advantage might offset a memory deficit.

In conclusion, in order to understand the nature of the comprehension difficulties of older listeners, it will be necessary to understand the complex of interactions between the perceptual and cognitive factors that support language comprehension.
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Dans les situations quotidiennes d’écoute, les adultes plus âgés, y compris ceux dont l’ouïe se situe dans la plage normale, trouvent d’ordinaire plus difficile de comprendre le discours que les adults plus jeunes. Ces difficultés liées à l’âge sont souvent attribuées à un déclin des processus cognitifs de niveau plus élevé comme la mémoire, l’attention, etc. ou à un ralentissement généralisé quant à la vitesse à laquelle ces processus cognitifs peuvent s’effectuer. Cependant, de la recherche récente suggère qu’une détérioration du système auditif lié à l’âge pourrait jouer un rôle prépondérant dans ces difficultés de compréhension du discours. Dans cet article, nous examinons les signes qui suggèrent que le déclin de l’ouïe est en grande partie à l’origine du déclin observé dans la compréhension du discours chez l’adulte plus âgé.

Une façon de déterminer la contribution relative des facteurs perceptifs et cognitifs à la compréhension du discours est de chercher des différences d’âge négatives entre des adultes plus jeunes et des adultes plus âgés dont le système auditif est équivalent à celui de plus jeunes. Si les différences d’âge négatives n’étaient pas touchées lorsque les deux groupes étaient mis en correspondance conformément à leur ouïe, l’on pourrait conclure que le déclin cognitif est le principal responsable des difficultés de compréhension du discours liées à l’âge. Inversement, si les différences d’âge négatives disparaissaient, l’on pourrait conclure que les processus perceptifs seraient à l’origine des difficultés de compréhension du discours chez les adultes plus âgés. Malheureusement, il est impossible à toute fin pratique de trouver des adultes plus âgés dont l’ouïe est équivalente à celui d’adultes plus jeunes. Par conséquent, pour établir un rapport d’égalité entre les individus en ce qui a trait aux processus de perception, nous avons décidé de rendre aussi difficile pour tous les participants d’identifier correctement les mots détachés lorsqu’ils n’étaient pas en contexte. Plus précisément, pour chaque individu, nous avons ajusté le niveau d’un babillage en arrière-fond (12 personnes parlant simultanément) de manière à ce que les personnes qui écoutent puissent toutes entendre seulement le dernier mot d’une phrase comme « Jane was thinking about the van », où le dernier mot ne peut pas être prévisible dans le contexte de la phrase. Après avoir ajusté la situation d’écoute pour la rendre également difficile pour tous les participants à entendre les mots détachés, les différences liées à l’âge dans la compréhension et le souvenirs du discours sont grandement atténuées ou disparaissent entièrement. Par surcroît, lorsque les stimuli sont ajustés de cette façon, l’introduction d’une tâche distraillante et concurrente a un effet tout aussi néfaste sur le rendement de chaque groupe d’âge. Ces résultats suggèrent que le déclin perceptif plutôt que cognitif est principalement responsable du déclin dans la compréhension du discours lié à l’âge.

D’autres travaux de recherche examinés ici suggèrent que le déclin lié à l’âge dans le traitement auditif temporel pourrait être un facteur décisif dans les difficultés de compréhension du discours des adultes plus âgés. Les signes de cette hypothèse proviennent des tentatives de stimuler un de ces défauts de traitement temporel (une perte de synchronie neuronale) chez les jeunes en giguant le signal de façon temporelle. Lorsque le signal a été gigué, il a eu l’effet de réduire chez les jeunes la capacité de reconnaître les mots détachés dans un bruit typique à celui qu’entendent les personnes plus âgées, ce qui vient à l’appui de l’hypothèse selon laquelle les pertes liées à l’âge dans le traitement temporel contribuent aux difficultés de compréhension du discours des adultes plus âgés.

La recherche sur laquelle on se penche ici suggère que pour comprendre la nature des difficultés de compréhension des personnes plus âgées, il faudra explorer le complexe d’interaction entre les facteurs de perception et cognitifs qui entrent en jeu dans la compréhension du langage.