Purpose: To summarize existing data on the interactions of cognitive function and hearing technology in older adults.

Method: A narrative review was used to summarize previous data for the short-term interactions of cognition and hearing technology on measured outcomes. For long-term outcomes, typically for 3–24 months of hearing aid use, a computerized database search was conducted.

Results: There is accumulating evidence that cognitive function can impact outcomes following immediate or short-term use of hearing aids and that hearing aids can impact immediate cognitive function. There is limited evidence regarding the long-term impact of hearing aids on cognition, and the most rigorous studies in this area have not observed a positive effect.

Conclusions: Although interactions have been observed between cognition and use of hearing aids for measures obtained following immediate or short-term usage of hearing technology, limited evidence is available following long-term usage, and that evidence that is available does not support an effect of hearing aids on cognitive function. More research is needed, however, including rigorous studies of older adults following longer periods of hearing aid usage.

Key Words: amplification or hearing aids, cognition, outcomes, response to intervention

As a part of the 2011 Starkey Research Summit, the authors were charged with the task of reviewing the literature for information available on the interaction of hearing technologies and cognition. This topic can be viewed from two quite different perspectives. In one case, cognition can be considered as a factor impacting the outcomes obtained from hearing aid intervention. In another case, one can examine the impact of hearing technologies on cognition. Both perspectives were considered here and were reviewed at the research summit.

Cognition as a Factor in the Outcome of Technological Intervention for Hearing Loss

There are two ways in which cognition is a factor in the outcome of treatments of hearing loss. First, an individual’s latent cognitive skills can determine the effectiveness of treatments. For example, given two older adults with hearing impairment who have identical hearing loss and wear identical hearing aids, if one of the two has superior verbal knowledge or cognitive processes, the hearing aid outcomes may be greater for this individual. Second, interventions for treating hearing loss can affect cognitive outcomes (such as deploying of attention and memory encoding). Peripheral sensory decline in older adults can have a negative impact on a variety of measured cognitive skills through acute information degradation or through chronic sensory deprivation (e.g., Lindenberger & Baltes, 1994; Schneider, Pichora-Fuller, & Daneman, 2010). An awareness of the interactions of cognition with peripheral sensory function makes it possible to envision hearing technology that is prescribed not just to a hearing-loss profile but also to the cognitive profile of an individual. Moreover, this perspective makes it possible to envision technology that restores or enhances cognitive function.

When we refer to technological intervention, our point of reference is acoustic amplification and signal processing found in hearing aids. We do not explicitly consider other interventions for hearing loss, such as cochlear implants or FM systems, although some of our discussion points may be applicable to them. We also do not discuss computer-based or other training programs because they are discussed in a companion article (see Pichora-Fuller & Levitt, 2012, in this issue). Finally, we also make a distinction between the short-term and long-term interactions of hearing technology and cognition in older adults. By far, the majority of the data available pertain to the impact of cognition on immediate or short-term (generally, ≤ 2 months) outcomes with hearing technology. In addition, there are a limited number of studies of the immediate influence of hearing technology on cognitive function and even fewer on the long-term (generally, 3 months–2 years) usage of hearing technology.
Short-Term Interactions of Hearing Technology and Cognition in Older Adults

It is hypothesized here that injecting a cognitive perspective into the design and deployment of technological interventions for hearing loss may help to overcome limitations of our current approaches. Current approaches to the design of hearing technology have focused on maximizing audibility and improving signal-to-noise ratio of speech while preserving sound quality. Most advances have been achieved through the introduction of sophisticated signal processing algorithms into hearing instruments, such as wide-dynamic-range multiband compressive amplification, multiband expansion, directional beam forming, noise reduction, environment detection and adaptation, adaptive null steering, and echo suppression. These approaches have led to technological interventions that have significantly reduced hearing handicaps for many listeners (Kochkin, 2011). Nevertheless, despite these successes, patients continue to have difficulties in complex and dynamic environments that introduce spatial and informational complexity and that require complex interaction (Kochkin, 2005).

Such shortcomings are understandable because hearing handicap is characterized not just by a deficit in speech reception but also by deficits in a wider range of abilities mediated by hearing, such as perception of environmental sounds, spatial perception, selective and divided attention in multiple-stream environments, and ease of listening (Gatehouse & Noble 2004). A focus on speech audibility fails to take into account that effective auditory communication involves, as noted by Kiessling et al. (2003), more than just hearing or passively receiving information. It requires listening to and selecting relevant information with attention and effort, comprehending the selected information by using contextual and stored knowledge, and finally acting on the received information by storing in memory or performing a contingent task. Cognitive processing is an essential component of these latter three processes. Accordingly, technological interventions should incorporate cognition if they are to treat the range of deficits associated with hearing handicap and to effectively restore all of the processes involved in auditory communication.

A role for cognitive processing in auditory function has been clearly demonstrated in the literature. Akeroyd (2008) completed a systematic review of 20 papers published since 1989 in which measurements of speech reception in noise and of cognitive function showed linkages that suggested that high-cognitive performers were more likely than low-cognitive performers to be adept at speech reception in noise. Pichora-Fuller, Schneider, and Daneman (1995) were one of the first to demonstrate the particularly important role of cognitive processing in speech understanding by older listeners with hearing loss. Using the difference in performance between low-context and high-context sentences in noise as a measure of cognitive-linguistic (semantic) processing, the experiment showed that older listeners with hearing impairment can achieve performance that is comparable to that of younger listeners with normal hearing but with greater reliance on higher level cognitive-linguistic processing.

Failing to treat hearing loss can have detrimental consequences not just for auditory function but also for cognitive function. The detrimental effect of hearing loss can persist over multiple time scales of cognitive function. For example, it shows up as greater reliance on effortful use of context to understand speech (Pichora-Fuller et al., 1995), degraded ability to use spatial selective attention to attend to foreground information presented in the midst of spatially separated background information (Neher et al., 2009), degraded short-term memory storage and recall (McCoy et al., 2005), degraded long-term episodic and semantic memory (Ronberg, Danielsson, et al., 2011), and even more dire consequences, such as increased risk of dementia (reviewed in the companion article [Tun, Williams, Small, & Hafter, 2012] that appears in this issue).

Intervention that successfully rehabilitates the entire auditory communication process may possibly include technology designed to restore or improve cognitive function. That such a scenario is possible is evident from emerging evidence showing that hearing technology can affect short-term cognitive processing. For example, Sarampalis, Kalluri, Edwards, and Hafter (2009) recently showed that noise reduction in hearing aids can reduce the cognitive load of listening to speech in noise in young adults with normal hearing. The study used dual-task divided-attention paradigms in which the primary task was always speech reception in noise, whereas the secondary task was either a complex visual reaction-time task or an auditory word recall task. In both versions, listeners understood speech in noise equally well whether noise reduction was activated or not, but the processing reduced reaction times and increased word recall at negative speech-to-noise ratios. The results indicated that noise reduction reduced the cognitive load of understanding speech in noise so that additional cognitive resources became available for improving performance on the secondary task. Evidence that technological intervention can reduce cognitive load in older listeners with hearing impairment is also emerging, and indeed evidence is emerging for a wider range of short-term cognitive outcomes, such as reduction of mental fatigue and preservation of the benefits of spatial selective attention, but the studies are still unpublished (e.g., experiment by Ng et al. described in Rомнberg, Rudner, & Lunner, 2011).

Whereas hearing technology affects short-term cognitive processing, the reverse is also true—the state of a listener’s cognitive system affects how information is used. For example, many studies have demonstrated recently that listeners with good cognitive function, particularly those with greater working memory capacity, are better at understanding speech in noise (Akeroyd, 2008). Such associations, particularly those relating benefit of intervention to cognitive skills, can help determine candidature for hearing technology. Indeed, it is even possible to deploy specific features of technologies to particular cognitive skills. Specifically, some researchers have advocated choosing fast time constants for dynamic-range compression only for high-cognitive performers, on the basis of findings that individuals who performed well on a working-memory task tended to derive additional benefit from fast-acting compression over slow-acting compression for speech reception in noise (Lunner, 2003; Lunner & Sundewall-Thoren, 2007), although such findings have not
been observed universally (Cox & Xu, 2010). Cognitive function is clearly related to speech understanding, although it is often secondary to hearing loss as a predictor of speech performance, especially for unaided listening (Akeroyd, 2008). Moreover, when significant associations emerge between cognitive function and either unaided or aided speech perception, the correlations are typically small, most often accounting for less than 20% of the variance (Akeroyd, 2008). The weak associations may be due to the speech tests not being complex enough to engage the cognitive system broadly. However, the inconsistent results across studies, the small correlations, and the possible inadequacy of the speech materials may also reflect our incomplete understanding of how cognitive processing acts and how cognitive subsystems interact and influence auditory function.

More complete theories for the influence of cognitive processing on auditory function, the ease of language understanding model being an example of such a theory applied to speech understanding (Ronnegberg, 2003), may more firmly establish the linkages and help apply this knowledge to individualization of treatment. Such an understanding should consist of not only how cognition affects auditory function and speech communication in a static manner but also how it is deployed dynamically, based on environment changes and needs. Emerging studies are finding physiological markers of cognitive function, such as pupil dilation (Zekveld, Kramer, & Festen, 2010, 2011) and brain imaging (Kerlin, Shahin, & Miller, 2010), which have the potential to measure momentary allocation of cognitive resources and thus can help explain the dynamic aspects of cognitive processing. Although these measures are still in their infancy, they open the possibility of deploying and adjusting hearing technology in response to online measures of cognitive state. For example, such a situational adjustment may take the form of slowing down the dynamics of a compressor on the basis of an online measure of the cognitive load of listening to speech in noise.

Injecting a cognitive perspective into the management of a patient’s intervention should help address two of the major problems in treatment of hearing loss—one being the substantial intersubject variability in outcomes and the other being the continued failure of hearing aids to alleviate hearing handicaps in complex real-world scenarios.

Long-Term Impact of Hearing Technology on Cognition in Older Adults

Thus far, when considering the influence of hearing technology on cognition, the focus of this review has been on the short-term impacts of technology on cognitive processing. That is, the focus has been on the immediate benefits of amplification on acutely measured cognitive processing. Is there any evidence regarding the long-term benefits of sustained use of hearing technology on cognitive function in older adults? Our focus in this brief review, and especially in this section, is on older adults, as they represent the most common purchasers of hearing aids and are an age group that is likely to experience some deficits in cognitive function. Many older adults have decreased cognitive function relative to younger adults. In “normal” or “healthy” aging, performance on fluid process-based aspects of cognition declines steadily throughout adulthood from about age 20 through age 80 years (e.g., Salthouse, 2010). In addition, the prevalence of subtle cognitive dysfunction, such as mild cognitive impairment, ranges from 3% to 18% among older adults (Mayo studies; e.g., Petersen et al., 2010). According to some theories, age-related changes in cognitive processing may be induced by or related to the presence of peripheral hearing loss in older adults (e.g., Lindenberger & Baltes, 1994; Schneider et al., 2010). Several theories of cognitive aging, such as the deprivation hypothesis and the information-degradation hypothesis (Schneider & Pichora-Fuller, 2000), imply that the observed cognitive dysfunction in many older adults may be a direct result of the diminished quality and quantity of sensory input with advancing age. This issue has received renewed interest empirically as well (e.g., Lin et al., 2011). As such, a prediction might be that use of hearing technology to overcome the loss of audibility from the peripheral hearing loss would have a positive impact on higher-level processing in older adults. What is the current status of the evidence regarding the effects of hearing technology on cognition in the elderly?

To answer this question, we did a literature search of PubMed with the MeSH terms “aid, hearing,” and “cognition.” The search initially yielded 131 articles. However, only six of the 131 articles studied the effects of hearing aids on cognitive function in older adults. Many of the others were studies of the influence of cognitive function on acute aided performance, similar to those summarized in the preceding section for young or older adults. In addition to these published studies, one of the coauthors of the current review (Larry E. Humes) directed an unpublished master’s thesis on this topic (Branam, 2002). Given the sparsity of information available in the published literature, this study was also included in this review. All told, counting this thesis, seven studies provided the evidence base with which to address the research question of interest.

Table 1 summarizes these seven studies, with the first being conducted more than two decades ago by Mulrow et al. (1990). Only one study (Acar, Yurekli, Babademez, Karabulut, & Karasen, 2011) failed to make use of a control group. Moreover, all studies involved older participants, and in six out of the seven studies that provided sufficient documentation, it appears that the hearing loss was typical of older adults. Five of the seven studies reported that the subjects had no prior hearing aid experience; two studies failed to report this information. The number and type of cognitive measures varied widely across studies, with some (Acar et al., 2011; Mulrow et al., 1990) using a single gross dementia-screening survey and the rest using several more rigorous laboratory or clinical measures of cognitive function. Unfortunately, sufficient details regarding the hearing aids used and their function were often missing, including whether the subjects were actually wearing their hearing aids and, if so, how much each day. Finally, as also noted in Table 1, the duration of hearing aid usage varied considerably across studies, from as short as 2–3 months to as long as 2 years.

Of the seven studies summarized in Table 1, four studies found few or no significant effects of hearing aid usage on cognitive function, and three studies found significant
<table>
<thead>
<tr>
<th>Study</th>
<th>No. of groups</th>
<th>Groups</th>
<th>N</th>
<th>Hearing loss</th>
<th>Age in years (M)</th>
<th>Prior HA use</th>
<th>No. of cog. measures</th>
<th>Cog. measures</th>
<th>HA fit</th>
<th>HA use</th>
<th>HA duration</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mulrow et al. (1990)</td>
<td>2</td>
<td>control</td>
<td>95</td>
<td>HFPTAbe = 51</td>
<td>71</td>
<td>Not reported</td>
<td>1</td>
<td>A Short Portable Mental Status questionnaire</td>
<td>97% monaural, 98% ITE; subjective benefit</td>
<td>30% 4–8 h/day, 55% &gt;8 h/day</td>
<td>4 mos</td>
<td>Significant effect of HA use</td>
</tr>
<tr>
<td>Tesch-Römer (1997)</td>
<td>3</td>
<td>EHI control</td>
<td>42</td>
<td>PTA = 26; HFPTA = 38</td>
<td>71.5</td>
<td>None</td>
<td>5</td>
<td>2 Proc speed (dig symbol, digit letter), 2 verbal fluency (animals, letter s, 1 vocabulary (spot-a-word), V</td>
<td>74% monaural fits, 51% ITE, objective benefit measured</td>
<td>6.5–7 h/day</td>
<td>6 mos</td>
<td>No effects of HA use on cognitive function, including when controlled for individual differences in daily usage</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ENH control</td>
<td>28</td>
<td>PTA = 12; HFPTA = 16</td>
<td>69.4</td>
<td>None</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>HA</td>
<td>70</td>
<td>HFPTA = 47</td>
<td>71.8</td>
<td>None</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Branam (2002)</td>
<td>2</td>
<td>control</td>
<td>13</td>
<td>PTA = 35; HFPTA = 47</td>
<td>72.9</td>
<td>None</td>
<td>11</td>
<td>WAIS–R scales, A &amp; V</td>
<td>Bilateral ITE, NAL–R, REM</td>
<td>8.9 h/day</td>
<td>2 yrs</td>
<td>No effects of HA use on cognitive function</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HA</td>
<td>13</td>
<td>HFPTA = 45</td>
<td>72.8</td>
<td>None</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>van Hooren et al. (2005)</td>
<td>2</td>
<td>control</td>
<td>46</td>
<td>HFPTA, best ear = 44</td>
<td>74.5</td>
<td>None</td>
<td>6</td>
<td>1 Sel Attention (Stroop), 1 Focus of Atten (Concept Shifting Task), 1 proc speed (Letter Digit Substitution), 2 Verbal Learning/Memory (Visual Verbal Learning Test), 1 Verbal Fluency (animals), ALL V</td>
<td>No information provided, but significant functional gain reported</td>
<td>Not reported, but 31 of 56 wore hearing aids at least 8 h/day</td>
<td>1 yr</td>
<td>No effects of HA use on any of the cognitive measures, even when the subgroup of HA users with at least 8 h/day of usage examined</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HA</td>
<td>56</td>
<td>HFPTA, best ear = 46</td>
<td>72.5</td>
<td>None</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lehrl et al. (2005)</td>
<td>2</td>
<td>control</td>
<td>15</td>
<td>Details not reported</td>
<td>71.2</td>
<td>None</td>
<td>3</td>
<td>Working Memory Capacity, Memory Span, Information Processing Speed, A &amp; V</td>
<td>13 of 15 bilateral</td>
<td>6.7 h/day</td>
<td>2–3 mos</td>
<td>HA group significantly improved for WM capacity (p = .012, one-tailed), but not for other two cognitive measures; moderate correlations between functional gain and WM cap gain</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HA</td>
<td>15</td>
<td>Details not reported</td>
<td>72.1</td>
<td>None</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acar et al. (2011)</td>
<td>1</td>
<td>HA</td>
<td>34</td>
<td>Mean PTA 0.5, 1, 2, &amp; 4 kHz = 56.8</td>
<td>70.1</td>
<td>None</td>
<td>1</td>
<td>MMSE, A</td>
<td>No details provided</td>
<td>No details provided</td>
<td>3 mos</td>
<td>Significant effect of HA use (MMSE increased from 20.4 to 23.0—both low)</td>
</tr>
<tr>
<td>Choi et al. (2011)</td>
<td>2</td>
<td>control</td>
<td>11</td>
<td>PTabe = 41; PTAwe = 44</td>
<td>63.1</td>
<td>Not reported</td>
<td>3</td>
<td>Korean Visual Verbal Learning Test: Recall, Delayed Recall, Recognition</td>
<td>No details provided</td>
<td>No details provided</td>
<td>6 mos</td>
<td>Significant effects (p &lt; .03) of HA for HA group on 2 of 3 cognitive measures: recall, recognition</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HA</td>
<td>18</td>
<td>PTAbe = 50; PTAwe = 64</td>
<td>69.5</td>
<td>Not reported</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

Note. No. = number; HA = hearing aid; HFPTAbe = high-frequency pure-tone average better ear; ITE = in the ear; h/day = hours per day; EHI = elderly hearing-impaired; PTA = pure-tone average; ENH = elderly normal hearing; proc speed = processing speed; dig symbol = digit-symbol test; HFPTA = high-frequency pure-tone average; WAIS–R = Wechsler Adult Intelligence Scale—Revised; NAL–R = National Acoustic Lab—Revised; REM = real-ear measurement; Sel Attention = selective attention; Focus of Atten = focus of attention; ALL V = all visual tests; WM = working memory; cap = capacity; MMSE = Mini-Mental State Examination; PTabe = pure-tone average better ear; PTAwe = pure-tone average worse ear.
effects. Two of the three studies observing significant effects, however, made use of gross, dementia-screening clinical tools to study the impact of hearing aids on cognition. Of the five studies making use of more rigorous and comprehensive measures of cognitive function, four did not observe significant effects of hearing aids on cognition, even with up to 2 years of regular (8.9 hr per day) usage of bilateral well-fit hearing aids. Of course, when one considers that typically 8–12 years pass from when older adults first suspect hearing loss to when they seek help and are fitted with hearing aids (e.g., Davis, Smith, Ferguson, Stephens, & Gianopoulos, 2007), perhaps it is unrealistic to expect changes in cognition when the “deprivation-like” effects of the hearing loss have been reversed for only 2 years.

In summary, there is no strong evidence for the long-term effects of hearing technology on cognition. The evidence available to date, however, is sparse, and no attempts have been made yet to apply the technologies that were successful in effecting acute short-term changes to the study of long-term benefits.

Research Recommendations

At the summit, we identified the following research topics that should be pursued in order to make advances on understanding the relationship between cognition and hearing technology.

- Identify measures that should comprise a cognitive profile that will be used for customizing technological intervention to individual patients.
- Define models for the cognitive factors underlying auditory function and speech communication, including (a) associations between cognitive skills and auditory function other than speech reception (e.g., auditory scene analysis, spatial hearing) and (b) associations between static cognitive skills and dynamic cognitive functions (e.g., relationship of working-memory capacity to selective attention and attention switching).
- Devise cognitive outcome measures that are sensitive to differences in hearing technology.
- Design interventions to achieve particular cognitive outcomes, such as enhanced attention to speech.
- Determine, in a rigorous manner, whether hearing aids improve long-term cognitive function by using multiple, reliable, and comprehensive measures of cognition for longer periods of time and with better documentation of the amplification provided.
- Document the effectiveness of interventions designed to restore cognitive functions in terms of improved satisfaction, reduction of handicap, improved uptake, and increased use.

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References


