Mechanisms of the Hearing–Cognition Relationship

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ABSTRACT

This review provides a description of age-related changes in hearing and cognition, the relationship between hearing and cognition, and several potential mechanisms that underlie the relationship. Several studies have shown a significant relationship between peripheral hearing loss and cognitive impairment/decline but other studies have not. Furthermore, poor performance on measures of central auditory processing has been significantly associated with cognitive impairment. Important to understanding these relationships are the nature of the underlying mechanisms. Possible mechanisms are overdiagnosis, widespread neural degeneration, sensory degradation/deprivation, cognitive resource allocation/depletion, and social isolation/depression. Overdiagnosis occurs when hearing loss impacts tests of cognitive function or vice versa. Widespread neural degeneration can impact hearing, cognition, or both. Sensory degradation/deprivation due to hearing loss can result in neural degradation and reduced cognitive function. Increased demands due to hearing loss can result in changes in neural resource allocation, reducing available resources for cognitive function. Finally, hearing difficulties can cause social isolation and even depression, increasing the risk for cognitive decline. Data from our laboratory provide support for cognitive resource allocation/depletion. Understanding all five of these mechanisms will advance the development of effective interventions and treatments, thereby enhancing the quality of life of older adults.

KEYWORDS: Hearing loss, peripheral hearing, central auditory processing, cognition, older adults

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Learning Outcomes: As a result of this activity, the participant will be able to (1) list the five key hearing–cognition mechanisms; (2) discuss the impact of hearing loss on cognition.

Research suggests a significant, albeit weak, relationship between hearing and cognition. Less is known about the mechanisms of this relationship or how this relationship informs clinical audiology practice. This review will provide a description of age-related changes in hearing and cognition, the relationship between hearing and cognition, and several potential mechanisms that underlie the relationship.

Hearing may be described as having two domains: (1) peripheral hearing—the transmission of sound through the auditory periphery (i.e., outer ear, middle ear) and encoding of sound by the cochlea; and (2) central auditory processing (CAP)—the processing and decoding of sound through higher levels of the central auditory nervous system (i.e., brainstem, midbrain, auditory cortex). With age, declines in both peripheral hearing and CAP occur. In fact, peripheral hearing loss is the third most common chronic health condition in older adults,[1] and CAP disorder affects ~23 to 76% of older adults.[2,3] Actual numbers may be larger, as many individuals with hearing difficulties do not pursue a hearing evaluation or diagnosis.[4,5] Hearing impairment in either domain negatively impacts communication, health, quality of life, confidence, and self-image and has been associated with feelings of frustration, loneliness, depression, anxiety, paranoia, and emotional turmoil.[6–9]

Another condition associated with aging is cognitive impairment. Age-related cognitive decline can progress to mild cognitive impairment (MCI) and further deteriorate into dementia. Dementia (e.g., Alzheimer disease [AD]) and the often precursory stage of MCI are considered to be the most feared and devastating conditions that older adults face.[10,11] MCI is estimated to affect 22.6% of older adults, and individuals with MCI are at an elevated risk of AD or related dementia.[11–13] The number of individuals with dementia is expected to double every 20 years, resulting in over 65 million affected people worldwide by 2030.[14] Most important for this review is the long-established relationship between impairment in both domains of hearing and impaired cognition.

THE AUDITORY SYSTEM AND COGNITION

Peripheral Hearing and Cognition

Peripheral hearing loss has been associated with poorer cognitive performance and accelerated cognitive decline.[15–17] Specifically, peripheral hearing loss has been associated with poorer performance on global cognitive assessments,[15,16,18–20] as well as cognitive measures of memory,[16,19,21–23] executive function,[15,16,19,24] and speed of processing.[19] In addition, the risk of cognitive decline increases linearly with hearing loss severity.[15] As the degree of hearing loss increases in older adults, the risk for dementia is thought to significantly increase.[25] Thus, there is potential to intervene before dementia onset. To this end, understanding the relationship between hearing and cognitive decline is of critical importance.

Still, most of the evidence examining the relationship between peripheral hearing and cognitive impairment is correlational and cross-sectional in nature. Thus, the cause–effect direction of the relationship is not clear. For example, cognitive changes in older adults, such as processing speed, memory, and attention, can impact the processing of auditory information. Indeed, cognitive decline has been associated with faster rates of decline in peripheral hearing sensitivity.[20,26,27] Kiely et al used established cohort data to follow audiological thresholds (0.5, 1, 2, 3, 4, 6, and 8 kHz), health data (e.g., blood pressure, hypertension, stroke, etc.), and global cognitive status (Mini Mental State Exam [MMSE]) for 4,221 participants (mean age = 73.6 years) for up to 4 sessions over an 11-year span.[20] Multivariate-adjusted linear mixed models indicated factors that were predictive of hearing sensitivity decline. After adjusting for socioeconomic status and health variables, cognitive status was associated with poorer pure tone average (PTA) and faster rates of change in PTA. These relationships were evident while controlling for age. The authors suggest that these results reflect effects of top-down processing such that impaired cognitive functioning may impact hearing performance.

Other studies have found no relationship between peripheral hearing loss and cognitive decline.[28–31] Lin et al examined the association between visual impairment (visual acuity worse than 20/40), hearing impairment (2 kHz threshold greater than 40-dB hearing level [HL]), and global cognitive status (greater than 1 standard deviation [SD] change in MMSE) across 4 years.[31] Visual impairment and combined sensory impairment were associated with cognitive decline. Peripheral hearing loss alone was not associated with cognitive decline. However, both the use of an insensitive measure of global cognitive status (MMSE) and the limited hearing measurement (threshold at 2 kHz only) could have been factors in the null results of this study.

Although large, longitudinal studies may offer greater insight into the time course of the relationship between hearing loss and cognitive impairment, few have been completed. One exception is a study by Lin et al in which 1,162 older adults with hearing loss (mean age 77.9 years) and 822 older adults without hearing loss (mean age = 76.8 years) were followed for 6 years.[15] Normal hearing was defined as a 4 frequency PTA (0.5, 1, 2, and 4 kHz) of 25-dB HL or better, measured at baseline. Cognition was assessed using the Modified Mini-Mental State Test (3MS; a measure of global cognitive status) and the Digit Symbol Substitution Test (DSST; a measure of cognitive speed of processing).[32,33] The 3MS is a global cognitive screening tool that briefly assesses orientation, concentration, language, praxis, and memory.[32] The DSST is a nonverbal test of speed of processing and also may tap executive function.[33] Using these two measures, adults with hearing loss were found to have annual rates of decline that were 30 to 40% higher than older adults with normal hearing. Rates of cognitive decline were linearly related to baseline hearing loss severity. Note that hearing sensitivity was measured only at baseline; subsequent audiometric assessments were not administered beyond the baseline assessment. In addition, only two cognitive measures (3MS and DSST) were used and one was a global screening measure (3MS); thus, only one cognitive domain (speed of processing) was assessed.

To more fully examine the relationship between peripheral hearing and the many facets of cognition, a variety of cognitive measures tapping different cognitive domains should be used. Bush et al examined the cross-sectional association between peripheral hearing (PTA for 0.5, 1, and 2 kHz), 10 measures of cognition, and one global measure of cognitive status. Measures of cognition were used to assess speed of processing (five tests), executive function (two tests), and memory (three tests).[19] Participants ($n = 894$; mean age = 73.47 years) from the Staying Keen in Later Life (SKILL) study cohort were used. Multiple regression analysis showed PTA in the better-hearing ear to be related to a broad range of cognitive measures even after controlling for known risk factors for peripheral hearing loss (i.e., age, race, sex, education, diabetes, hypertension, stroke, heart disease, and depression). When examining a subsample of individuals with hearing loss (PTA $\geq$ 25-dB HL), PTA accounted for a small but significant amount of the variance in measures of global cognitive status, executive function (one measure), and memory (three measures). However, no relationship between PTA and processing speed was found when examining the subsample of those with hearing loss.

Discrepancies exist regarding the relationship between peripheral hearing and cognition. Although some studies suggest a relationship between peripheral hearing and cognition,[15–17,24] other studies indicate no relationship.[28–31] Small, but significant relationships were found when large population samples were used,[15,17,24] but no significant relationships were found in smaller studies.[29,30,34] The cognitive outcome evaluated (cognitive performance, cognitive status, dementia diagnosis) also may have contributed to the fact that differing conclusions have been reported.[17,31,35]

Central Auditory Processing and Cognition

Unlike peripheral hearing, decreased CAP abilities have been associated with poor cognitive performance and cognitive decline in relatively small samples. MCI and AD have been associated with decreased performance on tests of CAP, such as speech in noise[28,29,34,36] and dichotic digits.[30,35,37,38] As performance on many CAP measures is related to the ability to understand speech in background noise,[39–42] the relationship between performance on CAP tasks and cognition may help identify sources of speech-in-noise difficulties often reported by older listeners. Anderson et al examined peripheral hearing, CAP, multiple cognitive skills (auditory attention, auditory short-term memory, and auditory working memory), and life experience (e.g., socioeconomic status, education level, physical activity level, and musical training) in 120 older adults (mean age = 69.89).[43] Cognitive and CAP abilities were significantly related to speech understanding in noise but peripheral hearing was not, supporting several other small sample studies that found no relationship between peripheral hearing loss and cognitive function when both peripheral and CAP factors were examined in concert.[29,30,34,36] Gates et al examined PTA (0.5, 1, and 2 kHz), performance on competing sentence tasks, and MMSE scores.[29] In another study, Gates et al examined pure tone thresholds (250 to 8,000 Hz), otoacoustic emissions, performance on competing sentence tasks, and scores on the Clinical Dementia Rating Scale.[44,45] Both studies showed significant relationships between CAP and cognitive function but not between peripheral hearing and cognitive function.

Recent studies in our laboratory have examined the relationship between peripheral hearing sensitivity, CAP (using both speech and nonspeech stimuli), and multiple measures of cognitive function.[46,47] Individuals with MCI performed significantly worse than individuals without MCI on competing sentence tasks (Synthetic Sentence Identification[41] and Dichotic Sentence Identification[39]) and temporal gap detection (Adaptive Tests of Temporal Resolution[40]), but peripheral hearing sensitivity did not differ between groups for this small sample ($n = 30$). The results of these studies suggest that CAP and cognition are related more strongly than are peripheral hearing and cognition. Additionally, CAP measures may be useful tools to help identify or assess cognitive impairment.

Auditory Event-Related Potentials and Cognition

The bulk of research examining hearing and cognition has relied heavily on behavioral measures, which have limitations such as listener attention and fatigue, and examiner subjectivity. A less subjective means of examining the hearing–cognition relationship may be auditory event-related potentials (ERPs). ERPs provide an objective, noninvasive method of examining both sensory and cognitive processes with high temporal resolution. Neural transmission time (latency) and strength of response (amplitude) can be recorded in response to various stimuli. ERPs can be effectively used to examine waveform latency and amplitude changes related to cognitive impairment and dementia.[48–50] Recent data have shown that among older adults with sloping high frequency hearing loss, the P1-N1-P2 complex is longer in latency and lower in amplitude for those individuals with MCI compared with individuals without MCI.[47] Increased P1 latency and amplitude and longer P3 latency also has been found for those with MCI.[49] In addition, the hemispheric activation pattern appears more diffuse for those with MCI.[47] These results suggest that the auditory signal traveling superiorly in the system appears to be degraded in individuals with MCI as compared with those without. Interestingly, ERPs may be useful indicators of emergent MCI or AD. Golob et al found ERP latencies (N1) to be longer in individuals with gene mutations consistent with familial AD than in individuals without the gene mutation, in the absence of any behavioral signs of MCI or AD.[51]

Regardless of the form they take, auditory identifiers of early cognitive impairment would be beneficial in guiding treatment in asymptomatic or prodromal stages of the disease. However, separation of peripheral, central, and cognitive processes is very difficult.[52] These processes are clearly interrelated and decreased functioning in one area may impact another as the degraded signal travels along the auditory pathway to the brain.

HEARING–COGNITION MECHANISMS

Despite the long history of behavioral studies and the recent history of ERP studies, little is known about the underlying mechanisms of the hearing–cognition relationship. Given the large number of Americans who have hearing loss and cognitive impairment, a better understanding of the hearing–cognition mechanisms is crucial. Several potential mechanisms have been suggested, including overdiagnosis,[23,53–55] widespread neural degeneration,[18,56,57] sensory degradation/deprivation,[26,58,59] cognitive resource allocation/depletion,[59–62] and social isolation/depression.[63–66] It is possible that the mechanism is the combination of any or all of these factors (e.g., multilevel model[61]). Furthermore, the relationship between hearing and cognition may be bidirectional in nature.[20] The potential mechanisms are discussed below.

Overdiagnosis

Many older adults do not seek diagnosis or treatment for hearing-related difficulties.[4] In addition, many older listeners with hearing aids or assistive devices may not use them routinely.[4] Older adults have been known to pretend they understand instructions or test prompts, rather than request clarification. Such behavior may reduce performance on cognitive measures and masquerade as clinically significant cognitive impairment.[53,67] In this case, treatment of the hearing impairment should resolve the appearance of cognitive impairment.

One of the most common tests used to assess global cognitive status and screen for cognitive impairment is the MMSE. This test is administered verbally, often in a physician's office with background noise present. Not only is the listener receiving degraded instructions and test prompts due to hearing loss, but he or she is also contending with distractions and distortions in the signal. Background noise can affect a speech signal by masking high-frequency cues, filling silent gaps, and temporally distorting the signal.[68–70]

To quantify the impact of aging and hearing loss on MMSE performance, Jorgensen examined the effects of simulated hearing loss on MMSE scores in 125 young adults.[55] Five audibility levels were used: no simulation (i.e., normal hearing) and four levels of simulated sloping hearing losses (mild to moderately severe, mild to severe, moderate to severe, and severe to profound). The MMSE was administered at all five levels. Results showed that MMSE performance was significantly affected by audibility, with incorrect identification of cognitive decline when hearing loss was simulated. At the highest audibility level used, a mild to moderately severe hearing loss, 16% of the young adults were misdiagnosed as having dementia. The rate of misdiagnosis increased with lower levels of audibility. The results suggest that hearing loss should be examined prior to cognitive assessment so that audibility may be ensured when administering cognitive assessments; this will reduce the chances of misdiagnosis.[55]

Widespread Neural Degeneration

Lindenberger and Baltes suggested a common factor between age-related changes in the brain and hearing, vision, and cognitive function.[71] Additionally, Anstey et al found age, speed, vision, and hearing comprised a common factor in age-related changes in cognition.[56] This common cause mechanism suggests that age-related changes have a central or neural component in addition to any peripheral or end organ source.[18]

Indeed, a genetic association between hearing loss and dementia, such as hereditary sensory autonomic neuropathy with dementia and hearing loss, has been found. Klein et al found gene mutations of DNA methyltransferase 1 (DNMT1) were related to both hearing loss and dementia.[72] DNMT1 is an enzyme involved in development, maintenance, and connectivity of neural cells throughout the central nervous system. Individuals found with DNMT1 mutations developed progressive hearing loss and sensory neuropathy when young (midteens to 30 years) and cognitive decline later in life (30 to 50 years). This association suggests that a widespread failing of neural function may first be evidenced by hearing loss and only later by clinical onset of dementia.

Sensory Degradation/Deprivation

Hearing loss results in a degradation of and loss of input to the brain. Peripheral hearing loss impacts the audibility and clarity of sound; thus, the information reaching the cortex is degraded and the cortex is deprived of quality sensory information.[26] Over time, this degradation/deprivation results in changes to the structure and function of the central auditory and cognitive systems, as shown in studies of animals and humans.[59,73–77] Lin et al found neuroimaging evidence of brain atrophy and volumetric decline (structural changes) in the right temporal lobe of individuals with hearing loss, as compared with individuals with normal hearing, across ~6 years.[16] Behaviorally, degraded auditory signals have been associated with functional changes such as decreased speech-in-noise performance,[26] comprehension and memory for spoken language,[78,79] and cognitive impairment.[59]

Another way to assess the impact of auditory sensory deprivation is to examine the cognitive changes that occur when hearing loss is treated with amplification. Studies have shown that hearing aid use improves signal detection and speech understanding; however, no strong evidence for long-term cognitive changes due to hearing aid use has been found.[4,80] Although they did not directly study cognition, Palmer et al assessed behavioral changes in individuals with MCI or AD after short-term use of amplification.[81] Caregivers reported greater compliance with hearing aid use, reduced problem behaviors, and reduced perceived hearing handicap after 2 months of amplification use. Many listeners wait years before seeking treatment for hearing loss; thus, the subsequent effects of long-term sensory deprivation may not be easily reversed. As with most diseases and disorders, early hearing loss identification leads to the best treatment effects. It is important to note that hearing aid use will not compensate for all the aforementioned effects of sensory degradation/deprivation; other accommodations may still be necessary when assessing cognitive function in individuals with hearing impairment.

Cognitive Resource Allocation/Depletion

When an incoming auditory signal is degraded due to hearing loss or external noise, a greater number of neural resources must be allocated for auditory processing of the degraded signal and, as a result, fewer resources remain for other, higher-level cognitive processes (e.g., working memory, recall).[16,26,82] Imaging studies have shown that brain activation patterns change when processing tasks are challenging.[83,84] In addition, decreased gray matter density in the primary auditory areas of individuals with hearing loss suggests a reorganization of processing systems when auditory stimulation is decreased.[76] MCI can impact resource allocation, as well. A recent study in our laboratory showed hemispheric activation during an auditory ERP task to be different and more widespread for individuals with MCI, suggesting a greater number of resources allocated to auditory detection.[47]

One way to examine allocation/depletion is to measure cognitive capacity following resource allocation in difficult listening situations (cognitive spare capacity). Mishra and colleagues examined the cognitive spare capacity of 24 older listeners (mean age = 69, SD = 4.7) with hearing loss (mean 4 frequency PTA = 34.5, SD = 3.6).[85] The Cognitive Spare Capacity Test was administered in quiet and in noise.[86] In addition, tests of cognitive ability (reading span, text reception threshold, letter memory, delayed free recall of the reading span test, and the Simon task) were administered. Amplification was used with the older listeners to compensate for hearing loss. Results were compared with similar, previous testing with young adults with normal hearing.[86] No difference in cognitive spare capacity was found between groups when the listening conditions were optimal. However, when presented in background noise, older listeners performed worse on the Cognitive Spare Capacity Test and cognitive tests. The background noise significantly affected older adults' performance, perhaps by decreasing the cognitive resources available to complete the tasks successfully. Therefore, cognitive function may be diminished in older listeners due to reallocation of valuable resources in an effort to process degraded auditory signals.

Social Isolation/Depression

As discussed, hearing difficulties place increased demands on cognitive processes and resources. Many social gatherings are held in meeting rooms, restaurants, and social halls where a high level of background noise is present, increasing the effort required to communicate and creating challenging situations for any listener. Many individuals with hearing loss and/or cognitive impairment withdraw from these situations. The result is social isolation or a reduction in association with family, friends, or colleagues. As the degree of hearing loss increases, so do the odds of being socially isolated.[66] Hearing loss has been associated with anxiety, depression, self-esteem, and well-being.[87] Specifically, older adults with hearing loss are more likely to experience depressive symptoms, lower self-efficacy and mastery, more feelings of loneliness, and a smaller social network than normally hearing peers.[63–65] Furthermore, studies have found that older adults with depressive symptoms (i.e., feelings of social isolation or loneliness) have an increased risk of cognitive decline.[88–91] This research implies a cascade from hearing loss to social isolation/depression to cognitive impairment. However, there is little, if any, research to help us understand how hearing, psychosocial, and cognitive factors interact. Such research is essential to design strategies to intervene at the point of hearing problems, social isolation, and/or cognitive difficulties.

CONCLUSIONS

Hearing loss may be a promising indicator of the prodromal stages of cognitive decline. A better understanding of the relationship between hearing and cognition is critical, as intervention prior to dementia onset may be possible. Currently, conflicting evidence exists regarding the respective contributions of peripheral hearing and CAP to cognitive function. More research is needed to tease apart the interaction between peripheral and/or central auditory function and cognitive decline.

Key to understanding this relationship is expanding our knowledge of the underlying mechanisms. Several potential mechanisms have been identified. Overdiagnosis can occur when undiagnosed hearing loss affects cognitive test results or vice versa, when undiagnosed cognitive impairment affects hearing evaluation results. Widespread neural degeneration due to aging can impact both sensory and cognitive function. In fact, certain genetic mutations are manifested first by hearing loss and then by cognitive decline. Sensory degradation/deprivation due to hearing loss can result in neural degradation and reduced function. Cognitive resource allocation occurs when a degraded sensory signal requires rearrangement of cognitive resources for processing, to the detriment of higher-order thinking and memory. Hearing loss can lead to social isolation and depression, resulting in an increased risk of cognitive decline. All five of these mechanisms demonstrate the delicate relationship between auditory and cognitive function. A better understanding of these mechanisms will advance the development of effective interventions and treatments, thereby enhancing the quality of life of older adults.

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