Chapter 9
Interactions Between Audition and Cognition in Hearing Loss and Aging

Chad S. Rogers and Jonathan E. Peelle

Abstract Successful speech understanding relies not only on the auditory pathway, but on cognitive processes that act on incoming sensory information. One area in which the importance of cognitive factors is particularly striking during speech comprehension is when the acoustic signal is made more challenging, which might happen due to background noise, talker characteristics, or hearing loss. This chapter focuses on the interaction between hearing and cognition in hearing loss in older adults. The chapter begins with a review of common age-related changes in hearing and cognition, followed by summary evidence from pupillometric, behavioral, and neuroimaging paradigms that elucidate the interplay between hearing and cognition. Across a variety of experimental paradigms, there is compelling evidence that when listeners process acoustically challenging speech, additional cognitive effort is required compared to acoustically clear speech. This increase in cognitive effort is associated with specific brain networks, with the clearest evidence implicating cingulo-opercular and executive attention networks. Individual differences in hearing and cognitive ability thus determine the cognitive demand faced by a particular listener, and the cognitive and neural resources needed to aid in speech perception.

Keywords Listening effort · Background noise · Speech perception · Cognitive aging · Sentence comprehension · Neuroimaging · Cingulo-opercular network · Executive attention · Pupillometry · fMRI

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9.1 Introduction

It goes without saying that the auditory system is of key importance for speech perception. However, a number of recent frameworks for speech understanding have emphasized the important additional contributions of cognitive factors (Wingfield et al. 2005; Peelle 2018). Although there are many reasons to consider cognitive processing in speech perception, one especially important catalyst has been the longstanding realization that hearing sensitivity, alone, is unable to fully account for challenges faced by listeners, particularly in noise (Plomp and Mimpen 1979; Humes et al. 2013). One explanation for this finding is that current tests of auditory function may be lacking, and that more informative tests are needed. However, another possibility is that individual differences in cognitive ability contribute to a listener's success understanding speech. Thus, clarifying the cognitive challenges associated with understanding acoustically challenging speech is not only of theoretical importance, but may significantly improve our understanding of communication in everyday situations.

Hearing loss affects listeners of all ages, and in the United States, it is estimated to affect 23% of those aged 12 or older (Goman and Lin 2016). The focus of this chapter is primarily on age-related hearing loss, given the particularly high incidence of hearing loss in adults over the age of 65 (Cruickshanks et al. 1998; Mitchell et al. 2011). Healthy older adults are also a prime group of listeners in whom to study the interactions of sensory and cognitive factors, given that changes in both of these areas are frequently seen as we age.

Figure 9.1 shows a schematic of speech comprehension that includes processing related to auditory, language, and memory systems (because listeners frequently would like to remember what they have heard), as well as domain-general cognitive processes that act on one or more of these stages. The following sections cover a number of these areas where age-related changes are reported, as well as others that seem to be relatively preserved in older age. An important point to keep in mind is the significant variability in individual ability in all of these domains.

Section 9.2 of this chapter highlights the most salient age-related changes in hearing and cognition. Following this, the ways in which these changes manifest during speech comprehension and inform broader understanding of auditory-cognitive interaction are examined.

9.2 Age-Related Hearing Loss

Age-related hearing loss is extremely common: Although estimates vary, some 40–50% of adults over the age of 65 years have a measurable hearing impairment, with this number rising to greater than 80% of those over the age of 70 years (Cruickshanks et al. 1998). Age-related changes in hearing occur at every level of the auditory system (Peelle and Wingfield 2016), and the specific etiology is likely to have consequences for information processing. Age-related hearing loss can be broadly categorized into

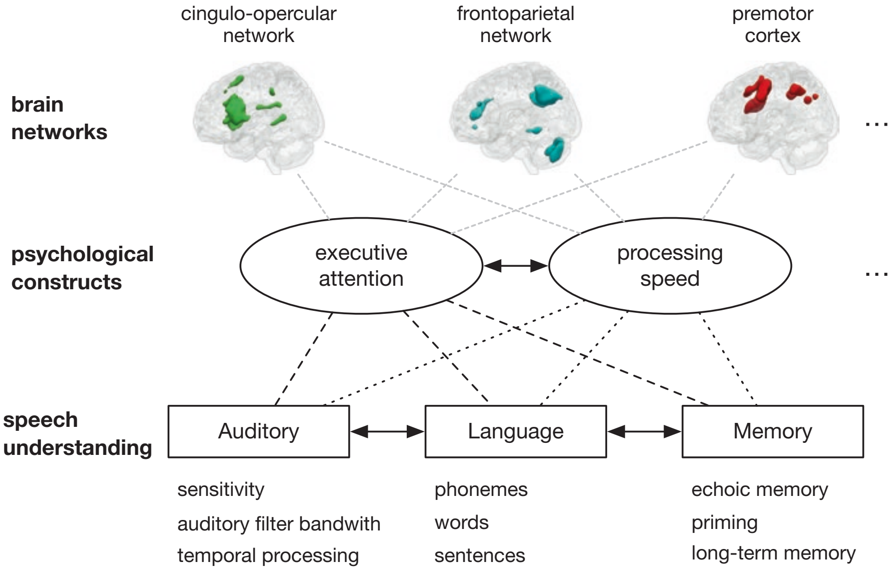

Fig. 9.1 Schematic of domains involved in speech processing. At bottom are stages of processing from low-level auditory perception through speech understanding, and on to tasks that might be done with the heard speech (such as remembering it). Bidirectional arrows signal interactivity between these levels (e.g., linguistic factors can bias auditory perception). At top are some example cognitive processes and corresponding brain networks that are used in understanding speech. The interaction between auditory and cognitive factors is thus a complex and highly interactive process spanning multiple levels of representation. (Figure available via a CC-BY4.0 license from https://osf.io/mv95h/)

peripheral hearing loss (having to do with the cochlea) or central hearing loss (having to do with the auditory nerve, subcortical structures, or cortex).

9.2.1 Peripheral Age-Related Changes in Hearing

A major cause of age-related hearing loss is a reduction in the number of outer hair cells of the cochlea. For reasons that are still not entirely clear, hair cell loss occurs primarily in the basal end of the cochlea responsible for encoding high frequency information (Merchant and Nadol 2010). Thus, the most striking characteristic of age-related hearing loss is a decrease in sensitivity to higher frequencies. Figure 9.2 shows median pure-tone sensitivity for adults of different ages, illustrating this characteristic pattern, as well as the characteristically poorer hearing of men relative to women in older age. Fortunately, hearing in the range most important for speech information (4 kHz and below) is generally relatively well preserved in cases of mild age-related hearing loss. However, some speech information (such as fricatives) can still be lost (Bilger and Wang 1976; Scharenborg et al. 2015), and as hearing sensitivity worsens speech intelligibility may decline.

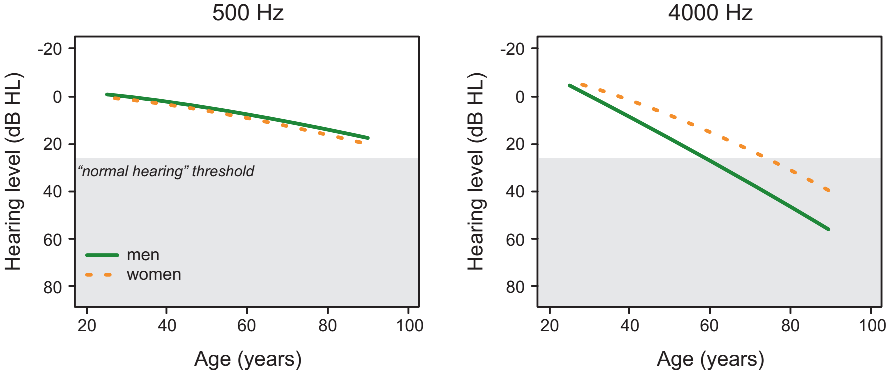

Fig. 9.2 Median pure-tone hearing levels for adult men and women at 500 Hz and 4000 Hz (cartoon based on Morrell et al. 1996). The shaded region indicates a typical cutoff for clinically normal hearing of 25 dB HL. (Figure available via a CC-BY4.0 license from https://osf.io/mv95h/)

Changes to peripheral hearing can also be caused by synaptic dysfunction and degeneration of cochlear nerve axons. In animal models, Kujawa and Liberman (2009) found that a single noise exposure can weaken cochlear afferent nerve terminals. This weakening was observed even when there was no apparent damage to hair cells, or evidence of a long-term threshold shift (i.e., differing sensitivity to pure tones—a change in the audiogram illustrated in Fig. 9.2). Because these changes are not always evident in pure-tone thresholds, they are sometimes referred to as "hidden" hearing loss. Although still a relatively new area, there is evidence suggesting that hidden hearing loss contributes to deficits in amplitude modulation coding (Paul et al. 2017) and temporal processing (Bharadwaj et al. 2015).

9.2.2 Central Age-Related Changes in Hearing

Data from both animal and human studies suggest age-related changes in spiral ganglion neurons (Bao and Ohlemiller 2010), cochlear nuclei, the superior olivary complex, and inferior colliculus (Caspary et al. 2008; Engle et al. 2014). In humans, much work has focused on age-related changes to the auditory brainstem response (ABR). The ABR is a time-locked electrophysiological response elicited by brief acoustic stimuli (e.g., clicks, or a phoneme), typically recorded from electroencephalographic (EEG) electrodes placed on the scalp. The amplitude and timing of the peaks of the ABR can thus be used to infer the fidelity of subcortical auditory processing. With advancing age, the peaks of the ABR show reduced amplitude, and some peaks show additional delays in their timing relative to stimulus onset (Skoe et al. 2015). Aging is associated with decreased precision of the ABR including longer delays and greater variability across trials (Anderson et al. 2012). Changes in speech-evoked ABRs are also evident in listeners with hearing loss, suggesting that changes subcortical representations may contribute to difficulties with speech-in-noise perception (Anderson et al. 2013).

Age-related changes are also evident in primary auditory cortex, reflected in both anatomy and electrophysiology. Parvalbumin is a calcium-binding protein expressed in auditory interneurons that play in important role in novelty detection and stimulus sensitivity. The number of parvalbumin-containing neurons is reduced in aging and is accompanied by reduced myelin (de Villers-Sidani et al. 2010; del Campo et al. 2012). Animal studies show that aging is also associated with a reduction in GAD, a GABA synthetic enzyme, in layers II–IV, probably reflecting a reduction in levels of GABA (an inhibitory neurotransmitter) (Ling et al. 2005; Burianova et al. 2009). Reports using magnetic resonance spectroscopy suggest some evidence consistent with the animal literature (Profant et al. 2013; Gao et al. 2015).

Noninvasive electrophysiological studies in humans suggest numerous age-related changes in the function of auditory cortex, including the magnitude of auditory evoked responses (Alain et al. 2014) and altered dynamics of stimulus adaptation (Herrmann et al. 2016). Finally, on a gross anatomical level, the volume of gray matter in auditory cortex is reduced in older adults with poorer hearing compared to those with better hearing (Peelle et al. 2011; Eckert et al. 2012). These macroanatomical structural changes may reflect changes in lower-level physiology associated with altered auditory processing.

9.3 Cognition in Older Adulthood

In addition to age-related changes to peripheral and central auditory structures that impact hearing, age-related changes to cognitive abilities are well documented (Salthouse 1991; Gordon-Salant et al. 2020). However, it is crucial to emphasize the significant variability in age-related changes to cognitive systems supporting speech understanding (Park et al. 1996). The differing consequences of aging for dissociable cognitive systems can elucidate the consequences of aging on speech understanding, and also help us better understand the underlying bases for speech processing in other populations of listeners (such as healthy young adults). The following sections highlight several cognitive systems closely related to speech understanding, and their potential for age-related decline: processing speed, inhibition and cognitive control, working memory capacity, episodic memory, and metacognition.

9.3.1 Age-Related Cognitive Decline

Age-related changes are observed in many domains of cognition, only a few of which are reviewed here. Because age-related changes are correlated across a large number of tasks, age-related change is frequently thought of in a factor-analytic framework, in which common variance across many tasks can be reduced to a smaller number of common factors. In the context of age-related cognitive decline, performance on many specific tasks might be better explained by declines in domain-general processing. Common domain-general constructs have included executive attention and processing speed (Salthouse 1996b; McCabe et al. 2010). As discussed throughout this section, changes in broad domain-general areas can also impact specific domains such as episodic memory or metacognition.

9.3.1.1 Processing Speed

Age-related changes to processing speed, or the rate at which tasks are performed, are ubiquitous in adult aging. Meta-analyses have revealed that older adults have slower reaction times than young adults in virtually every timed task (Cerella 1985; Verhaeghen and De Meersman 1998). These findings have led to an influential theory of general slowing in the cognitive aging literature (Salthouse 1996b), whereby age-related decline on cognitive tasks results from cascading failures of cognitive operations to complete on time. Evidence in support of this theory includes large-scale psychometric studies and meta-analyses that assess covariation among tasks assessing processing speed, memory, and executive attention, and find that the two-way relationships between aging and memory or aging and executive attention are minimized or eliminated after statistically taking into account the relationship between aging and processing speed (Salthouse 1996a; Verhaeghen and Salthouse 1997). Measures of processing speed have also been shown to correlate with neurobiological markers of aging (Eckert 2011). While this framework provides a powerful and parsimonious account for changes that occur as people grow older, one criticism is that it does not provide a straightforward account for the entire pattern of behaviors observed in the literature, particularly in areas in which age-related declines are not observed (e.g., Balota et al. 2000; McCabe et al. 2010).

9.3.1.2 Inhibition and Cognitive Control

In daily experience, people frequently need to ignore, or inhibit, information that is not relevant for a current task. A laboratory task which is a favorite among cognitive psychologists is the Stroop task (Stroop 1935). Participants are shown various words, including color words (e.g., “red”), that are written in different colors, and instructed to indicate the color the word is written in. For literate participants, the actual word (“red”) is processed automatically, but does not help with performance on the task (thus, “irrelevant”). When the word and its color agree (“red” written in red), participants respond more quickly; however, when the word and color disagree (“red” written in blue), participants are slower to respond. This general pattern is interpreted to reflect participants’ inability to ignore or inhibit the word information, which is irrelevant to the current task of naming the color a word is written in.

Older adults have a well-documented deficit in the ability to inhibit irrelevant stimuli (Hasher and Zacks 1988), which has been demonstrated in memory tasks (Gazzaley et al. 2005), visual tasks such as the Stroop task (Bugg et al. 2007), and auditory tasks such as dichotic listening (Rogers et al. 2018). In this last example, participants listened to simultaneously presented auditory streams of words, one stream to each ear, preceded by a visual arrow that indicated the ear to which participants should attend. Afterward, participants were shown a list of words—which could be from the attended ear, the unattended ear, or unrelated—and asked to indicate words that had been in the attended ear. Performance between young and older adults was equivalent in all conditions except for when recognition probes were words from the unattended stream. In those cases, older adults were more likely than the young adults to (erroneously) endorse those items, indicating a deficit in suppression of the unattended ear (Tun et al. 2002). This kind of deficit in selective attention suggests that older adults may actually encode more, not less, than young adults, but include both relevant and irrelevant information (Weeks and Hasher 2017).

9.3.1.3 Working Memory Capacity

Older adults also have deficits in working memory. In the classic model of Baddeley (1986), working memory contains both a verbal memory buffer (the phonological loop) and a visual memory buffer (the visuospatial sketchpad). These buffers allow for auditory and visual information, respectively, to be maintained for in an active state for a finite period of time. Baddeley's (1986) model also includes a central executive component which allows for manipulation and processing of information contained within these buffer and long-term memory systems in order to achieve goals of a specific task (Rudner and Ronnberg 2008). For example, retaining the digits of a phone number relies on short-term memory, whereas separating the digits into odd and even numbers then reciting them in ascending order would likely tap central executive processes (Belleville et al. 1998). The central executive component is considered to be the locus of age-related declines in working memory (Rose et al. 2009), specifically with regard to its role of suppression of task-irrelevant stimuli (Gazzaley et al. 2005).

9.3.1.4 Episodic Memory

Episodic memory is the capacity for memory for specific past events including details about where and when the event occurred (Tulving and Szpunar 2009), and allows people to remember specific autobiographical information about their own lives. For example, whereas semantic memory allows one to know what kind of dinner is served at an Italian restaurant, episodic memory allows for one to remember the last time they ate Italian food, who they ate with, and how good the food was.

Episodic memory is generally considered to decline as a function of age (Craik 2008), probably due to age-related changes in a number of related cognitive processes. Memory is often conceptualized as relying on at least three stages: encoding (when events are initially stored into memory), retention (when memories are held for a duration of time), and retrieval (when memories are accessed) (Melton 1963). Older adults have been shown to have declines in the ability to encode events into long-term memory (Craik and Rose 2012), with older adults less likely than young adults to engage in self-initiated elaborative encoding strategies that are beneficial for long-term retention (Craik and Rabinowitz 1985). In addition, older adults may have more difficulty than young adults encoding specific temporal associations, as is needed to recall a list of unrelated words (Golomb et al. 2008). When controlling for initial encoding, older and young adults are generally assumed to have relatively similar rates of memory retention (Park et al. 1988). However, older adults show deficits relative to young adults in the ability to retrieve memories when prompted (Craik and McDowd 1987; Wingfield and Kahana 2002). The largest evidence of age-related changes in retrieval is observed in free recall; when older adults are given helpful cues to facilitate retrieval, differences between young and older adults are minimized (Smith 1977).

9.3.1.5 Metacognition

One particularly interesting aspect of age-related cognitive change is the extent to which people have insight over their own cognitive states. For example, are listeners aware of the extent their hearing or cognitive abilities? Nelson and Narens' (1990) seminal framework describes metacognition as two processes that operate between the object level (e.g., *actual* cognitive processing) and the meta level (e.g., *awareness* of this processing). The flow of information from the object level to the meta level is called monitoring, and the flow of information from the meta level to the object level is called control. For example, monitoring occurs when one notices that they are having a hard time hearing the television after the air conditioner kicks on, and control occurs when one increases the television volume in response to that awareness.

Hertzog and Dunlosky (2011) report that older adults' monitoring is preserved relative to young adults in episodic memory tasks, and that their predictions and post-dictions of future and past performance are well calibrated. However, this pattern of age invariance does not appear to hold when tasks require executive attention at the object level (Souchay and Isingrini 2004). For example, in a study by Kelley and Sahakyan (2003), young and older adults studied pairs of words (e.g., CLOCK-DOLLAR), and were tested using a cued recall test (e.g., CLOCK-DO_ _ _ R). The pair CLOCK-DOLLAR is an example of a baseline item in which pairs of words were not semantically associated. Kelley and Sahakyan (2003) also used deceptive items in which the words pairs were not semantically associated at study (e.g., NURSE-DOLLAR) but the cue fragment at test could erroneously lead to a semantic associate of the first word (e.g., NURSE-DO_ _ _ R). Note that successful performance on these deceptive items requires inhibiting the semantic associate DOCTOR to respond correctly with the studied item DOLLAR. During each trial at test, participants made a cued recall attempt, then rated their confidence in their memory (e.g., monitoring), and then decided if they wanted their response to be scored for a later monetary reward (e.g., control). The results of that study showed that while cued recall for baseline items was poorer for older adults than young adults overall, metacognitive judgments by older adults in terms of their confidence and willingness to have their responses scored were just as well calibrated to their actual performance as young adults' metacognitive judgments. However, on deceptive items, where participants had to inhibit the semantic associate of the first word at recall, older adults' metacognitive judgments were poorly calibrated relative to young adults—older adults were more confident in their errors and more likely to volunteer to have their errors scored than were young adults. This study provides strong evidence that older adults have intact metacognition relative to young adults only to the extent that input to the monitoring process does not require executive attention.

9.3.2 Resilience to Age-Related Decline in Some Memory Systems Important for Speech Perception

Despite widespread findings of age-related cognitive change in many areas, there are others in which older adults perform very similarly to young adults. Areas of preserved performance in older adulthood are important because they may provide means for older adults to compensate for declines to hearing and cognition in service of speech understanding.

9.3.2.1 Echoic Memory

Echoic memory is a short-term auditory store that holds sensory-based auditory information for a very short period of time, probably on the order of hundreds of milliseconds (Cowan 1984). For example, during a telephone conversation where the listener asks the speaker to repeat themselves, and yet remembers what the speaker initially said before the speaker even attempts to repeat, it is likely that the listener was able to retrieve the spoken information from echoic memory. As with its visual analog, iconic memory (Sperling 1960), echoic memory has been shown to be invariant with age (Parkinson and Perey 1980) and is not typically considered to be a likely locus of age-related decrements to speech perception. The same age invariance has been found with an electrophysiological correlate of echoic memory derived from the mismatch negativity (Näätänen et al. 2007) wave of event-related potentials (Alain and Woods 1999).

9.3.2.2 Short-Term Memory

Short-term memory, also sometimes known as primary memory, is the capacity to maintain small quantities of information in the focus of immediate awareness for a short period of time (Waugh and Norman 1965), for example, holding a telephone number in mind long enough to enter it into a phone. This type of processing is reflected in tasks such as forward digit span, where participants listen to and repeat aloud a string of digits in the same order they were presented. While individual studies of forward digit span have revealed modest or no effects of age (Craik 1977), a meta-analysis by Verhaeghen et al. (1993) revealed that older adults do less well on forward digit span tasks than young adults. However, some have argued that the observed age difference in forward digit span is more likely to reflect age differences in long-term memory and speaking articulation rate, which is slower in older adults (Multhaup et al. 1996; Zacks et al. 2000).

9.3.2.3 Repetition Priming

Priming is a nonconscious form of memory typically associated with the perceptual identification of stimuli (Tulving and Schacter 1990). Studies of repetition priming commonly involve initial exposure of a target stimulus, and after a delay period that could vary from seconds to years, a test exposure of the same stimulus, albeit under some form of degradation, obliteration, or compression. A common example from the auditory domain is auditory noise masking, where a word could be spoken clearly, and then in a later test phase of the experiment, presenting that same word with a significant degree of noise. Typically, older adults show similar repetition priming to young adults, although older adults with Alzheimer's disease show impaired repetition priming (Fleischman and Gabrieli 1998).

9.3.2.4 Semantic Priming

In semantic priming, the accessibility of a target item can be changed by prior exposure to a different but conceptually related stimulus. A common example of semantic priming is that of paired associates, where a word comes to mind more easily in the presence of a semantically related cue word (e.g., in *dog*-*cat* or *ocean*-*water* the second word is more readily accessed than *dog*-*water* or *ocean*-*cat* because of the conceptual relationship of the pair). Studies of semantic priming have been used to understand how concept knowledge is organized. The most common form of semantic priming paradigm is when the relationship between the prime (e.g., *dog*) and the target (e.g., *cat*) is manipulated. Given *dog* as a prime, participants are quicker to identify the target word *cat* than when given *corn* as a prime (Neely 1977). To the extent that timing of these responses reflects the underlying semantic network, we can understand the spreading of activation from one lexical entry to another, and the relative integrity of the semantic system. Typically, older adults report equal or stronger semantic priming effects to that of young adults (Burke et al. 1987; Laver and Burke 1993).

9.4 Behavioral and Pupillometric Evidence for Interactions Between Hearing and Cognition

This section reviews studies that have highlighted the interactivity of different sensory and cognitive systems that operate in the service of speech perception and language understanding. While age-related declines to hearing loss and cognition are often studied independently, there is an increasing trend for researchers to study the interactions between hearing loss and cognitive decline as a way to understand the underlying basis for language comprehension. For example, to investigate the question, "How does attention enhance auditory perception?" it may be helpful to study older adults who have declines in attentional control. Conversely, researchers interested in the impacts of hearing on attention may study populations with hearing loss as a way of understanding the input to attentional control systems.

9.4.1 Pupillometric Measures

An exciting development in the understanding of the cognitive demands placed on listeners in difficult auditory environments arises from studies using pupillometry, which relies on measuring pupil size as an index of cognitive effort (Van Engen and McLaughlin 2018). Fluctuations in pupil size are known to happen as a result of light adaptation, but these have also been shown to reflect changes in task demands from attention and memory (Kahneman 1973). Thus, pupillometry provides an online physiological measure of demands incurred while listening.

In a study of middle-aged adults with normal or impaired hearing, Zekveld et al. (2011) found less of a change in pupil dilation when moving from easy to difficult levels of background masking, replicating a prior study conducted with young adults (Zekveld et al. 2010). In both studies, the authors argued this change in pupil dilation reflected a diminished release of effort when in less adverse listening conditions. Such release of effort is anticipated in participants when moving from difficult to less difficult listening conditions and has also been observed when participants give up on a difficult listening task (Zekveld and Kramer 2014).

Kuchinsky et al. (2012) tested older adults' ability to identify words in background noise and found that pupil size increased as listening became more difficult. Pupil size was also found to increase as a function of the number of phonological competitors of the target word, indicating that participants were experiencing more cognitive demand as a result of lexical competition (McLaughlin et al. 2021). Piquado et al. (2010a) found that linguistic variables such as sentence length and syntactic complexity impact pupil dilation in a task testing memory for spoken sentences. Interestingly, while Piquado et al. tested both young and older adults, only young adults revealed an effect of syntactic complexity on pupil dilation. The authors concluded this finding indicated that older adults were likely processing the syntactic complexity of the sentences to a poorer extent than the young adults, supporting a "good enough" approach to listening in older adults (Amichetti et al. 2016).

9.4.2 Episodic Memory

In a classic study, Rabbitt (1968) showed a remarkable dissociation between identification and memory for spoken words. Participants listened to and repeated spoken digits. In one experiment, the first half of a list was presented in quiet, but the second half could be either in clear or in noise. Items from early in the list (which were always presented clearly, and thus with full intelligibility) were remembered less well when the latter part of the list was in noise. This finding cannot be explained by differences in first-half item acoustics or intelligibility, which were identical in the two conditions. Rabbitt proposed that the effort used to identify words in noise prevented sufficient rehearsal and encoding of *prior* words into long-term memory, and thereby negatively impacted free recall. This mechanism was later confirmed in a study by Piquado et al. (2010b), who found that that acoustic degradation of a single word disrupts memory for not only the degraded word, but also the word presented immediately prior to it. That is, the acoustic degradation interrupted cognitive processes required for memory encoding. Such a finding is not explained by an "auditory-only" framework, but instead supports a role for non-auditory cognitive processes in understanding the degraded speech.

Nearly 25 years after his original experiment, Rabbitt (1991) performed a similar experiment with older adults, and, rather than manipulating the background noise within-subjects, compared groups of older adults with and without hearing loss. He found that those with hearing loss showed poorer free recall than those with good hearing for their age, even when both groups had displayed perfect identification accuracy. Surprenant (2007) found a similar pattern when manipulating noise within-subjects for older and young adults and found that even small levels of auditory degradation that do not show changes in identification accuracy can nevertheless decrease free recall.

To more directly investigate interactions between acoustic and linguistic factors, Koeritzer et al. (2018) presented young and older listeners with lists of spoken sentences in different levels of background noise (multitalker babble). The sentences varied in their linguistic challenge, with half containing one or more ambiguous words ("bark" could refer to the sound a dog makes, or the outer covering of a tree). These high-ambiguity sentences have been shown to rely on domain-general cognitive resources (Rodd et al. 2010, 2012) and may thus potentially interact with acoustic challenge drawing on these same resources. Following an aurally presented list of sentences, listeners performed a visual recognition memory test for those sentences, which revealed that memory was poorer for high-ambiguity sentences, poorer for sentences in more challenging noise conditions, and that the two factors interacted to challenge memory. Perhaps most telling, for the older adults tested, pure-tone hearing sensitivity and measures of verbal working memory both significantly correlated with memory performance in the most challenging condition.

The key takeaway from these studies is that breakdowns in sensory processing, either via hearing loss or acoustic degradation of the stimulus, have a cascading impact upon the cognitive systems required for understanding spoken language (Gordon-Salant and Fitzgibbons 1997). These experimental findings are consistent with the fact that participants with hearing loss report that certain noisy environments require more effort or concentration while listening (Xia et al. 2015). Even if immediate perceptual identification of the stimulus is not impacted, the additional demand on cognitive processing disrupts important functions for language understanding and memory.

9.4.3 The Modulatory Effects of Context

Additional cognitive demands incurred while listening to degraded speech can, in part, be mitigated by the supportive context that frequently occurs in natural speech. McCoy et al. (2005) used a free recall approach and found that hearing-impaired older adults did not have impaired free recall relative to older adults with good hearing when the words shared a semantic context. One reason this may happen is because supportive context may reduce the need for bottom-up sensory fidelity. To this point, Sheldon et al. (2008) found that older and young adults' perceptual thresholds for words were improved when preceded by facilitative priming, sentential context, or a combination of both.

The findings of McCoy et al. (2005) and Sheldon et al. (2008) complement a wider literature that has shown that older adults greatly benefit from the addition of facilitative context as a way to compensate for age-related hearing loss (Pichora-Fuller 2008). In this sense, context provides a basis for expectation and reduces the amount of bottom-up acoustic information needed to achieve successful identification of a stimulus. For example, in a study using a word-onset gating methodology (Grosjean 1980) where listeners were given incrementing 50 ms segments of target words until recognition was achieved, Lash et al. (2013) found that listeners required fewer segments when identifying words preceded by strongly constraining sentences (e.g., "He mailed the letter without a STAMP") compared to weakly constraining sentences (e.g., "He did not say anything about the STAMP"). Lash et al. (2013) also found that this benefit of context was larger for older adults compared to young adults. An initial explanation for older adults' use of context was provided by Sommers and Danielson (1999), who held that semantic and linguistic context improved word identification by reducing the set of potential competitors in the lexicon, reducing the requirement for inhibition of phonological competitors (especially useful for older adults, who have a well-documented inhibition deficit), and thereby facilitating lexical discrimination.

To assess the role of semantic context on speech perception, Rogers et al. (2012) measured young and older adults' word identification for masked target words preceded by clearly presented primes that created facilitative semantic context (e.g., "row-BOAT"), misleading semantic context (e.g., "row-GOAT"), and neutral context conditions (e.g., "cloud-BOAT"). The authors found that older adults had better performance than young adults on facilitative context conditions, but were more likely than young adults to falsely hear the word predicted by the misleading semantic context (e.g., reporting "BOAT" when given "row-GOAT"). This pattern was also reflected in the pattern of young and older adults' metacognitive monitoring (i.e., confidence in their responses), where older adults were much more confident in making responses that matched the semantic context, even when their responses were incorrect. Such a pattern indicates that context use by older adults does not improve hearing per se, but rather provides a basis for older adults to respond that could be either helpful, or misleading. In the real world, where context is much more likely to be helpful than misleading, this could be of real benefit. However, older adults' confidence in their responses indicates that this happens without their awareness, and may not be aware of when context is misleading (Rogers and Wingfield 2015; Rogers 2016). Exactly because this reflexive use of context may be useful in the world, it may reflect a "good enough" linguistic processing strategy, where older adults have learned that the potential drawbacks resulting from misleading utterances are not worth the effort needed to detect them (Ferreira et al. 2002; Christianson et al. 2006).

9.5 Neuroimaging Evidence for Interactions Between Hearing and Cognition

Complementing evidence from behavior and pupillometry is a growing literature of functional brain imaging studies that speaks to cognitive processes required to make sense of degraded speech. Only a small number of neuroimaging studies directly examine how hearing loss affects patterns of brain activity, but studies examining responses to a variety of acoustic challenges in listeners with good hearing help provide some context for the types of brain recruitment that might be expected.

9.5.1 Neuroanatomical Frameworks for Spoken Word and Sentence Comprehension

Before considering how aging and hearing loss might affect the brain networks used to understand speech, it is first useful to consider what a "core" language processing network in the brain looks like in the absence of these additional challenges. Fortunately, many decades of research on language processing in patients with brain damage, complemented by functional brain imaging in healthy listeners, have provided a relatively clear picture on what this network might look like.

Acoustic information first reaches the brain bilaterally in primary auditory cortex, and speech perception pathways flow from this initial point. As a general rule, “lower-level” speech features are processed bilaterally and in regions that are anatomically neighboring auditory cortex. Phoneme processing, for example, differentially modulates posterior superior temporal sulcus (STS) (Liebenthal et al. 2005), and single-word comprehension further activates regions of middle temporal gyrus (Binder et al. 2000). Evidence for word processing being supported to at least some degree by both left and right hemisphere comes from findings that listeners who have had their left or right hemisphere inactivated using a Wada procedure (in which a barbiturate is selectively administered to a single hemisphere) are still able to understand words (Hickok et al. 2008).

As the linguistic demands of speech become more complex, additional brain regions are engaged. For example, combinatorial processes that integrate information across multiple words (“plaid jacket” or “red boat” vs. “jacket” or “boat”) engage the angular gyrus (Price et al. 2015, 2016) and anterior temporal lobe (Bemis and Pylkkänen 2013; Ziegler and Pylkkänen 2016). The brain networks active during sentence comprehension frequently involve left anterior temporal lobe (Evans et al. 2014) and left inferior frontal gyrus (IFG) (Rodd et al. 2005; Davis et al. 2011), regions that frequently show additional increases when syntactic demands are increased (Peelle et al. 2010b). Thus, regions for speech processing radiate from auditory cortex along dorsal and ventral streams that process increasingly complex aspects of the speech signal (Hickok and Poeppel 2007; Peelle et al. 2010a), and the degree of lateralization depends (at the very least) on the level of linguistic processing required (Peelle 2012).

9.5.2 Executive Attention Networks Respond to Errors in Speech Recognition: The Cingulo-opercular Network

One of the most repeated findings in neuroimaging studies of speech comprehension is elevated activity in the cingulo-opercular network when speech is acoustically challenging enough to result in word recognition errors. The cingulo-opercular network is an executive attention network comprised of the anterior cingulate and bilateral frontal opercula (or perhaps the nearby anterior insulae). These regions can be thought of as a functional network because of their frequent co-activation during various cognitive tasks, and because of the strong correlation of their time courses during rest (Dosenbach et al. 2008; Power and Petersen 2013). The anatomical location of the cingulo-opercular network and its involvement in speech tasks is shown in Fig. 9.3.

The time course of cingulo-opercular activity can provide some indication of its function during cognitive tasks (Neta et al. 2015). Relative to rest, the cingulo-opercular network shows increased activation at the beginning of a task block. However, it shows further punctate increases following errors. Thus, although it appears to have a role in error-monitoring, its function seems better defined as broadly concerned with task engagement, which is needed at the outset of a task, and needs to be revisited following errors.

Activity in the cingulo-opercular network is seldom seen when listeners process unchallenging speech (e.g., speech in quiet). However, when speech is acoustically challenging enough that listeners make mistakes in comprehension or word recognition, the cingulo-opercular network is often engaged (Eckert et al. 2009; Lee et al. 2018). Cingulo-opercular activity has been seen in young adults with good hearing listening to noise-vocoded speech (Wild et al. 2012; Erb et al. 2013), older adults listening to noise-vocoded sentences (Erb and Obleser 2013), and older adults listening to single words in noise (Vaden Jr. et al. 2016).

A particularly informative study in this context was conducted by Vaden and colleagues (2013). They conducted an fMRI study of word perception, with single words presented in background noise at an SNR difficult enough that participants made errors in word recognition. As in prior studies, Vaden et al. found elevated activity in the cingulo-opercular network following these error trials. However, they went one step further and conducted a general linear mixed model (GLMM) analysis to see whether this elevated activity was related to accuracy on the *following* trial. In other words, was cingulo-opercular activity "merely" a response to an error, or did it actually relate to participants' future performance? Their analysis showed that increased activity in the cingulo-opercular network following a word recognition error was indeed correlated with improved accuracy on the next trial. This finding is consistent with a role for the cingulo-opercular network in task engagement and suggests that following an error, participants were able to re-engage with the task (and thus perform more accurately) in proportion to activity in their cingulo-opercular network. Although initially demonstrated in young adults, this finding has also been shown in older adults with age-related hearing loss (Vaden Jr. et al. 2015).

Activity in the cingulo-opercular network also relates to which words are remembered on a subsequent memory test. Vaden and colleagues (2017) conducted an fMRI study in which they played words embedded in background noise for young

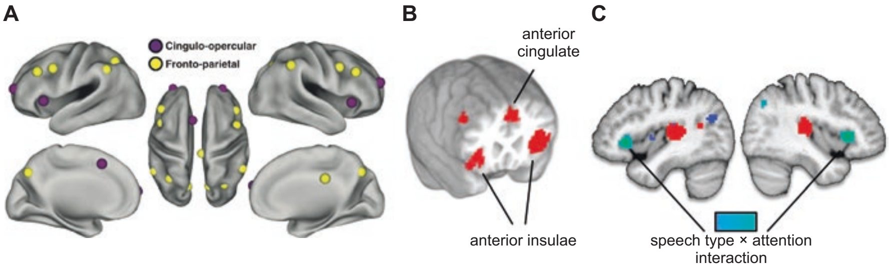

Fig. 9.3 The cingulo-opercular network. (**a**) Nodes of the cingulo-opercular and frontoparietal attention networks, defined by analysis of their time course during resting state fMRI scans (Power and Petersen 2013). (**b**) Increased activity in the cingulo-opercular network when listeners hear speech in noise (Vaden Jr. et al. 2013). (**c**) Interactions between speech clarity and attention during sentence comprehension in the cingulo-opercular network (Wild et al. 2012)

adult listeners with good hearing. Following the listening portion, listeners completed a recognition memory test on the presented words. They found that memory encoding in difficult listening conditions was poorer when cingulo-opercular activity was not sustained, suggesting a role for this network not only in perception but also in memory.

9.5.3 Responses in Prefrontal Cortex and the Successful Perception of Acoustically Challenging Speech

Although there is converging evidence regarding the role of the cingulo-opercular network when listeners make recognition errors, there is less agreement on what other neural and cognitive systems might be involved in supporting successful comprehension. Some additional anatomical evidence comes from studies showing increased activity in regions of prefrontal and premotor cortex when speech is acoustically challenging.

Davis and Johnsrude (2003) presented listeners with spoken sentences that parametrically varied in intelligibility as a result of three different acoustic manipulations: noise vocoding, background noise, or temporal interruption. Varying intelligibility in similar ways but using different signal processing approaches allowed the authors to examine whether responses to changes in intelligibility depended on the specific acoustic form of the signal. For speech that was acoustically degraded, the authors found a large swath of increased activity in left prefrontal cortex. This activity did not depend on the acoustic manipulation used, suggesting it reflects a higher-level response to a decrease of intelligibility.

Although activity in prefrontal cortex is frequently seen when speech is acoustically challenging, there is still a debate about what role this activity may be playing in perception. Some of these regions appear to overlap with portions of the frontoparietal attention network (Power and Petersen 2013), part of a set of regions that respond to a variety of general task demands (Duncan 2010; Jackson et al. 2017).

During acoustically challenging listening situations, activity is also seen in premotor cortex. This observation has led to the suggestion that motor representations may be engaged during speech perception (Watkins et al. 2003; Skipper et al. 2005). That is, when the acoustic signal is unclear, listeners may engage their own motor speech representations to help make sense of the degraded signal. However, it is important to note that the role of motor representations in speech perception is far from clear (Lotto et al. 2009). Outstanding questions remain regarding whether motor activity is obligatory or necessary during speech perception, and the degree to which its role may be influenced by the acoustic clarity of the signal (e.g., whether motor representations may be relied upon differently in quiet compared to in the presence of background noise).

9.6 A Framework for Considering Auditory and Cognitive Interactions in Speech Perception

Although this chapter has focused on auditory and cognitive interactions in listeners with age-related hearing loss, it has also emerged that principles learned from studying this group should generalize to other populations. This section presents a general framework for thinking about auditory-cognitive interactions during speech perception.

The framework, shown in Fig. 9.4a, focuses on speech perception at the level of the individual listener. In a given listening situation, the cognitive demand placed on a listener depends, minimally, on both the acoustic and linguistic challenge of the speech signal. The acoustic challenge reflects contributions of the listener (e.g., hearing sensitivity), the speech signal (e.g., clarity of articulation), and the environment (e.g., background noise) (Denes and Pinson 1993). The linguistic challenge reflects demands of speech processing (single words vs. sentences). For a given level of cognitive demand, the cognitive resources actually engaged by a listener depend on the available resources (e.g., a listener's verbal working memory capacity) and how motivated they are to engage resources to accomplish a task (Eckert et al. 2016; Richter 2016). The term "listening effort" is often applied to this act of cognitive engagement in service of speech comprehension (Pichora-Fuller et al. 2016; Peelle 2018).

An important aspect of this framework, illustrated in Fig. 9.4b, is that cognitive resources are not monolithic. That is, although it is a convenient shorthand,

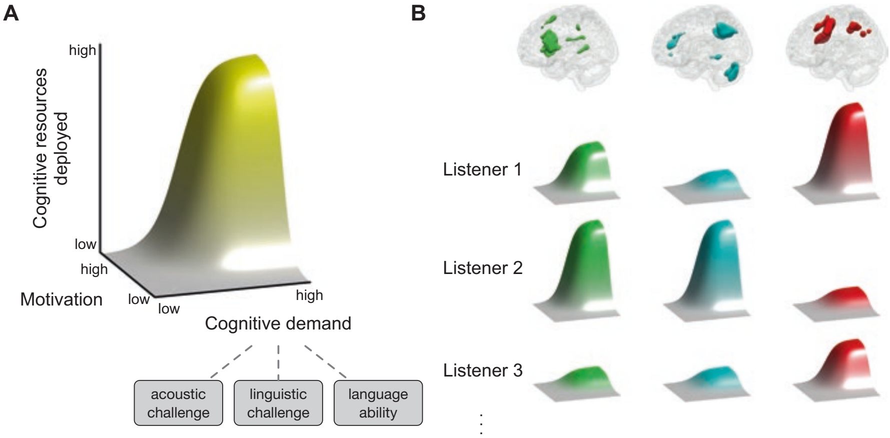

Fig. 9.4 Framework for cognitive resource allocation during speech understanding. (**a**) The cognitive resources engaged during speech understanding vary as a function of the cognitive demands of the task and a listener's motivation to understand what is being said. (**b**) Rather than monolithic "cognitive resources," different listeners may engage dissociable brain networks to various degrees in order to understand what they are hearing. (Figure available via a CC-BY4.0 license from https://osf.io/mv95h/)

speaking of a listener increasing "cognitive resources" grossly oversimplifies what listeners actually do (Wingfield 2016). Rather, each listener has a number of dissociable brain networks that support various cognitive functions, each with a biologically constrained capacity. These various networks can thus be engaged to differing degrees in a particular listening situation.

Another critical point, not necessarily obvious from Fig. 9.4, is that different listeners might achieve a similar level of performance through different patterns of neural engagement. That is, when listening to a talker in a noisy restaurant (causing cognitive demand), one listener may increase activity in the cingulo-opercular network whereas a second listener may increase activity in prefrontal cortex. One would expect this based in part on electrophysiological studies in other animals that suggest multiple combinations of neural activity can result in identical behavior (Prinz et al. 2004; Gutierrez et al. 2013). Thus, even when performance is equated across listeners (including when performance is essentially perfect), listeners may be engaging in different neural "strategies" to achieve this level of performance.

How might this framework be applied in the context of a group of young adults, all of whom have clinically normal hearing? One would expect that by measuring their hearing ability and cognitive ability it would be possible to predict the degree to which they would need to recruit cognitive resources in order to understand speech, assuming they were motivated to do so. And, in fact, if an individual's cognitive ability were lower than the demand, one would expect performance to suffer (e.g., speech might become less intelligible compared to its intelligibility for listeners with greater cognitive ability).

9.7 Summary

Understanding spoken language relies not only on the auditory system, but on linguistic and cognitive processing that acts on the acoustic signal. Individual differences in any of these abilities can affect a listener's success at understanding speech, and the cognitive and neural systems required to achieve this level of success. Because adult aging is associated with changes in both hearing and cognition, it provides an informative window into how these domains interact in all listeners.

One clear area for future growth is that of individual difference analyses, which are important for both theoretical and clinical reasons. Theoretically, contemporary theories (such as the framework outlined in Sect. 9.6) predict that individual differences in the amount of auditory challenge will relate to cognitive demand in individual listeners. Thus, accurate estimates of ability and challenge for an individual listener are required to test this prediction. From a clinical perspective, it is necessary to make judgments about the difficulties and interventions at the level of individual listeners, and thus accurate estimates are required without pooling data across a group. In this context, it will also be critical to ensure that any measures of brain structure or function are reliable at the individual level, which may require more data per individual than is typically collected for group studies (Gordon et al. 2017).

A second area where there is ample room for improvement is moving toward the use of more sophisticated measures of hearing and cognitive ability in the context of brain and cognitive measures. Many of the published studies—particularly fMRI studies—have relied heavily on pure-tone averages as a summary measure of hearing ability. Expanding measures of hearing ability to include multiple frequencies, indications of "hidden" hearing loss, temporal processing, and auditory filter bandwidth, is likely to prove more useful in estimating the auditory challenge faced by individual listeners. Similarly, age-related cognitive decline is a multifaceted concept, and will similarly benefit from more complex measurement approaches. Finally, these increased amounts of data will need more complex theories to constrain their interpretation. These theories need to reflect a more sophisticated understanding which cognitive processes are at play in speech perception and how accurately they can be assessed, so that the conditions under which they are engaged can be determined.

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