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## The Emergence of Cognitive Hearing Science

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## Abstract

Cognitive Hearing Science or Auditory Cognitive Science is an emerging field of interdisciplinary research concerning the interactions between hearing and cognition. It follows a trend over the last half century for interdisciplinary fields to develop, beginning with Neuroscience, then Cognitive Science, then Cognitive Neuroscience, and then Cognitive Vision Science. A common theme is that an interdisciplinary approach is necessary to understand complex human behaviours, to develop technologies incorporating knowledge of these behaviours, and to find solutions for individuals with impairments that undermine typical behaviours. Accordingly, researchers in traditional academic disciplines, such as Psychology, Physiology, Linguistics, Philosophy, Anthropology, and Sociology benefit from collaborations with each other, and with researchers in Computer Science and Engineering working on the design of technologies, and with health professionals working with individuals who have impairments. The factors that triggered the emergence of Cognitive Hearing Science include the maturation of the component disciplines of Hearing Science and Cognitive Science, new opportunities to use complex digital signal-processing to design technologies suited to performance in challenging everyday environments, and increasing social imperatives to help people whose communication problems span hearing and cognition. Cognitive Hearing Science is illustrated in research on three general topics: 1. language processing in challenging listening conditions; 2. use of auditory communication technologies or the visual modality to boost performance; 3. changes in performance with development, aging, and rehabilitative training. Future directions for modelling and the translation of research into practice are suggested.

## **Introduction**

Cognitive Hearing Science is an emerging field of interdisciplinary research concerning the interactions between human hearing and cognition. Its emergence follows a trend over the last half century for new fields to develop because an interdisciplinary approach is necessary to understand complex human behaviours, to develop technologies incorporating knowledge of these behaviours, and to find solutions for individuals who have impairments that undermine typical behaviours. The evolution of interdisciplinary approaches to research concerning the mind and brain is reflected in the formation of new societies. For example, the Society for Neuroscience, founded in 1969, brought together scientists and physicians studying the brain and the nervous system (Society for Neuroscience, 2009). Ten years later, in 1979, the Cognitive Science Society was established to promote research across traditional disciplines, including Artificial Intelligence, Linguistics, Anthropology, Psychology, Neuroscience, Philosophy, and Education, so that interchange between researchers in these disciplines could advance the common goal of understanding the human mind (Cognitive Science Society, 2009). By 1994, the Cognitive Neuroscience Society was formed to unite brain, mind, and behaviour researchers (Cognitive Neuroscience Society, 2004). More recently, in 2001, the Vision Sciences Society was formed to advance interdisciplinary understanding of vision, and its relation to cognition, action and the brain (Vision Sciences Society, 2009). Even more recently, in 2007, the Auditory Cognitive Science Society held its first meeting, with the name of the organization changing to Auditory Cognitive Neuroscience Society in 2009 (Auditory Cognitive Neuroscience Society, 2009). The purpose of this paper is to reflect on the past, present, and future of Cognitive Hearing Science as an interdisciplinary field.

### **Inter-twined histories of cognitive and auditory research**

Although the mind and knowledge had been studied by philosophers, physiologists, and psychologists for centuries, modern Cognitive Psychology emerged in the decades after World War II with a focus on human performance and attention, accompanied by synergistic developments in Computer Science and Linguistics (Anderson, 2000). In the post-WWII period, there was also a dramatic increase in the membership and publications of the Acoustical Society of America, the largest organization of hearing and acoustics researchers from disciplines spanning Physics, Engineering, Physiology, Psychology, Linguistics, Music, and Architecture (Acoustical Society of America, 2009). Thus, the study of the senses and the mind converged in the early years of the modern eras of Cognitive Psychology and Hearing Science. Indeed, groundbreaking work that spanned cognitive and auditory research was performed in the 1950's by Broadbent, Cherry and others in Cambridge (Broadbent, 1958) who studied dichotic listening and selective attention, coining the term 'cocktail party phenomena', which is still used to refer to prevailing research questions concerning how listeners perform in complex, realistic environments. Speech scientists developed new models and experimental phonetics methodologies to explore the relationships between the production, acoustics and perception of speech (Raphael, Borden, & Harris, 2007), while psycholinguistics began to investigate language behaviour from an information processing perspective (Kess, 1991). Furthermore, in the post-WWII era, Audiology was born as a field of clinical practice because of the need to rehabilitate veterans with noise-induced hearing loss, engineers used new knowledge of electronics to design smaller and more easily worn hearing aids, and auditory physiologists embarked on research to understand the afferent and efferent pathways from cochlea to cortex as they related to the auditory and cognitive processes involved in language, memory, and attention, even though this ultimate goal would not be attainable for many years (Davis & Silverman, 1970).

Despite the post-WWII historical connections between the study of hearing and cognition, in the last quarter of the 20<sup>th</sup> century, the study of cognition and hearing progressed in relative isolation. Cognitive psychologists streamlined behavioural research paradigms by minimizing confounds arising from sensory factors, while psychophysical paradigms were used to systematically investigate the capabilities of humans to respond to basic physical dimensions using artificially simple stimuli free of confounds from cognition. Indeed, ‘modularity of mind’ became a popular view that was consistent with the isolation of research in the domains of sensory and cognitive information processing (Fodor, 1983; Pylyshyn, 1999). In cognitive research, the organization of the brain was viewed primarily from a cross-functional perspective, with the aim of researchers being to determine the purpose of specific brain areas. It was easier for cognitive psychologists to conduct experiments involving reading or using visual stimuli rather than spoken language or auditory stimuli, and animals could be used to study higher-level visual perception, but not language or music processing. In hearing research, physiologists focused more on the cochlea than the cortex and more on afferent than efferent pathways, while psycho-acousticians focused more on peripheral and bottom-up processing than on central and top-down aspects of information processing. Engineers designed new hearing aid circuits informed largely by models of the cochlea, while audiologists were primarily concerned with pathologies of the ear and tests using signals such as simple pure-tones and isolated words which reflected problems in speech perception more than difficulties understanding naturalistic language or music or environmental sounds.

### **Emergence of Cognitive Hearing Science**

After a few decades of relative isolation between hearing and cognitive research, the number of publications linking hearing and cognition started to grow again, with a marked increase in activity over the last decade (see Figure 1; see also Pichora-Fuller & Singh, 2006).

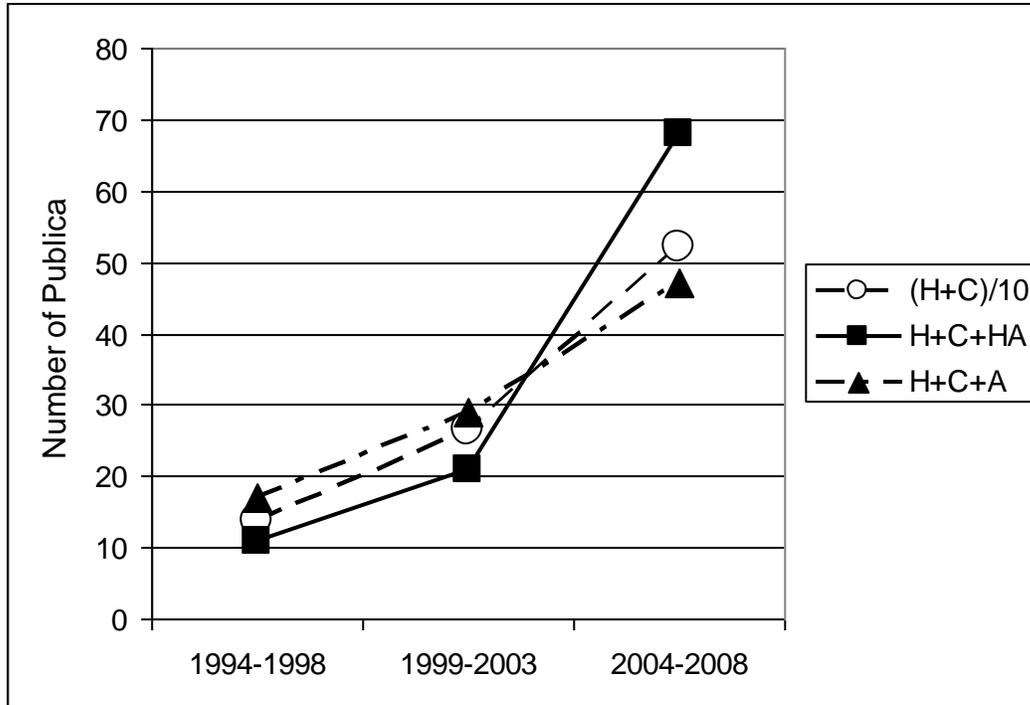


Fig. 1. *The number of publications in each of three five-year periods, based on bibliographic search in PubMed. Open circles represent the number of articles on hearing and cognition divided by 10. Triangles represent the subset of the articles on hearing, cognition and aging. Squares represent the subset of the articles on hearing, cognition and hearing aids.*

Numerous factors seem to have motivated the gradual convergence of auditory and cognitive research around the end of the millennium, including the need to understand how listeners perform in more ecologically realistic situations (Bregman, 1990; Handel, 1989; McAdams & Bigand, 1993; Neuhoff, 2004), how lifespan changes and impairments alter performance (Schneider & Pichora-Fuller, 2000; Wahlin, MacDonald, de Frias, Nilsson, & Dixon, 2006), how to design new communication technologies using advanced signal-processing and more customized ergonomics (Edwards, 2007), and how to implement educational and rehabilitation programs to enhance performance based on evidence of brain plasticity (Kraus et al., 1995; Tremblay, 2007). Advances have been fuelled by new opportunities to use more powerful research tools to study the interactions between auditory and cognitive processing,

including virtual reality simulations to present complex, realistic stimuli under precisely controlled experimental conditions (Durlach & Mavor, 1995), eye-movement tracking to record more sophisticated on-line measures of listening comprehension (Allopenna, Magnuson, & Tanenhaus, 1998), and rapidly advancing physiological methods to measure event-related brain potentials (ERPs) and functional magnetic resonance imaging (fMRI) of brain activity during listening (Belin et al., 1999, 2000; Rugg & Coles, 1995). Finally, progress is reflected in the proposal of new models concerning the interactions between auditory and cognitive processing during speech perception and language comprehension (Holt & Lotto, 2008; Stenfelt & Rönnerberg, 2009). Nevertheless, much work remains to be done to develop models and to translate research into practice concerning the design of new technologies, built environments, and behavioural interventions that will enhance human communication.

### **Recent research concerning the connection between hearing and cognition**

Cognitive Hearing Science is illustrated in research on three general topics: 1. language processing in challenging listening conditions; 2. the use of auditory communication technologies or the visual modality to boost performance; 3. changes in performance with development, aging, and rehabilitative training. The following review highlights some of the research on these topics.

#### **Language processing in challenging listening conditions**

Knowledge of speech perception and language comprehension advanced in the last quarter of the 20<sup>th</sup> century based primarily on research conducted in young adults with normal hearing and vision. Bottom-up, modular views opposed the idea that sensory and cognitive processing interacted, but rather held that higher-level cognitive processing was modality-independent and that lower-level sensory processing was usually so automatic that it was not affected by the top-down influences of cognition (Carpenter, Miyake, & Just, 1994, 1995). Concern with multi-modal speech processing was relatively rare (Massaro, 1997; Campbell,

Dodd, & Burnham, 1998) and reductions in hearing and/or vision were not considered in most of the early work on speech perception (Pisoni, 1981) or in work on language comprehension and working memory (Baddeley & Hitch, 1974; Daneman & Carpenter, 1980). For the most part, interactions between hearing, speech perception, and language comprehension were reserved for situations requiring more effortful error correction (Carpenter et al., 1994, 1995).

Conversely, researchers who were primarily concerned with hearing and hearing loss tended to use very simple non-sense syllables, isolated words, or words in simple sentences (Plomp & Mimpen, 1979; Hagerman, 1984; Nilsson, Soli, & Sullivan, 1994; Wilson, McArdle, & Smith, 2007), with an emphasis on controlling the acoustical parameters of the signal, such as sound pressure level and duration, or controlling simple linguistic factors such as phonetic and phonemic distributions, word frequency, and sentence length. Considerable effort was spent on research to predict word recognition performance from pure-tone threshold measures (Pavlovic, 1987) and to predict performance on more complex materials such as sentences from performance on simpler materials such as words and phonemes (Boothroyd, 2008). Some researchers attempted to vary the degree of semantic context (Kalikow, Stevens, & Elliott, 1977) or to use discourse level materials to test the performance of people with hearing loss (Cox & McDaniel, 1984; De Filippo & Scott, 1978); however, these developments took place in relative isolation from the developments taking place at the same time in Cognitive Psychology. Some research on deafness and the use of sign language raised interesting questions about modality-specific and modality-general aspects of language and cognitive processing (Rönnerberg, Öhngren, & Lyxell, 1987).

In general, it was productive for cognitive psychologists to study healthy young adults in ideal conditions and for audiologist to study the effects of hearing loss using simple speech

stimuli. However, later studies of listening in more realistic complex auditory scenes and studies of working memory marked renewed interest in the interaction of auditory and cognitive factors.

Listening in complex everyday environments. The auditory and cognitive factors needed to explain performance depend on the complexity of the listening situation. Pure-tone audiometric thresholds can be used to estimate a listener's ability to detect and perceive speech in quiet, at least to the extent that hearing loss, like filtering, renders components of the speech signal inaudible. However, despite the strong correlations between hearing thresholds and word recognition in quiet, correlations with word recognition in noise are relatively poor (Plomp, 1986). Measures of supra-threshold auditory processing, including spectral and temporal resolution and growth of loudness, can be used to estimate 'energetic' masking if the acoustical properties of the speech signal and noise masker are known. For example, knowledge of how speech intelligibility is affected by noise levels and reverberation has informed the formulation of architectural standards for room acoustics (ANSI S12.60, 2002; Bradley, 1986; Nábělek & Robinson, 1982). However, if the masker is meaningful, such as the speech of a second talker, then 'informational' masking also influences performance in ways that are not explained simply in terms of acoustics (Schneider, Li, & Daneman, 2007). In complex auditory scenes, where multiple meaningful inputs may be relevant to the listener, auditory as well as cognitive factors must be considered, including a listener's ability to segregate the auditory streams for distinct auditory objects and to allocate attention to an object or spatial location of interest (Bregman, 1990). For example, word recognition in multi-talker scenes is highly accurate when listeners know the spatial location of the target sound source, but accuracy decreases as the location becomes less certain, and this decrease is even more pronounced if the acoustical cues are impoverished (Singh, Pichora-Fuller, & Schneider, 2008). Furthermore, studies have shown that the complexity of the listening situation also affects memory, for example, listeners, especially

older listeners, recall less as the target materials become more complex, progressing from words to sentences, and as the background noise becomes more interfering, progressing from quiet, to a single competing speaker, to two competing speakers, to multi-talker babble, and to white noise (Tun & Wingfield, 1999; Wingfield & Tun, 2001).

Working memory and listening. Working memory refers to the ability to simultaneously store and process information over a short period of time (Daneman & Carpenter, 1980; Daneman & Merikle, 1996; Miyake & Shah, 1999; Repovs & Baddeley, 2006). General working memory capacity is typically assessed by asking individuals to read a series of sentences, to complete a task to confirm that they have understood the sentence, and then to recall some part of the sentence (usually the first or last word). Individuals with larger spans are considered to have better language processing abilities than individuals with smaller spans. For a given individual, conditions in which larger spans are measured are considered to demand less processing than conditions in which smaller spans are measured.

Based on studies concerning the effects of listening condition and/or hearing loss on working memory, Pichora-Fuller (2007) suggested that both inter-individual and intra-individual differences in working memory could be relevant in rehabilitative audiology. Rabbitt (1968) tested the effect of noise background on recall in four conditions (all in quiet, first half in quiet followed by half in noise, first half in noise followed by half in quiet, or all in noise). Recall of the first half was poorer when the second half was presented in noise, even when the first half had been heard in quiet, suggesting that the increased processing demands of understanding the material in noise reduced the resources available to store what had been heard. Rabbitt also found that listeners with mild hearing loss recalled the words less accurately than normal hearing controls, even though they had correctly repeated each word when it was presented (1990). More recently, insights into inter-individual and intra-individual differences in listening memory span

were provided by a study of the ability of younger and older adults to identify and recall words presented in sentences in varying signal-to-noise ratio (SNR) conditions (Pichora-Fuller, Schneider, & Daneman, 1995; Pichora-Fuller, 2007). Older listeners needed about a 3 dB better SNR to match the performance of the younger group, but they benefited more from sentence context than younger adults (Pichora-Fuller, 2008). Importantly, word identification and recall were poorer in the more adverse SNR conditions for both age groups. Similar findings have also been obtained when jittering was used to temporally distort sentences heard by younger adults such that their word identification as well as their recall performance as a function of SNR mimicked that found by older adults (Brown & Pichora-Fuller, 2000). In a related study, the use of visual speech cues to alleviate the challenge of the listening condition reversed the negative effect of SNR on both perception and recall (Pichora-Fuller, 1996). A recent review supports the conclusion that there is a link between cognitive skills and word recognition in noise, with measures of working memory being more effective in predicting performance compared to measures of global cognitive skills, such as IQ (Akeroyd, 2008). Taken together, the evidence suggests that the working memory span measure is sensitive to differences in listening effort that are modulated either positively by the availability of various supportive cues (context and/or visual speech cues), or negatively by listening challenges arising from various sources, including competing noise or distraction, real or simulated age-related auditory temporal processing deficits, or mild hearing loss.

Perceptual learning and brain plasticity. Recent studies using brain imaging have shown that there is more widespread brain activation, including activation of the left dorsolateral prefrontal cortical areas that are thought to be involved in semantic processing and working memory, when context is available to support listening to distorted sentences (Obleser, Wise, Dresner, & Scott, 2006; Scott & Johnsrude, 2003; Zekveld, Heslenfeld, Festen, & Schoonhoven,

2006). It has been suggested that more widespread brain activation is an indication of “thinking harder”, and that it may reflect the allocation of more working memory resources (Just & Carpenter, 1992; Petrides, Alivisatos, Meyer, & Evans, 1993). Furthermore, it seems that when listeners engage in more top-down context-driven processing, involving greater activation of prefrontal cortex, then perceptual learning of distorted speech is enhanced (Davis, Johnsrude, Hervais-Adelman, Taylor, & McGettigan, 2005). Interestingly, when younger and older adults perform equivalently on various perceptual and cognitive tasks, there is more widespread activation in older brains than in younger brains, with one interpretation being that this reflects compensatory processing (Cabeza, Anderson, Locantore, & McIntosh, 2002). Such compensatory brain activation could be consistent with the finding that older adults are better than younger adults at using context to compensate in challenging listening conditions (for a discussion see Pichora-Fuller & Singh, 2006; Pichora-Fuller, 2008).

Future Research. It may be reasonable for hearing researchers to ignore cognitive factors and for cognitive researchers to ignore auditory factors when they investigate the performance of listeners in ideal listening conditions. However, mounting evidence from behavioural and imaging studies, as well as our everyday experience that listening is sometimes effortful, now compels Cognitive Hearing Science researchers to study the interactions between auditory and cognitive factors when listeners use what they have heard to perform complex tasks such as understanding spoken language in complex auditory scenes. For example, in addition to long-standing measures such as the accuracy of word recognition, the use of new on-line methods, such as ERP and eye-movement tracking, promises to provide important new insights into how speech perception, lexical access, and language comprehension vary with the quality of the auditory input available to the listener.

**Use of auditory communication technologies or the visual modality to boost performance**

Computer scientists and engineers, especially researchers working on artificial intelligence and cognitive ergonomics, have made significant contributions to Cognitive Science over the last three decades. For example, researchers have been inspired to use Artificial Intelligence approaches to design machines that recognize acoustic and visual speech (Stork, 1997; Stork & Hennecke, 1996) and computational techniques have enabled the construction of increasingly sophisticated and dynamically interactive visual and auditory virtual reality simulations (Durlach & Mavor, 1995). Popular communication technologies and media associated with the use of the internet and ubiquitous computing have implemented features drawing on such research. Importantly, such advances in communication technologies have set the stage for the emergence of a new era of assistive technologies for people with hearing loss.

In the last 30 years, miniaturization of hearing aids permitted the design of devices that could be worn in the outer ear or ear canal. Cochlear implants (CIs), devices with a small number of electrodes surgically inserted into the inner ear to deliver signals from an external sound processing unit to the auditory nerve, became a widely used option for people with more extreme hearing impairment who could not benefit from conventional hearing aids. Although these technological advances are impressive, they were mostly inspired by knowledge of the peripheral auditory system, with the dominant engineering goal being to use a standardized approach to restore the audibility of sound, and with the pure-tone audiogram being the main yardstick that guided protocols for selecting fitting parameters (Byrne & Dillon, 1986; Cornelisse, Seewald, & Jamieson, 1995; Dillon, 1999; Moore, Alcántara, & Glasberg, 1998; Seewald, Ross, & Spiro, 1985). In general, benefit from linear hearing aids or cochlear implants has been easy to demonstrate in terms of increases in the accuracy of word recognition scores in quiet, ideal listening conditions, but difficult to demonstrate in the noisy and cognitively demanding conditions typical of everyday communication. Since the 1990s, more complex, non-linear digital

signal processing algorithms, including neural-network algorithms, have been inspired by more sophisticated computational models of the auditory processes involved in the perception of ecologically relevant signals such as speech and music in more realistic and demanding listening environments. Engineering goals have shifted from a focus on the ear to a focus the individual communicating in typical environments. The new ergonomic focus of hearing technology developers calls for consideration of both sensory and cognitive factors.

Hearing Aids. Today's hearing aids are capable of using complex, digital signal-processing algorithms to shape sound in ways that mimic aspects of the transduction of mechanical vibrations in the cochlea to electro-chemical neural signals that code information in the auditory system. For example, the amplitude of components of a complex signal such as speech can be amplified using amplitude gain and compression schemes that vary depending on the frequency and intensity of the particular components. Digital signal-processing algorithms are also used to optimize speech cues in a complex auditory scene; for example, when the presence of non-speech inputs is detected then noise cancellation protocols or adaptive directional microphones can be activated (Edwards, 2007).

Starting in 2003, landmark papers reported significant correlations between users' cognitive status and success with non-linear digital hearing aids. These papers challenged prevailing convictions that measures of audiometric hearing thresholds provided the best account of individual differences in speech performance with hearing aids. In large-scale studies of hearing aid wearers, those with lower performance on cognitive measures used hearing aids more (Humes, 2003) and had greater overall benefit from hearing aids (Davis, 2003) compared to those with higher cognitive performance. Experimental studies in which word recognition was tested in steady or fluctuating noise and with hearing aid compression options differing in the release time constants used in the channels of the automatic gain control system indicated that unaided word

recognition, as well as word recognition improvement (comparing aided to unaided conditions or comparing fast-acting to slow-acting options) was greater for individuals with higher than for those with lower performance on cognitive tests. Importantly, more of the variance in word recognition performance with complex, fast-acting compression hearing aids was explained by cognitive measures than by pure-tone hearing thresholds, especially when the background noise fluctuated (Gatehouse, Naylor, & Elberling, 2003, 2006; Lunner, 2003; Lunner, Rönnberg, & Rudner, 2009; Lunner & Sundewall-Thorén, 2007). Furthermore, the importance of cognitive factors in accounting for individual differences in speech understanding was clearly demonstrated in a series of studies in which speech was spectrally-shaped and amplified to ensure the audibility of frequency components up to at least 4 kHz (Humes, 2002, 2007). In addition, diary entries documenting everyday experiences with hearing aids over the period of a month suggested that listeners with higher cognitive performance were better than those with lower performance in identifying and reporting the specific effects of the speech-dependent signal processing (Lunner, 2003). Overall, consistent with the traditional view, performance on speech tests is explained better by auditory measures such as pure-tone thresholds when the signal is either not amplified or amplified by a relatively simple or slow-acting hearing aid used in steady background noise conditions. In contrast, performance is explained better by cognitive factors when the audibility of the signal is sufficient or when a more complex or fast-acting hearing aid is used in a fluctuating background noise. Studies comparing the relative merits of working memory and letter or digit monitoring measures suggest that measures of working memory span are the strongest cognitive predictor of hearing aid success (Foo, Rudner, Rönnberg, & Lunner, 2007; Rudner et al., 2008). Thus, the balance between the relative contributions of auditory processing and cognitive processing shifts according to the demands of the situation, and there are individual

differences in the point at which this balance tips (Pichora-Fuller, 2003, 2006; Wingfield et al., 2006).

Cochlear Implants. The auditory information provided by a cochlear implant through electrical stimulation of a limited body of surviving auditory neurons via a small number of electrodes is drastically reduced compared to what is provided by a normal peripheral auditory system or by a conventional hearing aid. Thus, it seems likely that individual differences in cognitive ability should play an important role in determining the adult CI-user's ultimate ability to understand speech given such limited auditory input. In addition, cognitive factors may be related to the extent of the effects of long-term sound deprivation prior to implantation and to the course of adjustment to new input post-implantation. A negative correlation between duration of severe hearing-loss ( $> 80$  dB HL) and performance on tasks measuring phonological skills suggests that deterioration is progressive in nature (Anderson, 2002). Importantly, a relationship has been demonstrated between the pre-operative cognitive skills of 11 deafened adults who were tested visually and their speech understanding performance 6 to 8 months post-surgery (Lyxell et al., 1996, 1998). Specifically, post-operative speech understanding was predicted primarily by the quality of the individual's phonological representation (i.e., the ability to match incoming sounds with existing representation of sounds), with working memory capacity and lexical speed also being predictive factors. Furthermore, it is obvious that the gradual improvement over time in speech recognition after cochlear implantation for patients with acquired deafness, which sometimes can be observed over 4-5 years, has a significant cognitive component (Tyler et al., 1997).

Speechreading. Speechreading (or lipreading) refers to the use of visual speech cues to understand what is said by a talker (Jeffers & Barley, 1971). In general, visual speech cues are complementary to auditory speech cues such that one modality can be used to compensate when

inputs in the other modality are diminished by adverse environmental conditions or by sensory impairments. It has been known since the post-WWII era that word recognition can remain highly accurate in adverse SNR conditions if visual speech cues are available (Sumbly & Pollack, 1954). Computer scientists have attempted to use visual speech cues to augment acoustic speech recognition by machines (Stork & Hennecke, 1996). Not only does support from visual speech cues in challenging listening environments improve the accuracy of word recognition, but it also alleviates processing demands that would otherwise consume working memory resources (Pichora-Fuller, 1996). Given the increasingly frequent use of multi-modal internet-based communication technologies, it seems that we have not yet even begun to explore the potential advantages of harnessing the cues provided by visual speech in new assistive technologies.

Speechreading in visual only conditions without any auditory input is difficult since a large part of the signal is not visible, yet many people who are deaf and do not use hearing aids or CIs benefit from visual only speechreading. Since only 10 – 15% of all spoken phonemes involve lip movements visible enough for decoding (Dodd, 1977; Jeffers & Barley, 1971), much information has to be inferred by the speechreader, necessarily drawing on the statistical properties (phonotactics) of the spoken language (Auer & Bernstein, 1997) and the individual's cognitive skills. Overall, studies of the relationships between visual speech recognition and cognitive skills indicate that working memory capacity (Rönnberg, 2003), verbal inference making (Lyxell & Rönnberg, 1989), lexical access speed and visual word-decoding skills (Lyxell & Rönnberg, 1991) are the most important cognitive skills (Rönnberg, et al., 1998).

Future Research. This research has raised questions about how cognitive measures should inform the design of new technologies, which methods should be used for selecting technologies for individuals, and the kind of rehabilitative training that should be provided for new users of technologies. Lunner et al. (2009) suggest a future development where the cognitive load is

continuously monitored in order to optimize the signal processing of the hearing aid according to the user's cognitive capacity. Although working memory promises to be a useful cognitive measure of individual differences that may guide choices in engineering and audiologic practice, future research may demonstrate the potential usefulness of measures of other aspects of cognition such as phonological skills, executive functioning, attention, or speed of information processing (Andersson, 2001, 2002; Cohen, 1987; Houtgast & Feston, 2008; Miyake, et al., 2000; Pichora-Fuller, 2008; Vaughan, Storzbach, & Furukawa, 2006; Wingfield & Stine-Morrow, 2000). With regard to why there should be a correlation between cognitive performance and success with new technologies, future research on perceptual learning and brain plasticity may illuminate how individual differences in top-down processing, including inference-making and the use of context, facilitate acclimatization as the brain remaps the connection between auditory input and meaning (Pichora-Fuller & Singh, 2006).

### **Changes in performance with development, aging, and rehabilitative training**

Although the relative isolation of auditory and cognitive factors did not impede basic research concerning the performance of healthy young adult listeners in ideal conditions, it is more difficult to advance knowledge of human development and aging or to apply theories to rehabilitation without considering the interactions between auditory and cognitive factors. Significant progress has been made in understanding the performance of listeners from these special populations.

Auditory Development. Over the last quarter of the 20<sup>th</sup> century, research by psychologists and physiologists charted the course of normal human auditory development (Schneider & Trehub, 1985; Werner & Rubel, 1992) while neonatology became a new medical specialization branching out from paediatrics. The human cochlea is fully formed in the third trimester and early auditory processing begins in utero, consistent with findings that very young

infants prefer the voice and language of their mother (Spence & Freeman, 1996). The auditory thresholds and the critical bandwidths of the auditory filters are almost adult-like even in infancy (Schneider, Morrongiello, & Trehub, 1990). Nevertheless, children are more susceptible to masking and they do not perform as well as adults when listening to supra-threshold complex signals, such as speech, in complex environments, such as when there is multi-talker background babble (Fallon, Trehub, & Schneider, 2001). Indeed, the neural connections between the cochlea and the cortex are not fully mature until the end of adolescence. The long time course of the maturation of the connections between the peripheral and central auditory nervous system seem to accompany the refinement of higher-level cognitive processing as learning continues in domains such as language and music (Werner 1996). Thus, there are important theoretical connections between auditory and cognitive development, with practical implications for education as well as for hearing health care. For example, with regard to education, international standards for classrooms acoustics were published recently in response to research showing that speech understanding, and in turn learning, by children requires a more favourable SNR conditions than would be required by young adults (ANSI S12.60, 2002; Yang & Bradley, 2009).

Following three decades of work lead by the multi-association Joint Committee on Infant Hearing in the United States, universal infant hearing screening programs have been implemented in many countries over the last decade (Joint Committee on Infant Hearing, 2009; Northern & Downs, 2002). The use of otoacoustic emissions testing to identify even mild and ear-specific hearing loss shortly after birth has revolutionized the care of children with hearing loss because it is now possible to intervene before valuable language learning opportunities have been lost in the early years of life. About 1 to 2 in 1000 children is born with a degree of hearing loss that would seriously impede the acquisition of spoken language. Cochlear implantation (CI) provides auditory sensations to children with a congenital, pre- or post-lingual deafness. Auditory

sensation opens up the possibility of a different course of development in a variety of areas related to cognitive development than would not have been the case without the CI (Geers et al., 2003; Pisoni et al., 2008; Richter, Eißele, Laszig, & Löhle, 2002; Spencer, 2004; Wass et al., 2008). Many children with CI develop cognitive skills that are comparable to hearing children, (Asker-Arnáson et al., 2007; Lyxell et al., 2008; Wass et al., 2008). In general, the degree of phonological processing included in the cognitive task seems to be critical, as the differences between hearing children and children with CI increase as a function of increasing demands on phonological processing. Development of language-related skills such as reading and writing (Asker-Arnáson, Wengelin, & Sahlén, 2008; Geers, Tobey, Moog, & Brenner, 2008; Lyxell et al 2008), word learning and grammar (Willstedt-Svensson, Löfqvist, Almqvist, & Sahlén, 2004), and conversational skills (Lyxell et al., 2008) are correlated with factors such as working memory capacity and phonological skills. Cognitive development is further related to factors such as age at implant and early pre-implant auditory experience (Geers et al., 2008; Pisoni & Cleary, 2003; Pisoni et al., 2008), where early implantation and early auditory experience are more beneficial for cognitive development. Based on a series of studies, Anu Sharma and her colleagues conclude that the optimal time to implant a congenitally deaf child with a unilateral CI is within the first 3.5 years of life when the central pathways show maximal plasticity (Sharma, Nash, & Dorman, 2009). Nevertheless, it remains to be determined how neurobiological development interacts with cognitive development. It is worth noting that considerable research has been conducted to investigate the similarities and differences in brain organization depending on whether children learn spoken or signed language (MacSweeney, Capek, Campbell, & Woll, 2008; Rönnberg, Söderfeldt, & Risberg, 2000), but it is beyond the scope of the present paper to discuss how research on deafness and sign language contributes to the field of Cognitive Hearing Science.

Age-related hearing loss. It is widely known that hearing loss increases markedly with age, beginning in the fourth decade (ISO 7029, 2000). The hallmark of age-related hearing loss is high-frequency threshold elevation and associated reductions in speech perception because speech sounds, especially consonants, become inaudible. However, older adults often report speech understanding difficulties that exceed those reported by younger adults with a similar degree of high-frequency hearing loss. Over the last two decades, progress has been made in differentiating the physiological bases of sub-types of presbycusis (Mills, Schmeidt, Schulte, & Dubno, 2006; Willott, 1991). One possible explanation for the disproportionate speech understanding problems of older adults is that, in addition to the typical auditory processing problems arising from damage to the outer hair cells in the cochlea, neural type presbycusis and associated auditory temporal processing problems may reduce the clarity of sounds even when they are audible (Pichora-Fuller & Souza, 2003; Pichora-Fuller et al., 2007; Pichora-Fuller & MacDonald, 2008).

In addition to age-related changes in the peripheral and central auditory system, cognitive aging has been considered as another possible explanation for the speech understanding problems of older adults (CHABA, 1988; Humes, 1996; Kießling et al., 2003; Pichora-Fuller, 2003). The first large-scale correlational studies investigating the contributions of auditory and cognitive factors to speech understanding found that the degree of audiometric loss accounted for most of the variance in performance, with less of the variance attributable to cognitive factors such as speed of processing and reduced working memory (Humes, 1996; van Rooij, Plomp, & Orlebeke, 1989; van Rooij & Plomp, 1990, 1992). Interestingly, although both factors were correlated with age, the balance between auditory and cognitive contributions to speech perception performance did not change with age (van Rooij & Plomp, 1992).

Numerous studies have shown that there is a correlation between loss of hearing and cognitive decline in old age (Granick, Kleban, & Weiss, 1976; Thomas et al., 1983; Lindenberger & Baltes, 1994; Baltes & Lindenberger, 1997; Li & Lindenberger, 2002), although Hofer, Berg, & Era (2003) found no significant correlation between hearing threshold levels and the outcome of a large number of cognitive tests on a group of 1041 subjects aged 75 years. In light of the correlations found between sensory and cognitive aging, experimental studies were conducted to investigate hypotheses that might explain the correlations. The Berlin group (Lindenberger & Baltes, 1994; Baltes & Lindenberger, 1997) proposed four hypotheses concerning possible explanations for the powerful inter-system connections between perception and cognition in aging: 1. declines are symptomatic of widespread neural degeneration (common cause hypothesis); 2. cognitive decline results in perceptual decline (cognitive load on perception hypothesis); 3. perceptual decline results in permanent cognitive decline (deprivation hypothesis); 4. impoverished perceptual input results in compromised cognitive performance (information degradation hypothesis). Anstey, Luszcz, & Sanchez (2001) tested 894 subjects between 70 and 98 years old and concluded that a common factor, representing general age-related changes in neurophysiological integrity, along with specific age-related and sensory-related factors, contributed to individual differences in cognitive performance in very old adults. Consistent with the deprivation hypothesis, in a study of an elderly Swedish cohort (Rönnerberg et al., 2009), degree of hearing loss (but not vision loss) in a sample of hearing aid wearers was correlated with measures of long-term episodic memory performance.

The information degradation hypothesis has been supported by a body of experimental research conducted over the last decade showing that apparent age-related cognitive differences in language comprehension and memory of incoming information are exaggerated when younger and older adults are tested without taking into account age-related differences in hearing or

vision, but that these effects are largely eliminated when the perceptual conditions are controlled (Pichora-Fuller, 2008; Schneider & Pichora-Fuller, 2000). Put another way, if younger and older adults are tested in the same physical conditions, then age-related differences in auditory and/or visual processing will render the testing conditions more challenging for the older adults than the younger adults; however, if adjustments are made to equate for perceptual difficulty then no difference in performance is observed. Thus, older listeners, even those with clinically normal audiograms in the speech range up to 4 kHz, are more disadvantaged in adverse acoustical environments such as when there is background noise or multiple talkers, likely due to age-related declines in auditory temporal processing, but with a consequence being reduced performance on cognitive tasks (Pichora-Fuller & Souza, 2003; Pichora-Fuller, 2003, 2008). Furthermore, the cognitive consequences of sensory declines have also been related to ability to perform activities of daily living entailing communication and social interaction (Marsiske, Klumb, & Baltes, 1997). Importantly, the information degradation hypothesis implies that age differences in cognitive performance could be alleviated by interventions.

Consistent with the information degradation hypothesis, clinical research has shown that the degree of dementia is significantly over-estimated in about 1/3 cases if tests are conducted without vs with hearing aids (Weinstein & Amstel, 1986). Importantly, hearing loss is found in up to 9/10 cases with dementia (Gold, Lightfoot, & Hnath-Chisolm, 1996), and it is more prevalent in those with dementia than in controls without dementia (Uhlmann et al., 1989a,b). For example, in one longitudinal study of 418 subjects, a decline in hearing at the start of the study was associated with worse cognitive performance 6 years later (Valentijn et al., 2005). Even more striking is the finding that auditory speech processing problems were predictive of future manifestation of dementia in longitudinal research conducted over periods of up to 12 years (Gates et al., 2002; Gates et al., 1996; Gates., Feeney, & Mills, 2008), with the possibility that

rehabilitative interventions could alter the time course of the manifestation of the symptoms of dementia. Furthermore, dual sensory loss (hearing and vision) is associated with the greatest odds for cognitive decline and for functional decline on everyday activities over a period of four years (Lin et al., 2004). Thus, several important theoretical and practical research questions require the combined study of auditory and cognitive factors in aging.

On a positive note, problem behaviours can be reduced if hearing aids are worn (Palmer et al., 1999) and remediation of hearing loss has been related to better emotional and social well-being and greater longevity (Arlinger, 2003). For example, two Italian population studies suggest that correction for hearing loss by the use of hearing aids may have a protective effect against reduced cognitive function and provide better quality of life for elderly people (Appolonio et al., 1996; Cacciatore et al., 1999). Importantly, following intervention with hearing aids, there is a reduced rate of decline on cognitive screening tests (Allen et al., 2003) and slower cognitive decline in Alzheimer's cases (Peters, Potter, & Scholer, 1988; Wahl & Heyl, 2003). For example, Lehl, Funk, & Seifert (2005) found that in a group of 70 year old subjects with hearing impairment, the introduction of a hearing aid for 2-3 months improved working memory capacity compared to controls matched on IQ, chronological age and hearing impairment. However, more global measures of cognitive skills, not necessarily measuring working memory capacity, showed no significant improvement following 6 months (Tesch-Römer, 1997) or 12 months of hearing aid use (van Hooren et al., 2005), although it is possible that performance may have declined if hearing aids had not been worn. Similar findings of improvements in working memory exist for vision after cataract surgery (Hall, McGwin, & Owsley, 2005). Thus, the need to integrate auditory, visual and cognitive findings in clinical practice is obvious and an important

direction for future research concerns how to assess dual sensory losses (Saunders & Eckert, 2007; Smith, Bennett, & Wilson, 2008).

Learning, expertise, and rehabilitative training. The interactions between auditory and cognitive processing change with normal development and aging, and also with the compensatory strategies that may be employed by individuals with hearing loss who use complementary modalities, or over the course of acclimatization to the novel input provided by technologies such as hearing aids.

Although cognition declines with age, the brain remains plastic and has a life-long capacity for plasticity and cortical reorganization (Mahnke et al., 2006), offering the possibility that some specific cognitive skills can be improved with appropriately designed cognitive training. For example, healthy older adults can benefit from memory training, as evidenced by differences in the patterns of brain activation before and after training (Nyberg et al., 2003). Furthermore, improvements in cognitive skill can be sustained after training and may generalize to other similar cognitive activities (Dahlin et al., 2008; Derwinger, et al., 2005; Mahnke, et al., 2006; Nyberg, et al., 2003). For the population of older adults with mild cognitive impairment (MCI), the picture is less clear with respect to possible improvements following a period of systematic cognitive training with most studies finding benefits from training, but some reporting no benefit (Belleville, 2008).

Results from three case-studies of expert speechreaders (GS, Rönnerberg, 1993; SJ, Lyxell, 1994; MM, Rönnerberg, et al., 1999) reveal a connection between exceptional skill level, cognitive skill and communication strategy. Each of the three cases uses a unique speechreading strategy (tactiling by GS; visual word-decoding by MM; repetition by SJ) that demands an extraordinary skill level in either working memory capacity or fast lexical access. Performance levels greater

than 2 standard deviations compared to controls were shown for the critical cognitive ability in relation to their respective strategies.

Early studies of acclimatization to hearing aids reported mixed findings and did not consider the role of cognitive variables in explaining individual differences (Turner, Humes, Bentler, & Cox, 1996). Although there was significant evidence of modestly increased benefit (3%) over time in the mean group data, the variability in acclimatization across participants was found to be very large (standard deviation of 9%). Thus, acclimatization does not necessarily occur in every hearing aid user, and when it does occur, there are noteworthy individual differences. Individual differences in cognition may be advantageous insofar as listeners with larger working memory capacities may be able to activate more of the brain and be better able to use context to facilitate learning to re-map altered signals to stored meanings (Pichora-Fuller & Singh, 2006). In this way, the link between higher cognitive performance and benefit from hearing aids may be explained.

Future Research. Much more research is needed on specific cognitive abilities and individual differences in balancing auditory and cognitive processing over the course of learning or relearning how to listen and to understand the auditory world. Auditory training programs have recently been inspired by new findings concerning brain plasticity and cognitive compensation (Kricos & McCarthy, 2007), but we know of no research that has examined the influence of hearing loss on cognitive training or the effectiveness of cognitive training focusing on cognitive abilities relevant to listening or speech understanding.

### **Conclusions**

Spoken language understanding, especially in adverse or complex auditory environments, seems to be strongly influenced by working memory capacity. In addition, when multiple sound sources overlap in time and/or space, it seems likely that other aspects of cognition such as

attention and executive functions play a role in how the listener responds to wanted and unwanted inputs. The balance in the listener's use of signal-based and knowledge-based information may shift depending on the immediate demands of the task and the situation, with associated variations in the speed and accuracy with which global and component (phonological, lexical, syntactic, semantic) processes are executed. In the longer term, the nature of the balance between bottom-up and top-down information processing may change with auditory deprivation, reliance on alternative modalities, learning of novel inputs produced by technologies such as hearing aids and cochlear implants, and the mastery of new listening strategies and phonological skills.

Existing models of language understanding must be revised to take into account how listening is altered in adverse and complex situations. Rönnberg (2003) described a framework that assumes a continuous interaction between auditory and visual input, long-term memory and working memory. His model for Ease of Language Understanding (ELU) describes the dynamic interplay between explicit (effortful) and implicit (effortless) cognitive functions in adverse listening conditions. The model includes four modality-general parameters: phonology, long-term memory access speed, explicit processing, and general storage and processing capacity in working memory. Further refinements of the model will need to account for longer term effects that may affect some parameters more than others. For example, phonological performance in some tasks may deteriorate as a consequence of a hearing impairment, whereas working memory seems to be unaffected by hearing impairment as shown by the absence of significant differences between groups of subjects with normal-hearing, hearing-impairment or acquired deafness (Andersson, 2001; Lyxell, Andersson, Borg, & Ohlsson, 2003). The ELU model should facilitate future theory development and help guide research concerning how best to measure cognition in relation to auditory and visual language understanding in a range of realistic conditions for listeners of all ages and with varying levels of impairments.

The field of cognitive hearing science has grown from a very limited area into a field of significant scientific interest. It is obvious that many questions remain to be answered, not the least of which involves the need to identify those cognitive characteristics that are most relevant for auditory communication in our complex modern society. For example, HearCom (2008), a large-scale European research project, includes a cognitive measure in a battery of tests to assess the restrictions in many daily activities that are caused by hearing loss and/or poor environmental conditions (Houtgast & Kramer, 2007). Future progress in Cognitive Hearing Science will be of great importance for very young and very old people with 'normal' hearing, as well as for people of all ages who have hearing loss ranging from mild to profound impairments. Emerging knowledge of the important connections between auditory and cognitive performance, and the deleterious consequences of combined hearing and cognitive impairments, challenge researchers from different disciplines and practicing professionals in health and engineering to work together to find new ways to measure key individual differences in hearing and cognition. These measures will be used to provide comprehensive solutions tailored to the needs of individuals by informing the design of new technologies, the building more accessible environments, and the development of more effective rehabilitation training programs.

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