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Use of supportive context by younger and older adult listeners: Balancing bottom-up and top-down information processing

Key Words

Adult aging
Auditory temporal processing
Context
Cognitive compensation
Crystallized knowledge
Speech understanding in noise

Abbreviations

ELU: Ease of language understanding
PET: Position emission tomography
SPIN-R: Revised speech perception in noise test

Abstract

Older adults often have more difficulty listening in challenging environments than their younger adult counterparts. On the one hand, auditory aging can exacerbate and/or masquerade as cognitive difficulties when auditory processing is stressed in challenging listening situations. On the other hand, an older listener can overcome some auditory processing difficulties by deploying compensatory cognitive processing, especially when there is supportive context. Supportive context may be provided by redundant cues in the external signal(s) and/or by internally stored knowledge about structures that are functionally significant in communication. It seems that listeners may achieve correct word identification in various ways depending on the challenges and supports available in complex auditory scenes. We will review evidence suggesting that older adults benefit as much or more than younger adults from supportive context at multiple levels where expectations or constraints may be related to redundancies in semantic, syntactic, lexical, phonological, or other sub-phonemic cues in the signal, and/or to expert knowledge of structures at these levels.

Sumario

Los adultos mayores tienen con frecuencia mayores dificultades al escuchar en ambientes desafiantes, que los adultos más jóvenes. Por una parte, el envejecimiento auditivo puede exacerbar y/o enmascarar, como en las dificultades cognitivas(,) cuando el procesamiento auditivo se enfatiza en situaciones desafiantes para escuchar. Por la otra, un sujeto mayor puede sobreponerse a algunas dificultades de procesamiento auditivo haciendo uso de procesamiento auditivo compensatorio, especialmente cuando existe un contexto de apoyo. El contexto de apoyo puede ser aportado por claves en las señales externas y/o por conocimientos almacenados internamente acerca de las estructuras que son significativamente funcionales en la comunicación. Parece ser que algunos oyentes pueden lograr una interpretación correcta de las palabras de diferentes maneras dependiendo de los retos y de los apoyos disponibles en escenarios auditivos complejos. Revisaremos las evidencias que sugieren que los adultos mayores se benefician tanto o más que los adultos jóvenes de los contextos de apoyo en múltiples niveles, en los que las expectativas y las limitaciones pueden relacionarse con la redundancia semántica, sintáctica, léxica, fonológica o de otras claves subfonémicas de la señal y/o evidenciar conocimiento de las estructuras en estos niveles.

Older adults often report problems understanding speech in the acoustically and informationally complex situations of everyday communication. Their difficulties may be attributed to a combination of auditory and cognitive declines (CHABA, 1988; Pichora-Fuller, 2003). However, the nature of these declines and how they interact is not simple (Pichora-Fuller, 2007; Schneider et al, in press). After describing key aspects of auditory aging and the deleterious effects of information degradation on cognitive processing, the paradoxical finding that older adults may compensate for auditory declines by using preserved cognitive abilities will be explored. The surprising ability of listeners, especially older listeners, to rebalance top-down and bottom-up processing during listening promises to be important to the development of both theories of language processing and new approaches to rehabilitation (Kricos, 2006).

Auditory aging

Presbycusis is a catch-all term for hearing loss in an older adult with no known cause. There are many causes of hearing loss in older people, including environmental factors such as exposure to noise or ototoxic drugs, genetic factors, and generalized effects of aging such as cell damage and neural degeneration. Most age-related hearing impairments are types of sensorineural hearing loss involving damage to the inner ear with high-frequency audiometric threshold elevation. In addition, aging auditory systems may be damaged in ways that are not typical in younger adults with cochlear hearing loss, and they often exhibit perceptual deficits disproportionate to those of younger adults with similar audiograms. Indeed, animal studies have provided evidence of declines in the auditory system with increasing age, even when all genetic and potentially damaging environmental effects are controlled (Mills et al, 2006).

The general term ‘presbycusis’ may be of limited usefulness compared to more precise diagnostic characterizations (Kiessling et al, 2003). The definition of sub-types of presbycusis according to the particular structures of the auditory system that are affected by aging has continued to be refined for over four decades. Animal research has established three main sub-types of hearing loss truly associated with biological aging (Mills et al, 2006). Two sub-types involve inner-ear damage with high-frequency hearing loss: one from damage to the outer hair cells

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and the second from stria vascularis damage resulting in reduced endocochlear potentials. A third sub-type involves damage to the auditory nerve, possibly without high-frequency loss. There may also be degeneration in the central auditory system (Frisina et al, 2001). Currently, the prevalence of sub-types of presbycusis is unknown and they are not differentiated clinically, although there is active interest in developing such assessment protocols (Gates & Mills, 2005; Mills, 2006; Rawool, 2007).

Some studies of the prevalence of presbycusis have attempted to differentiate 'peripheral' from 'central' types using tests to evaluate higher-level auditory functioning (e.g. dichotic tests). It seems rare for older adults to have isolated central presbycusis without accompanying peripheral presbycusis (Cooper & Gates, 1991; Gates et al, 2003; Gates & Mills, 2005). In one study, with audiometric loss controlled, central presbycusis increased with age in both non-clinical and clinical samples, but it was greater in the clinical sample, with 95% of those over 80 years old being affected (Stach et al, 1990). However, the test properties and test battery protocols employed may have overestimated the prevalence of central auditory problems (Humes et al, 1992; Humes, in press). In another study, it was estimated that auditory processing abnormalities increased by 4 to 9% per year for adults over the age of 55 years, and that they also increased by 24% with every one-unit decrease on the Mini-Mental State Examination (Folstein et al, 1975), a common screening test for cognitive impairment, even though most participants passed the test (Golding et al, 2006). Furthermore, measures of central auditory processing correlate with self-reported handicap when degree of audiometric loss and use of amplification have been controlled (Chmiel & Jerger, 1996: Fire et al, 1991). Central presbycusis may explain some of the specific problems older listeners have in noise.

Most studies of the relationship between speech understanding and hearing loss have used the audiogram to index degree of impairment, but sub-types of sensori-neural hearing loss have not been differentiated and often age is not controlled. To control for confounds between age and audiometric loss, older adults with clinically significant loss at frequencies below 4 kHz have often been excluded from laboratory studies (Pichora-Fuller & Souza, 2003). For the group of older listeners selected for laboratory studies, auditory temporal processing declines provide the favored explanation for their difficulties in challenging listening conditions. Therefore, what has been learned in the laboratory about the temporal aspects of auditory aging, or the cascading effects of auditory aging on cognitive processing (Divenyi & Simon, 1999; McCoy et al, 2005; Pichora-Fuller et al, 1995; Schneider et al, in press), may be more about neural presbycusis than about the other sub-types of presbycusis which are more commonly seen in clinical settings (Gates et al, 2003; Pichora-Fuller & MacDonald, 2008). Furthermore, when the contributions of peripheral hearing loss were ruled out, systematic relationships were found between measures of auditory processing and cognitive function in healthy older adults (Humes, 2005). In a longitudinal study, compared to audiometric measures, speech-processing tests of central auditory processing had a stronger positive predictive value of the likelihood of developing Alzheimer's disease (Gates et al, 1995, 2002). Until we are better able to differentiate patterns that might be associated with different sub-types of presbycusis, we should proceed with caution in considering the interactions between peripheral and central auditory and cognitive processing in aging adults. The remainder of this paper will concern what has been learned about the balancing of bottom-up and top-down processing in older adults with relatively good audiograms whose primary auditory deficits seem to involve auditory temporal processing.

Cognitive aging

The distinction between 'crystallized' and 'fluid' abilities is important to understanding cognitive aging. Crystallized abilities (e.g. vocabulary and world knowledge stored in long-term semantic memory) are largely preserved during adult aging. In contrast, fluid abilities involved in the moment-to-moment rapid processing of information (e.g. working memory and reasoning) decline with age (West et al, 1995). These two components of cognitive aging are highly relevant to spoken language comprehension (Kemper, 1992). According to the information degradation hypothesis (Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994, 1997), one of the possible explanations for the strong correlations observed between auditory and cognitive aging is that impoverished auditory input stresses cognitive processing, exacerbating the apparent cognitive declines often observed in older listeners (e.g. McCoy et al, 2005; Pichora-Fuller et al, 1995; Pichora-Fuller, 2003, 2006, 2007; Schneider et al, in press; Wingfield et al, 1999). Thus, age-related changes in auditory processing conspire with changes in fluid information processing abilities to reduce the spoken language comprehension of older adults.

Importantly, declines in fluid abilities are offset to some extent by the preserved crystallized abilities and expert knowledge of older adults (e.g. Charness & Bosman, 1990; Ericsson & Charness, 1994; Li et al, 2004). Paradoxically, it seems that older adults demonstrate cognitive strengths that counteract or compensate for cognitive declines. Compensation refers to the closing of a gap or the reduction of a mismatch between current skills and environmental demands (Dixon & Bäckman, 1995). When bottom-up auditory processing of the incoming signal is impoverished, top-down processing may enable compensation insofar as stored knowledge and converging inputs facilitate the listener in anticipating and resolving the degraded incoming information (Craik, 2007). The ability of older adults to use 'environmental support' has been related to compensation on memory tasks (Craik, 1983, 1986). Similarly, 'context' is used to advantage by older adults to compensate when performing spoken language comprehension tasks (Wingfield & Stine-Morrow, 2000; Wingfield & Tun, 2007).

A compatible set of findings concerning compensation is emerging from cognitive neuroscience research on age-related differences in the distribution of brain activation (Pichora-Fuller & Singh, 2006). The HAROLD model (hemispheric asymmetry reduction in older adults) is based on findings that prefrontal brain activity during cognitive performance (perception, memory, and attention) tends to be less lateralized with age (Cabeza, 2002). This functional reorganization, or plasticity, of the brain might result from dedifferentiation of brain function as a consequence of difficulty in activating specialized neural circuits, or it might result from compensatory adaptation to offset age-related declines. For example, PET studies during memory tasks show that there is activation in task-relevant brain areas for both younger and older adults, but additional brain activation for older adults suggests that they use different strategies or cognitive processes to maintain memory representations over short time periods (Grady, 1998, 2000, Grady et al., 1998). Evidence supporting the compensatory interpretation is that healthy older adults who have low performance on cognitive measures recruit the same prefrontal cortex regions as young adults, whereas older adults who achieve high performance engage bilateral regions of prefrontal cortex (Cabeza et al, 2002).

A general function of the prefrontal cortex is temporal integration of information (West, 1996). More specific to language comprehension, when listeners engage in more top-down, context-driven processing involving greater activation of prefrontal cortex, then perceptual learning of distorted (noise-vocoded) speech is accelerated (Davis et al, 2005), and similar brain activation patterns have been found when the perception of sentences in noise is facilitated by meaningful semantic context (MacDonald et al, 2008). Thus, increased frontal brain activation is observed if context is used to support comprehension when the signal is degraded. Next, evidence will be presented regarding age-related compensatory use of contextual support in spoken language understanding at multiple levels.

Age-related benefit from different levels of supportive context

Understanding a spoken word involves establishing a mapping between the speech signal and the corresponding semantic meaning and the relevant linguistic structures, depending on whether the word is presented in isolation or in an utterance. This process is complex and intuitively integrative, involving information from both low-level and high-level processes (Rönnberg et al, this volume). Seminal work on speech intelligibility has demonstrated clearly that as the quality of the signal is reduced (e.g. by decreasing the signal-to-noise ratio, SNR), the slope and mean of the psychometric function varies depending on factors such as whether the item is a non-word or a real word, the number of words in the response set size, whether the word is presented in isolation or in a sentence, or whether the sentence is presented for the first time or is repeated (Figure 1). In general, the more speech intelligibility is influenced by reductions in bottom-up or signal-based factors, the more the psychometric curve is shifted to the right, whereas the more speech intelligibility is influenced by increases in top-down or knowledge-based factors, the more the curve is shifted to the left. As noted in Figure 1, the psychometric functions will also depend on talker and listener characteristics, possibly including age.

Sentential level

A recurring finding has been that older adults are more vulnerable than younger adults to reductions in the quality of the signal, but that less age-related difference is observed when it is possible for older adults to compensate by using supportive sentential context (Perry & Wingfield, 1994; Pichora-Fuller et al, 1995; Gordon-Salant & Fitzgibbons, 1997; Sommers & Danielson, 1999; Dubno et al, 2000; Wingfield et al, 2005; Pichora-Fuller, 2006). Older adults are presumed to be particularly adept at using context to compensate when listening to degraded speech because they have developed expertise by frequently listening in everyday situations where the SNR is more challenging for them than it is for younger adults.

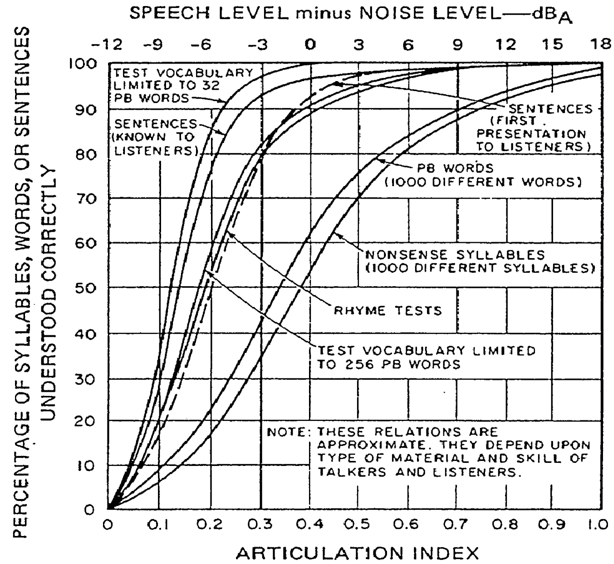

Figure 1. Percentage of syllables, words, or sentences understood correctly related to SNR (reproduced with permission from Kryter, 1994, pp. 324).

We have studied the performance of younger and older adults using the sentences and competing multi-talker babble of the revised Speech Perception in Noise Test (SPIN-R; Kalikow et al, 1977; Bilger et al, 1984). The SPIN-R materials consist of eight lists of 50 sentences; for half the items, the sentence-final target word is predictable from the sentence context (e.g. '*Stir your coffee with the spoon*') and for the other half, the sentence-final target word is not predictable from context (e.g. '*He would think about the rag*.'). Compared to younger adults, older adults benefit more from context, and their maximum benefit is found in conditions of less severe signal degradation (Pichora-Fuller et al, 1995). Similar results have also been found when the sentences have been unnaturally distorted by jittering (Pichora-Fuller et al, 2007), or by noise-vocoding (Sheldon et al, 2008b) to hamper the processing of temporal speech cues. In this set of studies, the compensatory rebalancing of top-down and bottom-up processing is more marked for older adults than for younger adults.

Figure 2 illustrates the SPIN-R results for older adults with relatively good audiograms (Pichora-Fuller et al, 1995) compared to the results for younger adults when the speech was presented either intact or distorted by temporal jittering of the frequency components up to 1.2 kHz (Pichora-Fuller et al, 2007). As expected, the functions for high-context sentences are shifted to the left with respect to the functions for low-context sentences. For low-context sentences, the function for younger adults listening to intact speech is shifted to the left compared to that for older listeners; however, the function for younger adults listening to jittered speech is similar to the function for older adults listening to intact speech. In contrast,

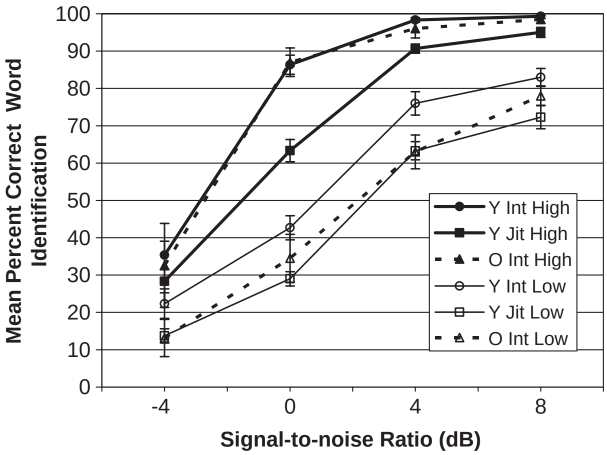

Figure 2. Mean percent correct word identification scores in intact and low-frequency jittered speech at -4, 0, $+4$, and $+8$ dB SNR on high-context and low-context SPIN-R sentences in younger listeners and for intact speech in the same SNR and context conditions for older listeners. Standard error bars are shown. (Data for younger adults are from the study of Pichora-Fuller et al, 2007; data for older adults are from Pichora-Fuller et al, 1995).

for words in high-context sentences, both younger and older groups perform well when speech is intact, but the performance of the older adults is significantly better than that of younger adults listening to jittered speech. One way to assess benefit from context is to compare the SNR at which 50% of the words are correctly identified in low-context sentences compared to high-context sentences. As shown in Figure 3, the difference between the 50% thresholds for words in high-context and low-

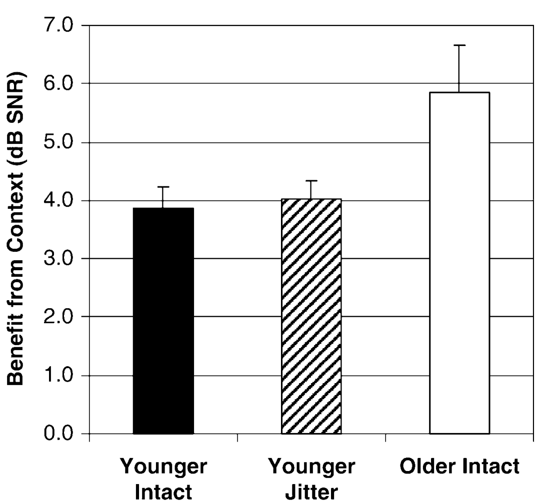

Figure 3. The benefit from context is shown for younger adults on intact sentences and on low-frequency jittered sentences, and for older adults on intact sentences. Benefit for each group is the average of the differences calculated as the SNR at which each participant scored 50% correct for target words in low-context sentences, minus the corresponding SNR threshold for target words in high-context sentences. Standard errors are shown. (Data are from the same studies as the data shown in Figure 2).

context sentences is about 2 dB greater for the older group than it is for the younger group in either the intact or jittered speech conditions. The benefit due to context derived by the younger group is similar in the intact and jittered conditions, $t(11) = .414$, $p > .05$. Importantly, compared to the younger group in jittered conditions, the older adults benefit significantly more from sentence context, $t(18) = 2.35$, $p < .02$. Older adults may be able to deploy expertise that is not readily available to younger adults, perhaps because older adults more often need to use context to follow conversation in the noisy conditions of everyday life.

Older adults are also able to deploy context to compensate for listening challenges posed by more novel signal distortions. Noise-vocoding is a type of distortion that is not experienced in nature, although it has been used often in the lab (often to simulate cochlear implant processing). In noise-vocoding, the speech signal is broken into a number of frequency bands and for each band the temporal amplitude envelope is preserved while the fine structure is replaced by noise, and then the bands are recombined. In quiet, younger adults with normal hearing are able to follow speech with surprisingly few bands of noise-vocoding (e.g. Eisenberg et al, 2000; Shannon et al, 1995). In the first study to test older listeners with relatively good hearing using this type of distortion, the SPIN-R sentences were noise-vocoded using 16, 8, 4, and 2 bands (Sheldon et al, 2008b). In one experiment, younger and older adults were tested with a SPIN-R list in each of the degrees of noise-vocoding (the entire sentence, including the context and sentence-final target word were noise-vocoded). In a second experiment, the same test materials were used, but before hearing each noise-vocoded test sentence, the listeners were primed. Priming refers to the enhancement in the processing of a stimulus following prior exposure to a related stimulus. In this case, prior to the presentation of the noise-vocoded test sentence, listeners were primed by the presentation of the intact sentence with the target word replaced by a burst of white noise. Figure 4 shows the number of bands of noise-vocoding at which younger and older listeners achieved 50% correct word identification for words in low-context and high-context sentences when the sentence was presented alone or following a prime. Figure 5 presents the benefit due to context that was achieved by younger and older groups. Even though the distortion was more deleterious for the older group, compared to the younger group, the older group again showed greater benefit from context and also from priming (for details see Sheldon et al, 2008b). In essence, the prime reinforces the context because the initial part of the sentence is presented in quiet during the prime and listeners do not have to struggle to hear the distorted context to be able to take advantage of contextual support. Interestingly, there was some benefit from priming even for words in low-context sentences, perhaps because the prime guided listeners in knowing when to listen to the relevant portion of the distorted test sentence.

Lexical level

Even when words are tested in isolation, without the possibility of compensation based on supportive sentence context, knowledge of the lexicon seems to explain why some words are easier to understand than others. The SNR required to correctly identify a word 50% of the time is correlated with word frequency, word familiarity, and the size of the neighborhood

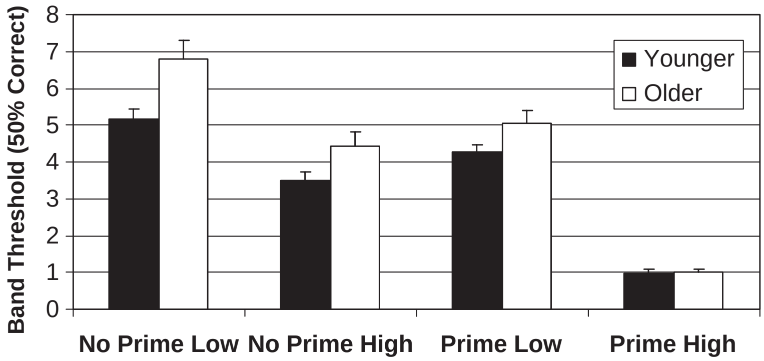

Figure 4. The mean threshold (number of bands of noise-vocoding required for a participant to achieve 50% correct word identification) for younger and older groups on low-context and high-context SPIN-R sentences presented either without or with priming before the presentation of each test sentence. Standard error bars are shown. Adapted from Sheldon et al, 2008b.

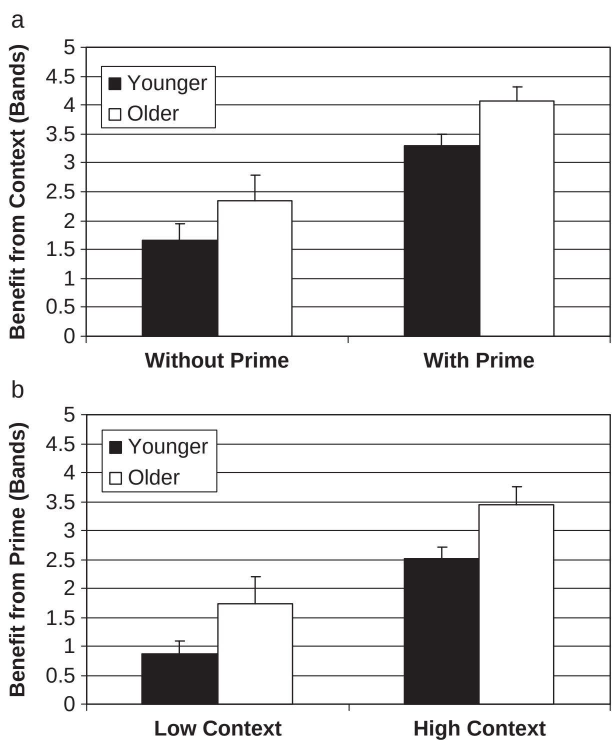

Figure 5. a. The benefit from context is shown for younger and older adults when SPIN-R sentences are presented either without or with priming before the presentation of the sentence. Benefit from context for each group is the average of the differences calculated as the band threshold (number of bands of noise-vocoding at which each participant scored 50% correct for target words) for low-context sentences, minus the corresponding band threshold for target words in high-context sentences. b. The benefit from priming is shown for younger and older adults when low-context and high-context SPIN-R sentences are noise-vocoded. Benefit from priming for each group is the average of the differences calculated as the band threshold (number of bands of noise-vocoding at which each participant scored 50% correct for target words) for primed sentences, minus the corresponding band threshold for target words in unprimed sentences. Standard errors are shown. (Data are from the same studies as the data shown in Figure 4).

of confusable words (Luce & Pisoni, 1998; Plomp, 2001). Using noise-vocoded monosyllabic word lists with different degrees of noise-vocoding (2, 4, 8, and 16 bands), older adults needed significantly more bands (8.55) than younger adults (6.13) to achieve 50% correct word identification (for details see Sheldon et al, 2008a). These age-related differences were observed when each word was presented only once; however, no such differences were found in a companion experiment using a procedure in which the number of bands was incremented until each word was correctly identified. Each word was first presented with one band of noise-vocoding, and if it was not correctly identified then it was presented with two bands, and so on, with the number of bands increasing by one to a maximum of 16 bands until the word was correctly identified. Using this procedure, age-related differences were eliminated and both groups were able to identify half of the words with an average of 5.25 bands (Figure 6).

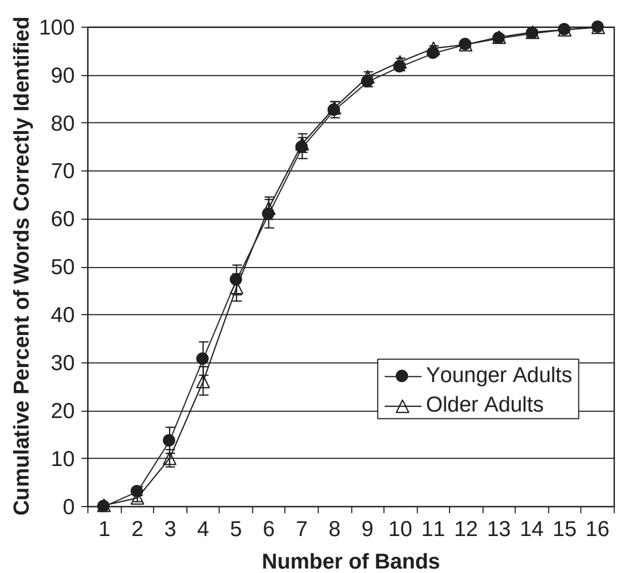

Figure 6. The cumulative percentage of words correctly identified, averaged across participants, as a function of the number of bands of noise-vocoding for younger and older participants. Standard error bars are shown. Adapted from Sheldon et al, 2008a.

Some of the 200 words tested in the study of Sheldon and colleagues (2008a) could be identified with very few bands, whereas other words required the maximum number of bands. The number of bands needed to identify the words was significantly correlated with word frequency for both younger adults ($r = -.225$, $p < .0005$) and older adults ($r = -.267$, $p < .00005$), as well as with word familiarity for the older adults ($r = -.119$, $p < .05$), but not for the younger adults, and not with the size of the neighborhood for either age group. There was also a significant correlation between age groups in the number of bands needed to identify the words ($r = .768$, $p = .00001$). The pattern of results again suggests that signal distortions have a more deleterious effect on word identification for older compared to younger adults. Nevertheless, the opportunity to hear a slightly enriched repetition of the words using the band-incrementing procedure enabled older adults to overcome the age-related differences that were observed when no repetition was provided. Furthermore, knowledge of words in terms of both word frequency and word familiarity seems to be strongly related to the performance of listeners in both age groups, but especially for the older listeners.

Phonological level

A common way to measure auditory temporal resolution is to determine the smallest silent gap that a listener can detect between leading and lagging sound markers. The size of the smallest detectable gap varies with the properties of the markers. The spectral symmetry, or the similarity in frequency content of the leading and lagging markers, is a key property to consider in relating the gap detection thresholds measured in psychoacoustic experiments using non-speech stimuli to the potentially functional role of gap detection during speech processing. A brief silent gap serves as a cue to the presence of a stop consonant (e.g. /p/) and it can enable a listener to distinguish between words such as '*spoon*' and '*soon*'. In general, gap thresholds are about ten times larger in 'between-channel' conditions, where the leading and lagging markers are spectrally different (e.g. /s/ leading and /u/ lagging the /p/ in *spoon*) compared to gap thresholds in 'within-channel' conditions. In 'within-channel' conditions, the leading and lagging markers are spectrally identical such that if there is no gap then one longer sound would be heard (e.g. one long /u/ would be heard if there were no detectable gap in the nonsense disyllable /upu/). It has been suggested that within-channel gap detection is achieved by simply detecting a discontinuity in a signal, whereas higher-level timing analyses are required to detect a gap in between-channel conditions (Phillips et al, 1997). 'Between-channel' gap detection is more easily related than 'within-channel' gap detection to typical phonological processing.

Younger adults can detect gaps that are significantly smaller than the smallest gaps that can be detected by older adults and these age-related differences are not correlated with audiometric thresholds (e.g. Schneider et al, 1994; Snell, 1997; Snell & Frisina, 2000). Gap detection findings have been related to age-related differences in speech processing (e.g. Gordon-Salant et al, 2006; Pichora-Fuller et al, 2006). In one study, age-related differences were investigated using analogous 40-msec, spectrally asymmetrical, non-speech and speech stimuli (Pichora-Fuller et al, 2006). For both the younger and older groups, gap detection thresholds for non-speech stimuli were about three times larger than those for corresponding speech stimuli (Figure 7). Importantly, the age-related differences in mean gap detection thresholds were about 50 ms less for speech than for the corresponding non-speech conditions. This pattern of results was interpreted as evidence that older adults were able to compensate for their auditory temporal processing difficulties by activating well-learned, gap-dependent phonemic contrasts and knowledge of the phonological structure of language.

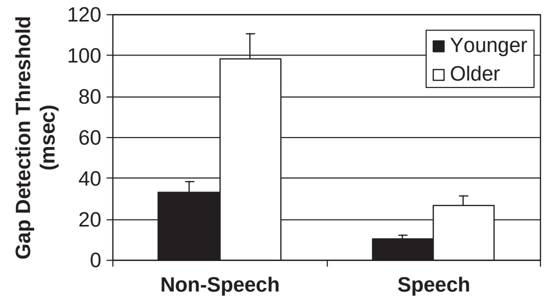

Figure 7. Mean gap detection thresholds for the younger and older group in asymmetrical, short-duration, non-speech, and speech marker conditions. Standard errors are shown. Adapted from Pichora-Fuller et al, 2006.

Sub-phonemic level

In everyday situations, listeners must understand talker-specific variations in speech production and speech produced by one talker when there are competing talkers in an auditory scene. Acoustic cues associated with talker-specific phonetic variation or with variations in the spatial location of talkers are two examples of sub-phonemic acoustical cues. The effect of age on the use of these two types of cues will be considered next.

INTER-TALKER VARIATION

Sub-phonemic inter-talker differences may influence the ease and accuracy of word identification, even when the same words are spoken by different talkers. In one study, the accuracy of word identification was measured for younger and older adults when the SPIN-R test was conducted using the sentences recorded by the original talker or using a new recording by a talker who was selected because his voice fundamental frequency (121–122 Hz) and speech rate (4.3 syllables/s) were matched to the original SPIN-R talker (Goy et al, 2007). The original and new recordings were low-pass filtered at 6 kHz to reduce spectral differences due to recording technique, and the recordings for the two talkers were equated for duration and average sound level. The lists were presented with speech at 70 dB SPL in the SPIN-R babble at 0 dB SNR. For both groups, word identification was better when the target words were presented in high-context than low-context sentences (Figure 8). It was also better for the new talker than for the original talker, although no single acoustical factor seems to explain the talker effect on word identification (Goy et al, 2007).

To determine the benefit due to context and talker, the raw scores were transformed into rationalized arcsine units (Studebaker, 1985) and the transformed scores were used to calculate the benefit from context (high-context – low-context transformed scores) and the benefit from talker (new talker – original talker transformed scores) for each participant. Two ANOVAs

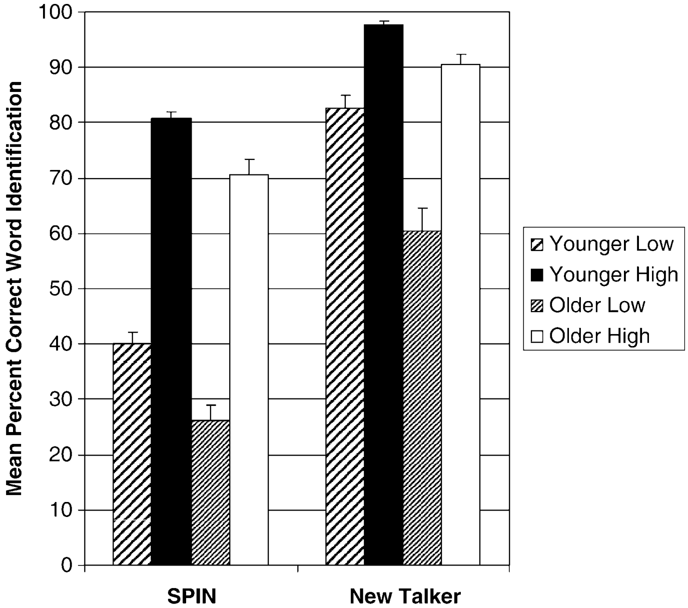

Figure 8. Mean percent correct word identification on the SPIN-R test when the sentences are spoken by the original talker or the new talker for the younger group when the target words occur in high-context sentences or low-context sentences, and for the older group for words in high-context or low-context sentences. Standard errors are shown. Adapted from Goy et al, 2007.

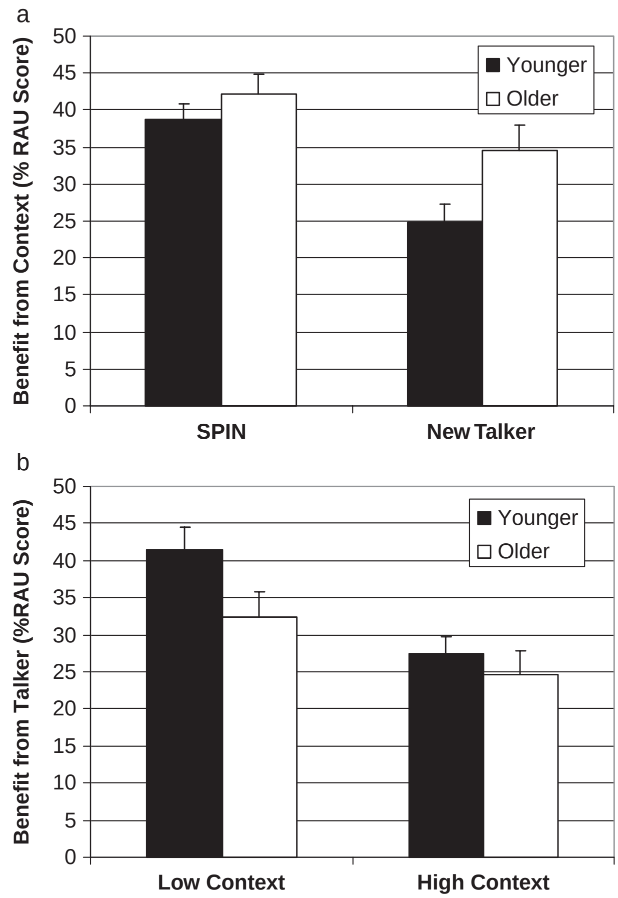

Figure 9. a. The benefit from context is shown for younger and older listeners when the SPIN-R sentences are spoken by the original talker or the new talker. Benefit from context is calculated as the group average of the differences for each participant between the percent correct word identification score transformed into rationalized arcsine units for target words in high-context sentences, minus the corresponding score for target words in low-context sentences for each participant in each group. b. The benefit from talker-specific cues is shown for younger and older listeners when the target words were presented in low-context or high-context sentences. Benefit from talker-specific cues is calculated as the group average of the differences for each participant between the percent correct word identification score transformed into rationalized arcsine units for target words in sentences spoken by the new talker, minus the corresponding score for target words in sentences spoken by the original SPIN talker for each participant in each group. Standard errors are shown. (Data are from the same study as the data shown in Figure 8).

were conducted, one to investigate the effects of age and talker on benefit from context, and another to investigate the effects of age and context on benefit from talker. As shown in Figure 9 (a), there were main effects of talker, with both age groups realizing greater benefit from context with the original talker than with the new talker, $F(1,30) = 13.54$, $p < .01$, and age, with older listeners realizing greater benefit from sentence context than younger adults, $F(1,30) = 6.95$, $p < .05$. As shown in Figure 9 (b), there was a main effect of context, with both age groups realizing benefit from talker-specific cues more for low-context than high-context sentences, $F(1,30) = 13.54$, $p < .01$; however, the main effect of age was not significant, $F(1,30) = 4.11$, $p = .52$. No interaction effects reached significance in either ANOVA. Thus, there are age-related differences in the use of context, but both groups are influenced similarly by inter-talker differences.

Spatial separation of multiple talkers

In a three-talker auditory scene where each talker's voice is presented from its own loudspeaker location, younger adults are nearly perfectly able to understand word pairs from a closed set (one of four colours followed by one of eight numbers) if they are told in advance the location of the target talker and/or the noun (callsign name) at the beginning of the target utterance (Kidd et al, 2005). Using the same method, we tested the ability of younger and older adults to use *a priori* knowledge of the location of a target talker when there was real spatial separation between the three talkers in the auditory scene, and we also examined their performance when the spatial separation of the talkers was simulated using restricted acoustic cues (Singh et al, 2008). In the simulated spatial separation conditions, all three sentences were presented from two loudspeakers, one to the right and one to the left, but time delays between the presentations of the sentences from the two loudspeakers were manipulated so that the sentences were perceived to originate at different locations. When a sentence was presented simultaneously from both loudspeakers, it was perceived to originate centrally. If the presentation from one loudspeaker led the presentation from the other loudspeaker by 3 milliseconds, because of the precedence effect, the resulting percept was localized to the side of the leading loudspeaker. In this way, spatial separation between the

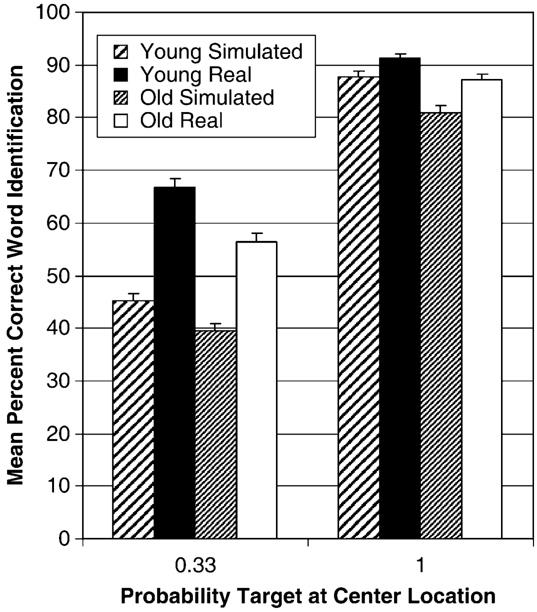

Figure 10. Mean percent correct word identification when the probability of the target being located at the center location was either 0.33 (chance) or 1.0 (certain) for the younger group when spatial separation of the three voices was real or simulated using the precedence effect, and for the older group when spatial separation was real or simulated. Standard errors are shown. Adapted from Singh et al (2008).

three talkers was perceived while the contribution of some of the acoustical cues (i.e. inter-aural level difference cues) arising from actual spatial separation were largely eliminated (e.g. Freyman et al, 1999; Li et al, 2004). As shown in Figure 10, both age groups understood more target words when the *a priori* probability of the target being located at the center was perfect (1.0) compared to when it was chance (0.33), and both age groups understood more target words in the real spatial separation conditions compared to the simulated spatial separation conditions (for details see Singh et al, 2008).

To determine the benefit that listeners derived from the probability cue and from the richness of the spatial cues, the raw scores were transformed into rationalized arcsine units (Studebaker, 1985) and the transformed scores were used to calculate the benefit from the cues for each participant. Two ANOVAs were conducted, one to investigate the effects of age and probability on benefit from binaural cues, and another to investigate the effects of age and binaural cues on benefit from the cues. There was a main effect of binaural cue on benefit from the probability cue, $F(1,14) = 29.97$, $p < .001$, with greater benefit from the probability cue being realized in the simulated than in the real conditions; however, there was no significant main effect of age and no interactions (Figure 11 (a)). There was a main effect of probability cue on benefit from binaural cues, $F(1,14) = 29.97$, $p < .001$, with greater benefit from binaural cues being realized in the chance than in the certain probability conditions; however, there was no significant main effect of age and no significant interactions (Figure 11 (b)). Older adults were able to compensate as well as younger adults by using either the probability cue or the enriched natural binaural acoustic cues.

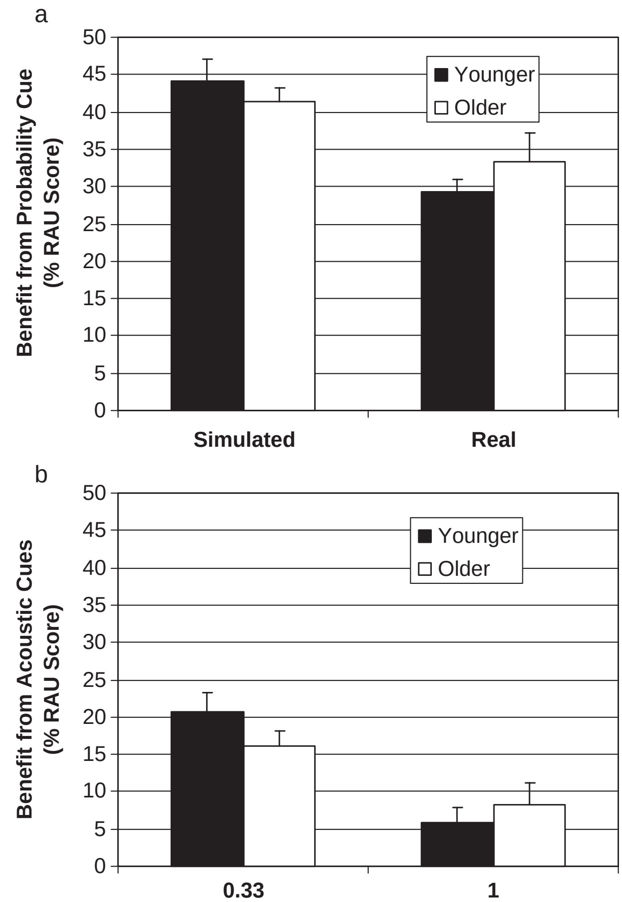

Figure 11. a. The benefit from the probability cue is shown for younger and older adults when the spatial separation of the three voices is real or simulated using the precedence effect. Benefit from the probability cue is calculated as the group average of the differences for each participant between the percent correct word identification score for target words in the certain (1.0) probablity conditions minus the corresponding score for target words in the chance (0.33) probability conditions for each participant in each group. b. The benefit from binaural cues is shown for younger and older adults when the probability cue is 0.33 or 1.0. Benefit from binaural cues is calculated as the group average of the differences for each participant between the percent correct word identification score for target words in the real spatial separation conditions minus the corresponding score for target words in simulated spatial sepration conditions for each participant in each group. Standard errors are shown. (Data are from the same study as the data shown in Figure 10).

Thus, even support derived from acoustical, non-linguistic cues can be used by older listeners as well as it is by younger listeners.

Discussion

There are inter-individual as well as intra-individual differences in how speech processing varies with the degree of challenge posed by the complexity of the listening condition and task requirements (Pichora-Fuller, 2007). Regardless of age, any listener will shift from relatively effortless or automatic processing to more effortful or controlled processing of incoming speech information when the listening conditions or task demands become sufficiently challenging (see the working memory model for ease of language understanding, ELU, for a similar distinction between implicit and explicit speech processing; Rönnberg et al, this volume). One critical question is when the shift between automatic and effortful listening occurs for an individual (or in the ELU model when a 'mismatch' occurs due to poor or unexpected signal properties).

A key question is how listeners muster various supportive cues to compensate for degradations in the signal. The use of supportive context from enriched low-level acoustic cues (such as binaural cues or favorable talker-specific variations in speech production) could facilitate implicit processing by off-setting otherwise significant reductions in signal quality (such as when the SNR is adverse). The use of supportive context from higher-level knowledge or external environmental supports could also facilitate implicit processing by providing an alternative fast route to a match between signal and meaning despite reduced signal quality, such as when expectancies are formed based on prior sentence context, priming, or other *a priori* knowledge about the signal. The use of supportive context could also play a role in explicit processing when a mismatch does occur by enabling ambiguous alternatives to be resolved using non-signal sources of information such as lexical and semantic knowledge.

These studies suggest that older adults have remarkable abilities to deploy a wide range of supports to compensate when listening conditions are challenging. Future studies are needed to discover how and over what time course different levels of support are used. Both theories of language processing and the development of more effective rehabilitation would be informed by better understanding of the compensatory advantage conferred by the use of multiple levels of supportive context.

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