CHAPTER

9

Audition and Language Comprehension in Adult Aging: Stability in the Face of Change

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INTRODUCTION

> *Tout d'abord poussé par ce qui se fait en aviation, j'ai appliqué aux insectes les lois de la résistance de l'air, et je suis arrive…à cette conclusion que leur vol est impossible* (Magnan, 1934).

Older adults are the fastest-growing segment of the US population, with the number of adults age 65 or older expected to grow to 70.3 million in 2030 (Kempler, 2005). Among this group, hearing loss is the third most prevalent chronic medical condition, exceeded only by arthritis and hypertension (Lethbridge-Ceijku, Schiller, & Bernadel, 2004).

Although hearing loss is a common accompaniment of adult aging, it has historically been considered as an independent issue in aging research. We now know, however, that there are effects of hearing loss beyond simply missing or misidentifying individual words in a spoken message. That is, even with milder hearing losses the perceptual effort required for successful speech recognition may draw on cognitive resources that would otherwise be available for downstream comprehension operations (Wingfield, McCoy, Peelle, Tun, & Cox, 2006) or encoding what has been heard in memory (Pichora-Fuller, 2003; Rabbitt, 1991; Surprenant, 2007; Wingfield, Tun, & McCoy, 2005). When combined with age-related declines in working memory, processing speed, and executive function (Salthouse, Atkinson, & Berish, 2003), comprehension of everyday speech can represent a significant challenge at both the perceptual and cognitive levels.

Challenges for Speech Comprehension

The efficiency with which everyday spoken discourse is comprehended belies the number and complexity of the operations that must be performed for its success. As speech arrives at a rate that averages between 140 and 180 words per minute (wpm), the listener must: (i) extract the physical features of the acoustic signal and resolve the speech phonology; (ii) match this input phonology in a best-fit manner with phonological representations of potential word candidates in the listener's internal lexicon; (iii) determine the syntactic and semantic relations among the lexical elements in the utterance, and detect the underlying propositions or "idea" units represented; (iv) determine the relations among these propositions in order to construct overall coherence to the utterance, often with the need for extended inference. This is not merely a feed-forward system, however, but one in which operations overlap in time and involve continual feed-back from higher levels at each level of analysis.

Unlike reading, where the reader can use eye movements to control the rate of input, with speech, the rate of input is controlled by the speaker and not by the listener. Those operations that cannot be performed "on-line" as the speech is being heard, must be accomplished retrospectively on a brief, capacity-limited memory trace of the original input. As an added challenge, much of everyday speech is notably underarticulated, such that word recognition must rely heavily on acoustic and linguistic context (Lindblom, Brownlee, Davis, & Moon, 1992). That this lack of articulatory clarity goes unnoticed in everyday listening reflects the continual interaction between the *bottom-up information* supplied by the sensory input, supported by *top-down information* from linguistic and real-world knowledge.

Albeit more subtle in normal aging than in neuropathology such as Alzheimer's disease or other dementing illness, the biological changes that accompany adult aging have a measurable impact on structure and network dynamics that carry cognitive function (Burke & Barnes, 2006). The consequences of these changes are seen in declining effectiveness of episodic memory (Wingfield & Kahana, 2002), reduced processing speed and working memory capacity (Salthouse et al., 2003), and reduced efficiency in executive function and inhibition

(Hasher, Lustig, & Zacks, 2007; McCabe, Roediger, McDaniel, Balota, & Hambrick, 2010).

In spite of these impediments, the comprehension of spoken language in healthy aging typically reflects relative stability, or at most a gradual decline, rather than an abrupt or catastrophic failure. The question is thus not only why performance in some aspects of language tasks declines in adult aging, but why in normal aging performance remains as stable as it does. In phrasing the question this way, we address one of the most fundamental questions in current neurobiology: how stable behavior can be produced in spite of changes in underlying neural structures and circuit parameters (Prinz, Bucher, & Marder, 2004).

Our goal in this chapter is to examine the effects of cognitive change and age-related hearing loss on speech comprehension, and on memory for what has been heard. As we do this we consider the two sides of the aging, hearing acuity, and speech comprehension coin. On the positive side we show how spared linguistic knowledge can overcome sensory and cognitive decline to maintain stable speech comprehension in adult aging. On the negative side we present the cognitive costs that come with age and the perceptual effort attendant to reduced hearing acuity. (A good discussion of age-related issues in language production can be found in Burke & Shafto (2004).)

AGE-RELATED HEARING LOSS

Although population studies show a general decline in hearing acuity in adult aging, there is wide variability from individual to individual. Estimates of the incidence of age-related hearing loss (*presbycusis*) vary, but a reasonable estimate is that some 40–45% of adults over the age of 65 show some degree of hearing loss, with this number increasing to 83% in the population over the age of 70 (Cruickshanks, Wiley et al., 1998).

In clinical audiology the degree of hearing loss is categorized based on hearing acuity in the major speech frequency range, and is referred to as *slight*, *mild*, *moderate*, *severe*, or *profound* (Katz, 2002), with the single largest group of older adults with impaired hearing falling in the mild-to-moderate range. It is a public health issue that the majority of individuals who would benefit from amplification do not regularly wear hearing aids, especially those in the moderate loss range (Chien & Lin, 2012; Fischer et al., 2011).

Audition: Some Preliminaries

The detection of speech, or any other auditory stimulus, begins with the mechanical transmission of vibrations of the eardrum (*tympanic membrane*) induced by the sound energy arriving at the ear. This vibration sets in motion three small articulated bones in the *middle ear*, collectively called the *ossicles*. The function of the ossicles is to transmit, and mechanically amplify, these vibrations to a second membrane (the *oval window*) that separates the middle ear from the *inner ear*. Vibration of this second membrane sets in motion a fluid located in the *cochlea*, a snail-shaped structure about the size of a pea or the nail on one's little finger. Located inside the cochlea is a thin membrane (the *basilar membrane*) that runs the length of the cochlea, along which lie some 12,000–15,000 *outer hair cells*. The motion of the *cochlear fluid* causes a wave-like movement of the basilar membrane that translates into differential movement of the hair cells along different regions of the membrane sensitive to particular sound frequencies. This movement of the outer hair cells stimulates approximately 3500 *inner hair cells* that transduce this stimulation into coded neural impulses that pass through the *cochlear nuclei* and *superior olivary complex* in the brainstem, the *medial geniculate nucleus* in the thalamus, and end in the primary auditory receiving area of the brain (*Heshl's gyrus*) located along the superior portion of the temporal lobe.

Types of Hearing Loss

The term, *peripheral hearing loss* includes either a conductive (middle ear) or sensorineural (inner ear) hearing loss. These are typically measured by determining the lowest intensity at which pure tones of various frequencies can first be detected (*pure-tone thresholds*). As we shall see, however, in the case of age-related hearing loss, such auditory thresholds tell only part of the story.

Conductive Hearing Loss

Any dysfunction in the outer or middle ear is termed a conductive hearing impairment. (The *outer ear* refers to the ear canal [*external auditory meatus*], the cartilaginous tube that runs from the ear itself [the *pinna*] to the tympanic membrane). The consequence of a conductive loss is a general attenuation of the loudness of the sounds one hears. The most common, and easily treatable, cause of a conductive impairment is a plugging of the ear canal by an excess accumulation of cerumen (ear wax). More serious is a conductive loss due to restricted movement of the ossicles themselves, whether due to inflammation or infection in the middle ear (*otitis media*), or an age-related stiffening of the ossicles. The integrity of ossicle movement in the middle ear can be measured using *tympanometry*, a relatively non-invasive procedure in which the eardrum, and hence the ossicles, are set in motion by a controlled burst of air pressure, with the measured strength of the pressure return serving as an index of the conductance properties of the ossicles (Fowler & Shanks, 2002). Available medical and surgical treatments can often ameliorate this type of loss.

Sensorineural Hearing Loss

The emblematic type of hearing loss in adult aging, however, is a sensorineural hearing loss that results from the loss of hair cells in the inner ear, especially from the high-frequency-sensitive region of the basilar membrane. This loss or attenuation of high-frequency sounds can have a debilitating effect on speech recognition especially for high-frequency speech sounds, such as the "s" as in "same," the "f," as in "fish," or the voiceless "th" as in "thing."

Hair cell loss in different frequency regions of the cochlea can be detected by measuring *distortion-product otoacoustic emissions* (DPOAEs). In this test pure tones of particular frequencies are delivered to the ear, with a small but sensitive microphone placed in the ear canal that can detect the sound of hair cell movements, if present, in the region of the basilar membrane most sensitive to these frequencies. Auditory evoked potentials (AEPs), including the auditory brainstem reflex (ABR), which measure neural responses to clicks or tones recorded from surface electrodes, can assess the integrity of the ascending auditory pathways.

Although hearing acuity is often represented as an average pure tone threshold (pure-tone average; *PTA*) for sounds in the major speech frequency range (e.g., a PTA across 500, 1000, 2000, and 4000 Hz), a more complete picture of an individual's acoustic sensitivity is depicted with an *audiogram*, which is a plot of the sound level, measured in decibels (dB), needed to detect sounds across a range of frequencies. A 0-dB line in the upper part of the audiogram represents a hearing level (HL) at each frequency normed for young adults with good hearing; hence the possibility of a hearing threshold of less than 0 dB.

Figure 9.1 shows the typical shape of an audiogram for an older adult with a sensorineural hearing loss plotted for the left and the right ears over the range of frequencies from 250 Hz to 8000 Hz. One can see a mild attenuation at the lower frequencies (e.g., 250–500 Hz) with a gently increasing degree of loss in the higher-frequency ranges. The shaded region in Figure 9.1 represents the primary frequency range of speech, with vowels represented at the lower part of this frequency range (e.g., 500 Hz) and

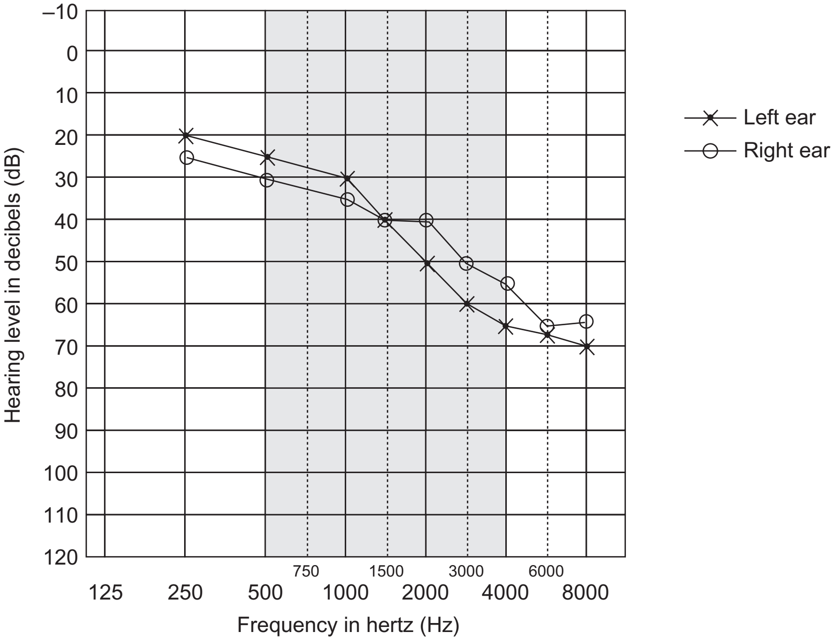

FIGURE 9.1 Typical shape of an audiogram representing age-related sensorineural hearing loss. The abscissa shows frequencies tested (in Hz); the ordinate shows sound level (in dB) necessary to hear pure tones at each of the tested frequencies. The shaded portion represents the major speech frequency range.

higher-frequency speech sounds, such as the voiceless consonants, at approximately 4000 Hz, although the full range of human speech can even be somewhat higher. (A conductive hearing loss will show a relatively flat profile across the frequency range, while a noise-induced hearing loss often shows a selective loss at about 4000 Hz within an overall steeply sloping loss across the high-frequency range.)

Central Processing Deficits

Although pure tone thresholds are the most commonly used index of hearing acuity, for many older adults sensitivity to pure tones is not a good predictor of their hearing for speech. In addition to reduced acuity, per se, the older auditory system often shows decreased efficacy in temporal and spectral resolution that can significantly degrade the clarity of the speech signal (Humes & Dubno, 2010). These so-called "central" deficits can contribute to the common complaint of many older adults of a special difficulty in understanding speech, even when amplified. The nature of these central processing disorders represents an area of active research in regard to testing (Cox, McCoy, Tun, & Wingfield, 2008), definition (Humes et al., 2012), and anatomy (Canlon, Illing, & Walton, 2010). An excellent review of major findings from animal and human research on the nature of age-related hearing loss, its epidemiology, and training possibilities to enhance everyday communication can be found in Gordon-Salant (2014).

Variability in Age-Related Hearing Loss

The previously noted variability in hearing acuity among older adults, like many changes in adult aging, can be accounted for by genetic as well as environmental influences. In the case of hearing acuity environmental factors include exposure to noise, medications with ototoxic properties, and risk factors such as cardiovascular disease (Gates, Cobb, D'Agostino, & Wolf, 1993), cigarette smoking (Cruickshanks, Klein et al., 1998), and diabetes (Bainbridge, Cheng, & Cowie, 2010).

In a study of genetic influence on hearing acuity we compared hearing acuity for 179 monozygotic (MZ) twin-pairs and 150 dizygotic (DZ) twin-pairs ranging in age from 52 to 60 years. Although there was a significant correlation between the hearing acuity of the DZ twin-pairs, the correlation was significantly higher for the MZ twin-pairs, with biometrical modeling indicating that between 65% and 70% of the variance in better-ear hearing acuity in the middle- and high-frequency ranges could be accounted for by genetic influences (Wingfield, Panizzon, Grant et al., 2007). The specific genes that appear as risk factors for age-related hearing loss remain an active area of research (Yamasoba et al., 2013).

Speech in Noise: A Hallmark of Aging Hearing

Listening to speech in a noisy environment is a part of one's listening life: whether one is attempting to listen to a companion over the sound of traffic, or the "babble" of many people speaking in a noisy restaurant. Although a challenge for all listeners, one of the hallmarks of aging hearing is a special difficulty for speech recognition in noise, even when speech recognition in quiet is relatively good (Gordon-Salant & Fitzgibbons, 1995; Humes, 1996).

Separating Speech from Noise

Energetic masking refers to the reduced audibility of a target speaker caused by the fusing of the acoustic energy from the target speaker and background noise. Among the features listeners use to perceptually separate a single speaker from the "noise" of other speakers are differences in spatial location made possible by such factors as intensity and phase differences at the two ears, and the use of voice quality, speech rate and the metrical patterns of the various speakers.

Older adults with reduced auditory sensitivity can be deprived of some or all of these cues, making separation of a complex auditory environment into separate acoustic "streams" especially difficult (Marrone, Mason, & Kidd, 2008; Singh, Pichora-Fuller, & Schneider, 2008). Although this early-stage perceptual separation is often considered to be an automatic, resource-free process, there is evidence that this early-stage separation may be resource-demanding (Heinrich, Schneider, & Craik, 2008). Good reviews of the processes involved in auditory stream segregation and "auditory scene analysis" can be found in Bregman (1993) and Shinn-Cunningham and Best (2008).

Informational Masking

Informational masking refers to interference from concurrent stimuli beyond energetic masking alone. A prime example is the finding that attempting to attend to a target speaker with one or two other talkers in the background, in which individual words can be identified, causes more interference than a background "babble" of many voices, in which no individual words can be distinguished (Tun & Wingfield, 1999).

The term, *cocktail party problem* was coined by Cherry (1953) to refer to one's ability to attend to a single speaker while apparently ignoring the content of other speakers' voices. In young adults this ability to filter or attenuate distraction from a second speaker is well developed. For example, in an experiment in which young adults were instructed to "shadow" (repeat while listening) the content of a target speaker heard in one ear over earphones, listeners were often unaware that the voice of a concurrent, to-be-ignored speaker delivered to the other ear, had changed from speaking English to speaking French (Treisman, 1964). Although attention may appear to be absolute, some monitoring of an apparently unattended speaker must be occurring, as one can, about a third of the time, hear one's name when it is spoken by an "unattended" speaker (Conway, Cowan, & Bunting, 2001; Moray, 1959).

Selective attention to a single speaker in a cocktail party situation is less effective in older adults (Tun, O'Kane, & Wingfield, 2002) and especially so for adults with hearing loss (Shinn-Cunningham & Best, 2008). This decrement in attending to a target speaker with another talker in the background is due in part to energetic masking, and in part to informational masking at the cognitive level. For example, consistent with Treisman's (1964) findings, an experiment conducted by Tun et al. (2002) found that young adults were no more distracted by a competing speaker speaking in English than they were by a competing speaker speaking in an unfamiliar language (Dutch). By contrast, older adults showed differentially greater interference when the competing speaker was speaking in meaningful English, suggesting that in the older adults the to-be-ignored speech was not only "leaking through" an inhibitory filter but that its content could not be fully ignored (Tun et al., 2002). This content-specific interference effect is consistent with arguments for an inhibition deficit in adult aging (Hasher et al., 2007).

COMPENSATION THROUGH LINGUISTIC KNOWLEDGE

We began this chapter with a quote from the French entomologist, Antoine Magnan, writing in 1934 that the wing-size to weight-ratio of many flying insects, such as the bumble bee, should make it impossible for them to fly. The answer, of course, is that these early calculations failed to take into account the full complexity of factors relating to the structure and movement of insects' wings that do in fact allow them to fly (Sane, 2011). In a similar way, when one contemplates the age-related limitations on processing speed, working memory, inhibitory processing, and reduced hearing acuity, one may ask why comprehension of connected speech by older adults is as good as it is. The answer in this case is older adults' ability to compensate for these processing deficits with linguistic knowledge, typically spared in healthy aging (Kempler & Zelinski, 1994). This compensation occurs at both the neural and behavioral levels. At the neural level, when challenged by syntactically complex sentences older adults engage a compensatory recruitment of regions in the frontal and temporoparietal cortices bilaterally in support of left hemisphere core sentence-processing regions to a degree not shown for young adults (Peelle, Troiani, Wingfield, & Grossman, 2010; Wingfield & Grossman, 2006). In the following sections we focus on compensation at the behavioral level; first for the perceptual identification of individual words, and then for comprehension and recall of spoken sentences.

Effects of Age and Hearing Acuity on Word Recognition

In the absence of a linguistic context there are a number of word-level factors that influence the ease with which a spoken word will be recognized. These include the relative frequency with which a word occurs in the language, with common words recognizable with less sensory information than rare words (Grosjean, 1996; Howes, 1957), and easier recognition of words with fewer words that share phonology with the target word (Luce & Pisoni, 1998). This latter point is embodied in the *neighborhood activation model* (NAM) of word recognition. This model posits that the more words that share phonology with a target word (its phonological density) the greater the difficulty of recognizing that word when, for example, it is degraded by background noise (Sommers, 1996). A complementary model, the *onset cohort* *model*, places an emphasis on the beginnings of words, with the suggestion that hearing the onset of a word will activate all words that share that beginning sound, with the size of the onset cohort trimmed as the word unfolds in time and more of the word onset is heard (Marslen-Wilson & Zwitserlood, 1989). In either case, the differences in articulatory clarity and variability in speakers' utterances demand that models of word recognition must be based on a best fit rather than an absolute fit between a sensory input and potential word candidates.

Although hearing acuity will affect the probability and/or speed with which a word will be correctly identified, Sommers and Danielson (1999) have shown that older adults, even when hearing acuity is taken into account, require differentially greater signal clarity than young adults to identify words that share phonology with a large number of words than for words with fewer phonological neighbors. The problem is not the loss of vocabulary knowledge. Indeed, while young adults may outperform older adults on tests of word retrieval, older adults often outperform young adults on tests of vocabulary knowledge (Kavé & Yafé, 2014). Rather, the Sommers and Danielson finding can be viewed as a second incidence of an age-related inhibition deficit affecting speech processing. In this case it is the suggestion that older adults' word recognition is negatively influenced by a reduced ability to inhibit phonologically similar but incorrect competitors that were initially activated along with the ultimately correct response (Sommers, 1996; Sommers & Danielson, 1999).

Effects of Contextual Facilitation

Over a century ago, James McKeen Cattell observed that a word presented in the context of a sentence, or a letter in the context of a word, could be recognized faster than when the same stimulus was presented without such contextual constraints (Cattell, 1886). This reflects a general principle of perception that the more probable a visual or auditory stimulus, the less sensory information will be needed for its correct recognition (Morton, 1969). This principle has long been instantiated for spoken words by showing facilitated word recognition whether the probability of a stimulus word is increased by giving a semantically associated word, by providing a category description of the target word or by presenting the word within a linguistic context (Black, 1952; Bruce, 1958). Analogous studies have shown that older adults' recognition of degraded words is facilitated to an equal, and often greater, degree than for young adults when a word is heard within a sentence context relative to a neutral context (Cohen & Faulkner, 1983; Pichora-Fuller, Schneider, & Daneman, 1995; Wingfield, Aberdeen, & Stine, 1991).

Although many studies have contrasted recognition for words in a neutral versus a constraining linguistic context, one can examine the degree to which systematically increasing the degree of contextual constraint affects the ease of word recognition. This can be done by using a so-called "cloze" procedure (Taylor, 1953), in which the transitional probability of a word in a sentence context is estimated by the percentage of individuals who give that word when asked to complete a sentence with what they believe would be the most likely final word. Using such materials it has been shown for written words (Morton, 1964) and spoken words (Wingfield et al., 1991) that the ease of word recognition is inversely proportional to the transitional probability of the word in a sentence context.

Benichov, Cox, Tun, and Wingfield (2012) conducted a study with participants aged 19–89 years, with levels of hearing acuity ranging from normal hearing to mild-to-moderate hearing loss. (As previously noted, this is the most common degree of loss among hearing-impaired older adults.) A regression analysis showed that hearing acuity, although a predictor of the signal-to-noise ratio necessary to correctly recognize a word in the absence of a constraining linguistic context, dropped away as a significant contributor to recognition of sentence final words by the time the linguistic context yielded an average cloze probability 0.53. By contrast, cognitive ability, represented as a *z-score* composite of the individuals' episodic memory, working memory, and processing speed accounted for a significant amount of the variance in word recognition for words heard in a neutral context and for all degrees of contextual constraint examined.

Expectation and Entropy in Word Recognition

An interesting finding in the Benichov et al. (2012) study was that age contributed significant variance to recognition scores even when word recognition was statistically controlled for hearing acuity and cognitive function. Although the cognitive battery sampled several components of cognitive function, inhibition was not specifically tested. This aspect was investigated by Lash, Rogers, Zoller, and Wingfield (2013), who examined effects on word recognition of age, hearing acuity, and expectations for a word based on a linguistic context, but also on effects of competition from other words that might also fit the semantic context. The technique used was *word onset gating*, in which a listener is presented with increasing amounts of a word's onset duration until the word can be correctly identified (Grosjean, 1996). Computer editing was used to present participants with just the first 50 ms of a target word, with instructions to say what they believed the word might be. If unable to do so they were presented with the first 100 ms of the word, then the first 150 ms of the word, and so forth, with the amount of word onset duration increased in 50 ms increments until the word could be correctly identified. (To put these figures into perspective, the average duration of a word-initial consonant-plus-vowel (CV) is just over 200 ms.)

Figure 9.2 shows the mean amount of word onset information (gate size in ms) needed for correct identification of a target word when heard in a neutral context ("The word is…") or when the word was preceded by a linguistic context with a measurable but low probability of suggesting the target word (e.g., "The cigar burned a hole in the FLOOR" [$P = 0.03$]), a medium probability level (e.g., "The boys helped Jane wax her FLOOR" [$P = 0.10$]) or a higher probability (e.g., "Some of the ashes dropped on the FLOOR" [$P = 0.43$]).

It can be seen on the left side of Figure 9.2 that when heard in a neutral context older adults with a mild-to-moderate hearing loss (poor hearing) required a significantly greater amount of a word onset to correctly identify a target word than a group of age-matched older adults with good hearing acuity for their ages, and with these participants in turn requiring a greater amount of word onset for recognition than a group of young adults with age-normal hearing acuity. As would be expected from our prior discussion, one also sees in Figure 9.2 that the difference between these three participant groups diminishes as the transition probability of the target word in a particular sentence context is progressively increased to the point where the differences between the older adults with poor and good hearing acuity is no longer significant.

An advantage of published cloze norms e.g., (Lahar, Tun, & Wingfield, 2004), is that when participants have been asked to complete sentence stems, also reported is the full range of responses given by each of the participants, and the number of participants giving these alternative responses. These data allow one to estimate not only the expectancy of a sentence final word based on the transitional probability of that word in the sentence context, but

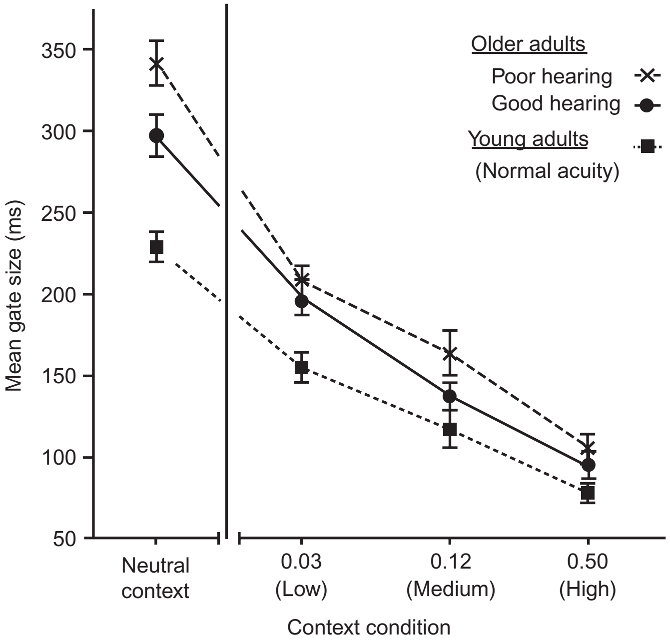

FIGURE 9.2 Mean amount of word onset information (onset gate size in ms) needed for correct identification of a sentence-final target word heard in a neutral context or when the word was preceded by a linguistic context with a low, medium or high probability of suggesting the target word. Probabilities are based on published norms representing the likelihood that individuals will complete a sentence with the target word. *From Lash et al. (2013, p. 243). Copyright 2013 by Taylor & Francis. Reprinted with permission.*

also the uncertainty (*entropy*) implied by the number, and probability distribution, of alternative responses also potentially implied by the context. When this was done, it was shown that more of a word onset was needed for recognition when the sentence context activated a large number of highly competitive word possibilities, with this effect of competition more detrimental to the older adults. That is, while context-based expectancy facilitated word recognition for all three participant groups, a negative effect of a distribution of strong competitor responses was a factor related to age, independent of the older adults' level of hearing acuity (Lash et al., 2013). These results are consistent with Sommers and Danielson's (1999) proposition that older adults have greater difficulty than their young adult counterparts in inhibiting non-target responses. In Sommers and Danielson's case the competition came from the presence of a larger number of phonological "neighbors" of target words. The present case differed only in that response competition came from the distribution of words that also shared a contextual fit with the semantic context.

The study by Lash and colleagues, like most studies of contextual facilitation on word recognition, examined effects of a preceding linguistic context. It often happens, however, that one realizes the identity of an indistinctly heard word only retrospectively, as one hears the context that follows the acoustically ambiguous word. It is here that older adults with reduced working memory capacity are at a disadvantage. Although older adults can make good use of a preceding context to aid word recognition, they are less effective relative to young adults in retrospective word recognition based on a following context that implies a need for an effective memory trace of the acoustically ambiguous region (Wingfield, Alexander, & Cavigelli, 1994).

Comprehension and Recall at the Sentence Level

Among the best-studied linguistic challenges are those related to complex syntax. Consider the following sentence that expresses its meaning using a subject-relative embedded clause structure: "*The author who insulted the critic hired a lawyer.*" There are two major thematic roles represented in this sentence: the author, who is the agent who performs both actions (insulting and hiring), and the lawyer, who was hired. Comprehension requires the listener to understand that *The author hired a lawyer* is the main clause of the sentence, interrupted by the relative clause, *who insulted the critic*.

Now consider a second sentence with the same nine words but with the meaning expressed using an object-relative embedded clause structure: "*The author who the critic insulted hired a lawyer.*" In this type of structure, not only does the embedded clause interrupt the main clause, but the head noun phrase (the author) functions as both the subject of the main clause (hiring the lawyer) and the object of the relative clause (being insulted). Because the thematic roles in object-relative sentences require extensive integration, they are more difficult to process, and hence give the listener a greater cognitive burden, than subject-relative sentences (Carpenter, Miyaki, & Just, 1994). Another impediment is that the non-canonical word order of object-relative sentences violates the expected frequency-based subject–verb–object word order in English. This word order expectancy would ordinarily work in most cases of everyday speech, but in this case the expectancy must be inhibited for a correct interpretation. (See Novick, Trueswell, & Thompson-Schill, 2005, for arguments relating to frontal lobe function for effective inhibition of syntactic expectations when sentences with non-canonical word orders are encountered.)

Whether on-line syntactic parsing draws on attentional resources or whether these resource limitations operate at the level of post-interpretive processes remains an issue for debate (Caplan & Waters, 1999). It is well established, however, that age-related resource limitations constrain successful comprehension of sentences, most notably when complex syntax places a heavy demand on working memory (Carpenter et al., 1994).

Figure 9.3 shows data from Stewart and Wingfield (2009) for participants who heard isolated monosyllabic words versus subject-relative and object-relative sentences of the sort described above. The stimuli were presented to older adults, either with a mild-to-moderate hearing loss or with good hearing for their ages. A group of young adults with age-normal hearing acuity was included to illustrate a maximal performance level for the task. The stimuli were initially presented below the level of audibility and then increased in loudness in 2-dB increments until the single-word stimuli and all nine words of the sentence stimuli could be correctly reported.

The three panels in Figure 9.3 show the cumulative percentage of stimuli correctly reported as a function of increasing amplitude in 2-dB increments for the three groups of participants. Although all show similar S-shaped psychophysical functions, each group reaches the 50% correct threshold (indicated by the horizontal dotted lines) with different sound levels. The finding that accurate recall appears with at a lower sound intensity for the two types of sentences relative to correct recall of the isolated words illustrates the effectiveness of linguistic support for recognition and recall. A comparison of the top, middle, and

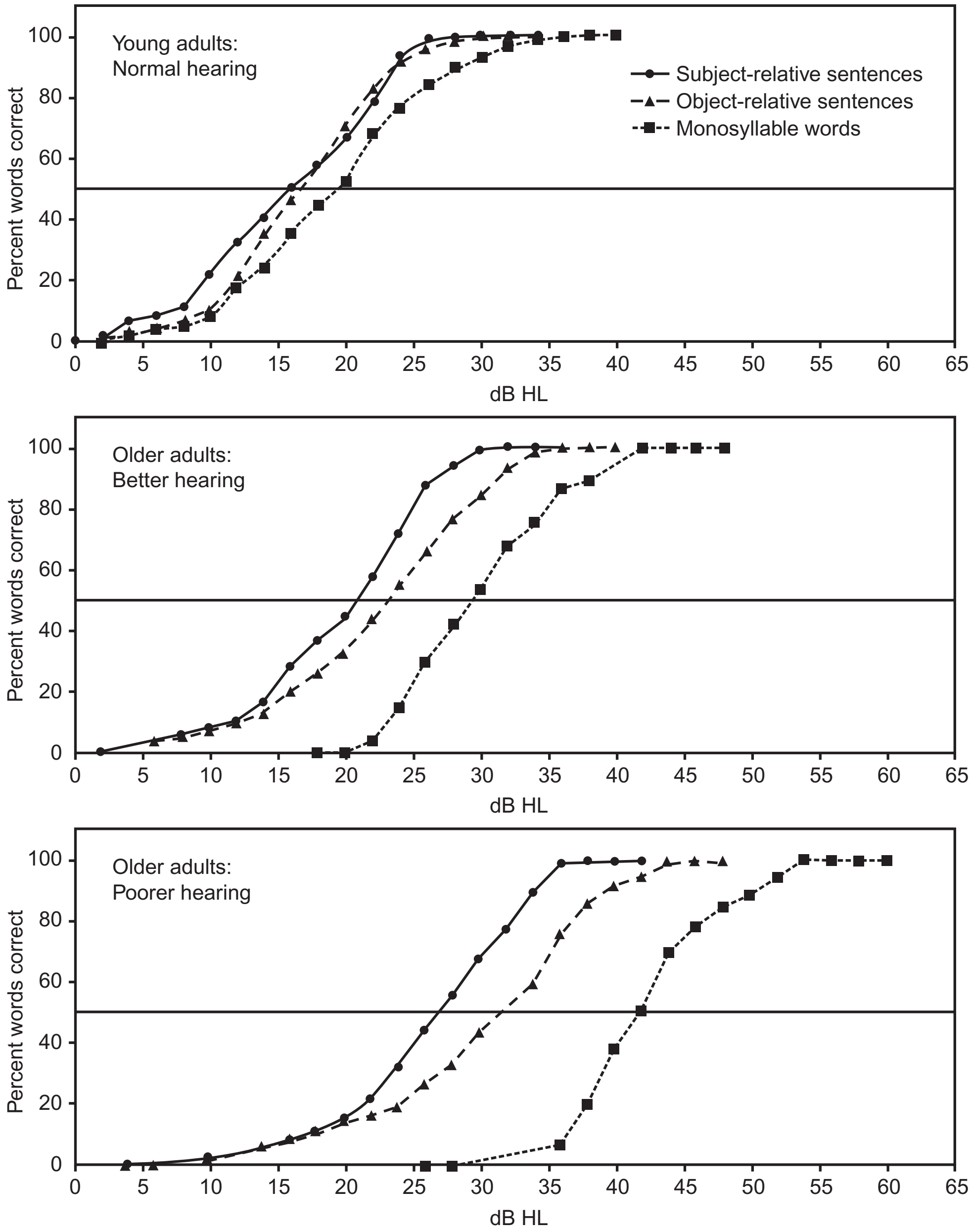

FIGURE 9.3 Cumulative percentage of words correctly reported for single-word stimuli and for sentences with subject-relative and object-relative clause syntactic structures as a function of sound level increased in 2-dB increments. Data are shown for young adults with normal hearing (top panel), older adults with good hearing acuity (better hearing; middle panel), and older adults with mild-to-moderate hearing loss (poorer hearing; bottom panel). The horizontal lines in each panel show the points at which 50% of the words in each of the three conditions were reported correctly. *From Stewart and Wingfield (2009, p. 151). Copyright 2009 by the American Academy of Audiology. Reprinted with permission.*

lower panels of Figure 9.3 shows there to be a greater degree of facilitation for sentences versus words that is larger for the older adults with good hearing acuity relative to the young adults, and larger still for the older adults with hearing impairment.

Figure 9.3, however, also illustrates a limiting factor in older adults' sentence recall. This is the observation that accurate sentence recall appears with a lower sound level for the simpler subject-relative sentences than the more complex object-relative sentences, with the magnitude of this difference reflected in the greater displacement of the curves for the older adults with hearing impairment. To put this in practical terms, for the better-hearing older adults, increasing the syntactic complexity from a subject-relative to an object-relative structure was equivalent to decreasing the sound level by an average of 4.8 dB. For the older adults with mild-to-moderate hearing loss it was equivalent to a 7.8-dB decrease in sound level. Importantly, this is so even though the two sentence types were both meaningful English, spoken by the same speaker, and contained the same words, differing only in the syntactic structure used to express the meaning.

These findings fit well with the assumptions of age-related resource limitations and our understanding of sentence processing (Carpenter et al., 1994). To the extent that resolving the meaning of object-relative and subject-relative sentences serves as a precursor to their effective recall, the greater demands on working memory resources of comprehending object-relative sentences would have a differentially greater impact on older relative to young adults due to older adults' more limited initial working memory resources. To this one may add older adults' reduced efficiency in inhibition that would, as indicated earlier, put them at a disadvantage in dealing with the non-canonical (unexpected) word order of object-relative sentences. The exaggeration of the syntactic effects by hearing loss suggests a further drain on resources needed for perceptual operations; a perception-based reduction in resources that might otherwise be available for syntactic resolution and encoding what has been heard in memory.

The most direct way to separate the effects of aging and hearing acuity is to use a four-group design consisting of good-hearing and impaired-hearing young adults and good-hearing and impaired-hearing older adults. This can be illustrated in a study that combined two perturbations that differentially challenge older adults: complex syntax and rapid speech rates. The stimuli in this study were short, six-word sentences, in which either a male character (e.g., boy, uncle, king, nephew) or a female character (e.g., girl, aunt, queen, niece) was the agent of an action. Critically, the sentences were heard either with a subject-relative structure (e.g., "Men that assist women are helpful") or an object-relative structure ("Women that men assist are helpful"). The listener's task was simply to press a key to indicate whether it was a male or a female who was performing the action, with the sentences presented at a fast-normal rate of 205 wpm or computer time-compressed to be heard in 80%, 65%, or 50% of their original playing time (corresponding to speech rates of 258, 321, and 410 wpm).

The data from this experiment are shown in Figure 9.4 for a group of young and older adults with good hearing acuity for their ages, and young and older adults who had a mild-to-moderate hearing loss. Inspection of the left panel of Figure 9.4 shows that comprehension accuracy for the simpler subject-relative sentences, as measured by correct selection of the gender of the agent of the action, was unaffected by either hearing acuity or speech rate within the limits tested. For the older adults hearing acuity only begins to appear as a comprehension challenge at the two highest compression ratios tested. A very different picture emerges for the counterpart sentences with an object-relative structure heard by the same

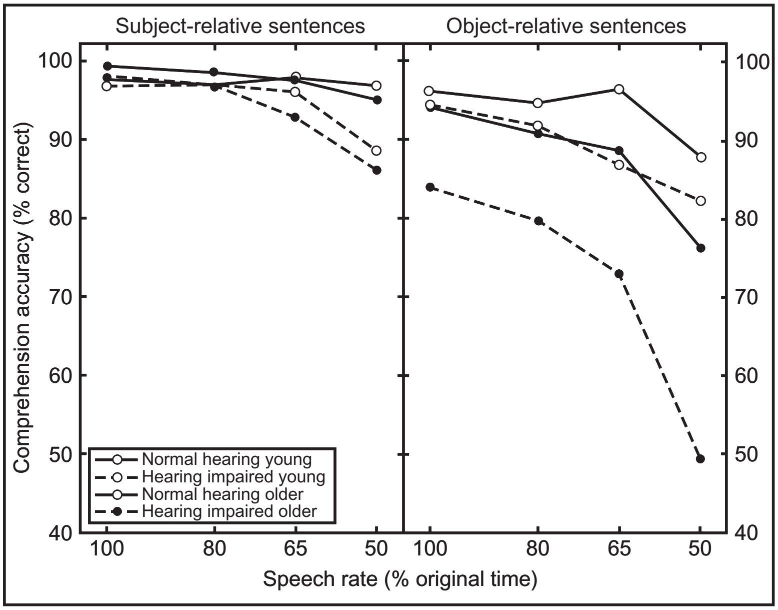

FIGURE 9.4 Comprehension accuracy for sentences with a subject-relative clause structure (left panel) and with an object-relative clause structure (right panel) as a function of speech rate expressed as a percentage of original speaking time. Data are shown for young and older adults with good hearing for their ages and young and older adults with a mild-to-moderate hearing loss. *From Wingfield et al. (2006, p. 493). Copyright 2006 by the American Academy of Audiology. Reprinted with permission.*

participants. In this case one sees an effect of hearing acuity for the young adults at all but the original fast-normal speech rate, and an even greater effect of speech rate, amplified by hearing loss, for the older participants.

This experiment illustrates two important points. The first is that older adults, to include those with a mild-to-moderate hearing loss, can be expected to show excellent speech comprehension with the linguistic support inherent in meaningful sentences, even with relatively rapid speech rates, so long as sentence length and syntactic structure do not put special demands on working memory resources. The second point is that age differences in comprehension accuracy for speech will appear when the processing load is increased either by syntactic complexity of the speech materials, reduced hearing acuity, or both. These results also serve to emphasize that neither age-related cognitive constraints, nor hearing acuity alone, will give the full picture for individuals' effectiveness in sentence comprehension.

There are two detrimental effects of time compression, both of which put the older adult at a special disadvantage. One is the removal of ordinarily available processing time at the level of linguistic processing that would especially challenge a slower processing system. This factor can be revealed by the insertion of pauses at linguistic boundaries that allow older adults' processing to "catch up." When this is done one can raise both younger and older adults' performance to a level close to their comprehension performance for non-compressed speech (Wingfield, Tun, Koh, & Rosen, 1999). The second factor is at the perceptual level where, with a very high compression ratio (in this study equivalent to an unnaturally rapid rate of 300 wpm), there is a loss of richness of the speech signal that, for older adults, cannot be rescued even with the insertion of periodic silent periods (Wingfield et al., 1999).

Compensatory Support from Speech Prosody

Prosody is a generic term for the full array of acoustic features that accompany natural speech. These include the intonation pattern (pitch contour) of a sentence that is carried by the fundamental frequency (*Fo*) of the voice, and word stress (a complex subjective variable based on loudness (amplitude), pitch and syllabic duration). An especially important feature of speech prosody that specifically aids syntactic parsing is syntax-tied timing patterns, such as the pauses that sometimes occur between major syntactic elements of a sentence and the lengthening of clause-final words that signal that a major clause boundary has been reached. Like the use of linguistic context to aid word recognition, older adults can be shown to make good use of prosody to guide syntactic parsing, and often to a differentially greater degree than their young adult counterparts (Kjelgaard, Titone, & Wingfield, 1999). They also give the same relative weighting to each of the major prosodic features (timing, stress, pitch contour) to aid syntactic parsing as young adults (Hoyte, Brownell, & Wingfield, 2009).

Support from Other Sensory Cues

Being able to see a speaker's face when he or she is speaking can sometimes produce better speech recognition than simply hearing the person in the absence of visual cues, especially when there is background noise. That is, there may be supplemental information available to a listener if the listener can see the speaker's articulatory movements as they are talking. Gaining such an advantage requires both effective extraction of the visual cues, and then the ability to integrate the auditory and visual information into a single percept. It may be that older adults are less effective than young adults in initial detection or encoding of the visual cues but perhaps not in combining the information from the two modalities (Sommers, Tye-Murray, & Spehar, 2005). In considering these issues it is also important to recognize that being able to see a speaker while he or she is talking can help focus one's attention to the speaker, with attendant benefits to selective listening in the presence of noise. A good review of the literature and discussion of these issues can be found in Mishra (2014, pp. 13–15).

DOWNSTREAM EFFECTS OF PERCEPTUAL EFFORT

We have several model assumptions that guide our approach to understanding the mechanisms by which a constrained cognitive system accompanied by reduced hearing acuity affects older adults' speech comprehension at the word, sentence, and discourse levels: (i) at the level of word identification we assume a reciprocal balance between bottom-up information determined by the clarity of the speech signal and top-down information supplied by linguistic knowledge (Morton, 1969), with the latter largely preserved in healthy aging; (ii) the application of this knowledge is supported by temporally overlapping memory systems varying in duration and content characteristics (Mattys, 1997) that include a very brief *echoic* trace in the order of several seconds (Darwin, Turvey, & Crowder, 1972) that allows for maintaining the coherence of speech streams and for local misrecognition repair; (iii) comprehension of sentences with complex syntax, and full narrative comprehension at the discourse level are assumed to be carried by an age-limited working memory system guided by executive control processes that includes elements of inhibition (Cowan, 1999; Engle, 2002; McCabe et al., 2010); (iv) in the case of degraded input, perceptual operations will be slowed by a shift from automatic to controlled processing, with the latter increasing the drain on working memory resources (Rönnberg et al., 2013), with such a shift seen in graded rather than dichotomous terms (Chun, Golomb, & Turk-Brown, 2011). To the extent that controlled processing engages working memory resources, both age-related limitations in cognitive control and perceptual effort associated with hearing loss would have a negative effect on speech comprehension, especially under conditions representing heavy processing demands. Such high-demand conditions would include on-line analysis of speech with complex syntactic or propositional structures, often when the processing load is further compounded by rapid or degraded speech input.

An independent measure of the resource drain associated with perceptual effort can be revealed by a decline in secondary-task performance (Fraser, Gagne, Alepins, & Dubois, 2010; Larsby, Hallgren, Lyxell, & Arlinger, 2005; Sarampalis, Kalluri, Edwards, & Hafter, 2009). For example, Tun, McCoy, and Wingfield (2009) using a four-group design (young and older adults with good hearing acuity and young and older adults with a mild-to-moderate hearing loss) measured the moment-to-moment accuracy in using a computer mouse to track a randomly moving visual target on a computer screen while listening to and recalling a spoken word list. Relative to the single-task tracking performance of each group, older adults showed a greater cost of dividing attention than young adults as measured by a decline in tracking accuracy during recall. Within each age group, however, those with hearing impairment showed reduced accuracy in concurrent visual tracking, and especially so for the hearing-impaired older group. Such results are consistent with a shared-resource argument in which hearing-related listening effort drew resources needed to support accuracy in the visual-motor tracking task. Additional evidence for effects of listening effort appears in the measurement of pupil dilation based on the finding that greater cognitive load causes an increase in pupil size (Piquado, Isaacowitz, & Wingfield, 2010). Reliable data are beginning to appear in the literature that show an increase in adjusted pupil size while listening to speech for older adults, and older adults with hearing impairment (Kuchinsky, et al., 2012; Zekveld, Kramer, & Festen, 2011).

These findings are compatible with a so-called "effortfulness hypothesis" (Rabbitt, 1968, 1991); the general notion that successful perception in the face of a degraded input may draw resources that would ordinarily be available for downstream operations, in this case, such as comprehension of sentences with complex syntax and for encoding what has been heard in memory. As such, many failures in comprehension and/or recall of spoken language may have a sensory source, even when it can be shown that the speech itself had been successfully, albeit effortfully, processed. This view has been reinforced by experiments with normal-hearing participants in which speech passages, word-lists and verbal paired-associates have been acoustically masked. These studies have reliably shown a recall decrement for the materials, even when the level of masking has been adjusted to add perceptual difficulty while not preventing successful word identification (Amichetti, Stanley, White, & Wingfield, 2013; Murphy, Craik, Li, & Schneider, 2000; Surprenant, 2007). Indeed, even masking a single word in a word-list can have a negative effect on recall, not merely for that word, but for the one or two words prior to it (Cousins, Dar, Wingfield, & Miller, 2014).

BROADER ISSUES OF AGE-RELATED HEARING LOSS

Many older adults with hearing loss express the mental, and sometimes even a physical, toll taken by the continual daily effort expended on simple audition and the need to understand often complex speech from a less than clear input. In addition, and perhaps as a consequence of this effort, hearing loss can lead to reduced social interaction, isolation and loss of self-efficacy (Kramer, Kapteyn, Kuik, & Deeg, 2002).

It is the case that, as the nervous system ages, one may expect changes in sensory and cognitive systems along with other biological change (Li & Lindenberger, 2002). Recent large-scale studies have affirmed a small but statistically significant correlation between the presence and degree of peripheral hearing loss among older adults as measured by pure-tone sensitivity, and the appearance of all-cause dementia, as well as performance on cognitive tests in non-demented individuals. Strikingly, this relationship appears even when the data are statistically controlled for age, gender, education, presence of diabetes, smoking history, and hypertension (Lin, 2011; Lin et al., 2011).

As Lin (2011) has pointed out, a relationship between hearing loss and cognitive decline does not tell us whether the continuous cognitive effort hearing loss imposes on a daily basis takes a cumulative toll on cognitive reserves, whether the cognitive decline is caused or exacerbated by depression and social isolation that often accompanies hearing loss, or whether the concurrent decline in hearing acuity and cognitive function are both a reflection of an aging nervous system. Undoubtedly, all of these factors may be contributing in varying degrees to this relationship (cf., Gates, Anderson, McCurry, Feeney, & Larson, 2011; Humes, Busey, Craig, & Kewley-Port, 2013; Peelle, Troiani, Grossman, & Wingfield, 2011).

CONCLUSIONS

Traditionally, theorists have focused on just one direction of effects of limited resources, whether the focus is on a concurrently performed cognitive task constraining perceptual effectiveness (Kahneman, 1973) or perceptual effort reducing effectiveness of concurrently or sequentially performed cognitive tasks (Rabbitt, 1968, 1991; Murphy et al., 2000). However, one can postulate a single interactive dynamic in which limited resources may impede successful perception when the quality of the sensory information requires perceptual effort for success, while successful perception in the face of a degraded input may draw on resources that might otherwise be available for concurrent or downstream cognitive operations.

The related notions of cognitive effort and resource allocation have had descriptive utility in the literature for over a century (Titchener, 1908, and later Kahneman, 1973), yet the mechanisms that may underlie the negative effects of effortful listening on comprehension and recall remain to be determined. At issue is why the processing of a degraded input impairs the ability to recall identifiable words relative to clearly articulated, non-acoustically degraded words (Cousins et al., 2014; Piquado, Cousins, Wingfield, & Miller, 2010).

For older adults with a hearing impairment perceptual effort is a constant in their lives, and, as we have noted, it can be a source of stress and mental fatigue (Fellinger, Holzinger, Gerich, & Goldberg, 2007). Indeed, although our focus in this chapter has been on the effects of age-related hearing loss on spoken language comprehension, analogous concerns arise for written materials in the presence of degraded vision (Dickinson & Rabbitt, 1991; Gao, Levinthal, & Stine-Morrow, 2012). At a public health level, studies such as those cited above raise the question of whether the availability of well-fitting hearing aids may have ameliorating effects on potential age-related cognitive decline. To date this remains an interesting but still open question. A part of this question will not merely be the use of hearing amplification, per se, but also possible differential effects of different signal processing algorithms becoming available in modern hearing aids. This question of cognitive amelioration may also be extended to the increased employment of cochlear implants for older adults with more severe hearing loss (Lin et al., 2012).

Listening to and comprehending spoken language is an important human capability regardless of age. This comprehension places demands on the effectiveness of both cognitive and sensory processes. A major theme of this chapter has been the relative stability of speech comprehension in spite of the sensory and cognitive changes known to accompany adult aging. As we have seen, this stability is maintained by the compensatory utilization of age-spared linguistic knowledge, to include such features as vocabulary, syntactic knowledge, and the ability to effectively use speech prosody to aid in syntactic operations. On the negative side, we have seen that perceptual effort attendant to reduced hearing acuity can take a toll on downstream cognitive operations, such as effective encoding of what has been heard in memory.

Since the pioneering work of Welford (1958), the cognitive aging literature has been consistent in representing mental performance in adult aging as a balance between declines in basic processes such as memory, attention, and processing speed, versus the maintenance of skills and knowledge acquired through a lifetime of experience. As we have attempted to show in this chapter, comprehension and memory for spoken language stand as a model of this delicate balance.

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