Cognitive aspects of auditory plasticity across the lifespan

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This paper considers evidence of plasticity resulting from congenital and acquired hearing impairment as well as technical and language interventions. Speech communication is hindered by hearing loss. Individuals with normal hearing in childhood may experience hearing loss as they grow older and use technical and cognitive resources to maintain speech communication. The short- and medium-term effects of hearing-aid interventions seem to be mediated by individual cognitive abilities and may be specific to listening conditions including speech content, type of background noise, and type of hearing-aid signal processing. Furthermore, some aspects of cognitive function may decline with age and there is evidence that age-related hearing impairment is associated with poorer long-term memory. It is not yet clear whether improving audition through hearing-aid intervention can prevent cognitive decline. Profound deafness from an early age implicates a set of critical choices relating to possible restoration of the auditory signal through the use of prostheses including cochlear implants and hearing aids as well as to mode of communication, sign or speech. These choices have an influence on the organization of the developing brain. In particular, while the cortex may display sensory reorganization in response the linguistic modality of choice, cognitive organization seems to prevail.

INTRODUCTION

For the majority of the population, speech is the main mode of communication. Because the auditory signal provides the main channel of speech reception, any impairment of the auditory system makes speech communication more difficult. This has consequences that differ according to the time of life at which hearing impairment occurs and the compensatory choices made by individuals with hearing impairment and their significant others. Hearing aids represent a technical form of compensation that acts directly on the auditory channel, while use of sign language is a sociocultural form of compensation that is independent of the need for auditory processing. Both technical and sociocultural compensation may cause plasticity of the neurocognitive mechanisms that support communication. Further, the nature and degree of any such plasticity may depend both on the timing and efficiency of compensation as well as the onset, nature, progression, and severity of hearing loss.

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SPEECH COMMUNICATION UNDER ADVERSE CONDITIONS

Hearing loss is just one of a wide range of suboptimal or adverse conditions for speech communication that include unfamiliar language, unfamiliar speaker characteristics and signal degradation as a result of external noise and reverberation, and internal adverse conditions as a consequence of hearing impairment such as masking, filtering, and distortion as well as the individual cognitive limitations of the listener, including fatigue and cognitive load (Mattys *et al.*, 2012). It goes without saying that each and any of these additional adverse conditions may make speech communication even more problematic for the listener with hearing loss, for whom the target signal is already attenuated and distorted as a consequence of physiological degeneration. Loss of sensitivity can often be compensated by amplification and parts of the distortion (the abnormal loudness growth imposed by sensorineural hearing impairment) may be compensated by non-linear signal processing. However, even with hearing aids, the segregation abilities of persons with hearing impairment are not as good as those of persons with normal hearing. Furthermore, the technologies they use to optimise hearing may generate additional distortion of the speech signal. Thus, although hearing aids may ameliorate some adverse conditions, others they cannot influence; indeed hearing aids may even generate adverse conditions of their own. When speech communication takes place under adverse conditions, high level cognitive resources such as working memory (WM) are brought into play.

WORKING MEMORY FOR COMMUNICATION

WM is the ability to keep relevant information in mind briefly while at the same time processing it. This ability is fundamental to many mental activities including language processing. For example, to achieve comprehension, individual words may have to be kept in mind until a particular statement is complete. WM capacity is limited and may differ substantially between individuals. Even under ideal conditions, most people cannot retain more than about seven unrelated words or other items of information (Miller, 1956), while some exceptional individuals may retain as few as five and others as many as nine. Short-term retention of words, which is part and parcel of language comprehension, is often conceived of in terms of the phonological loop of WM (Baddeley, 1986). Loop capacity can be measured using simple span tests such as digit span in which spoken digits in series of increasing length are presented for immediate serial recall until performance breaks down. However, simple span tests which merely tap individual storage capacity tend not to be predictive of the ability to perform challenging language tasks (Unsworth and Engle, 2007). On the other hand, complex span tests such as reading span (Daneman and Carpenter, 1980), which require simultaneous storage and processing capacity, are reliable predictors of language processing under challenging conditions, probably because they demand the ability to strategically deploy cognitive resources online. Current versions of the task (Rönnberg *et al.*, 1989) typically require first a semantic judgment of each sentence in a set of sentences followed by cued recall of the words occurring at a particular position in each sentence in the set. As set size increases, more storage is required while ongoing semantic processing competes for limited resources. In a review article, Akeroyd (2008) identified the reading span task as a good cognitive predictor of the ability to understand speech in noise, especially in older individuals with hearing impairment.

Recent models of working memory (Baddeley, 2012; Rönnberg *et al.*, 2013) are characterized by an episodic buffer component whose function is the integration and processing of multimodal representations based on input from multiple sources including the senses and long term memory (Rudner and Rönnberg, 2008). Whereas Baddeley's (2012) model is a general working memory model, the WM model for Ease of Language Understanding (ELU, Rönnberg *et al.*, 2013) specifically addresses cognition for communication. The ELU model proposes that the episodic buffer deals with Rapid, Automatic, Multimodal integration of PHOnology and is thus referred to as RAMBPHO. RAMBPHO function is smooth when communication conditions are optimal, and as a result, speech understanding proceeds rapidly and automatically. However, when adverse conditions prevail, explicit, or consciously recruited, cognitive processing resources are brought into play. Thus, speech communication relies not only on an efficient RAMBPHO but also on the ability to strategically deploy explicit processing resources. It is this dual ability that is tapped by the reading span task.

HEARING AIDS AND SPEECH PERCEPTION IN NOISE

Hearing aids are designed to help persons with hearing loss hear better. One of the technologies used to achieve this is Wide Dynamic Range Compression (WDRC) that compensates the abnormal growth of loudness resulting from sensorineural hearing loss. However, speech intelligibility may not be improved if the parameters of the WDRC scheme do not suit the characteristics of the individual (Lunner *et al.*, 2009). One critical individual characteristic seems to be WM capacity. Ten years ago it was established that the benefit obtained from WDRC was contingent on an interaction between cognitive ability and the time-constants of the compression system (Gatehouse *et al.*, 2003; Lunner, 2003). Since then, it has been shown that this relationship is influenced by type of background noise (Foo *et al.*, 2007; Lunner and Sundewall-Thorén, 2007; Rudner *et al.*, 2008) and the type of target speech material (Foo *et al.*, 2007; Rudner *et al.*, 2009; 2011). The combination of modulated noise and fast-acting compression seems to provide a particular challenge to cognitive resources (Lunner and Sundewall-Thorén, 2007; Rudner *et al.*, 2008; 2009; 2011; 2012) especially when the predictability of the target speech is low (Rudner *et al.*, 2011). Furthermore, these complex relations change over time (Cox and Xu, 2010; Rudner *et al.*, 2009; 2011) suggesting plasticity. In particular, it seems that the disadvantage of WRDC initially experienced by persons with low WM capacity may become less apparent after a period of familiarization (Rudner *et al.*, 2011). This suggests that persons with lower WM may experience more plastic change than persons with high working-memory capacity.

The work reviewed here, relating to the role of cognition in WDRC benefit, was conducted by investigating the relation between independently-measured cognitive capacity and speech reception thresholds measured in the traditional manner at relatively poor signal-to-noise ratios (SNR). The disadvantage of this approach is that although poor SNRs may occur in exceptional circumstances they are not representative of everyday communication (e.g., Smeds *et al.*, 2012) and thus may be misleading in terms of day-to-day functioning. There is much more to communication than just perceiving target speech. Above all, the message has to be understood and retained for further processing. Thus, in order to determine the efficacy of hearing-aid signal processing in terms of everyday communication it may be more useful to assess the ability to retain and process audible information presented in a relatively low level of background noise. This ability may be termed Cognitive Spare Capacity (CSC, Mishra *et al.*, 2010).

COGNITIVE SPARE CAPACITY

Sarampalis *et al.* (2009) showed that hearing-aid signal processing in the form of noise reduction can improve retention of heard speech in adults with normal hearing thresholds. This finding was recently extended to persons with hearing impairment (Ng *et al.*, 2013a). Experienced hearing-aid users listened to sets of sentences with high intelligibility and repeated the final word of each sentence. At the end of each set, they were prompted to recall all those words. Despite high intelligibility, background noise disrupted recall ability. However, the noise reduction processing (Wang *et al.*, 2009) reduced the negative effect of noise on recall. This effect was particularly marked for participants with good WM capacity and for sentence final words that occurred towards the end of each sentence set. A follow-up study replicated the positive effects of noise reduction on memory for sentence final words (Ng *et al.*, 2013b) and showed that this effect was similar in magnitude to that obtained by replacing native-language competing talkers by foreign-language (Chinese) talkers. The follow-up study also showed that when the memory load was reduced by decreasing sentence set size, beneficial effects of noise reduction generalized to individuals with lower WM capacity. These findings show that hearing-aid signal processing can improve retention of heard information, even when intelligibility is good, and demonstrate the need for new tools to study CSC (Rudner and Lunner, 2013).

The Cognitive Spare Capacity Test (CSCT, Mishra *et al.*, 2013a; 2013b) was developed to meet this need. In particular, it provides a tool to measure the ability to maintain and process intelligible information. In the CSCT, sets of spoken two-digit numbers are presented and the participant is required to report back at least two of those numbers depending on specific instructions designed to elicit executive processing of those numbers. Two executive processes are targeted: updating and inhibition. These two particular executive processes are likely to be engaged during speech understanding in adverse conditions. Updating ability is likely to be required to strategically replace the contents of WM with relevant material while inhibition ability is likely to be brought into play to keep irrelevant information out of WM. In the CSCT, WM load is manipulated by requiring participants to hold an additional dummy number in mind during high-load conditions. In everyday interaction, visual information can enhance speech perception by several dB and to determine the influence of visual cues on CSC, the CSCT manipulates whether the talker's face is visible or not. Finally, the CSCT can be administered in quiet or in noise. Results of studies employing this paradigm are beginning to delineate the nature of CSC (Mishra *et al.*, 2013a; 2013b; Rudner *et al.*, 2013b). For adults with normal hearing, provision of visual cues actually reduces performance in quiet conditions, probably because visual cues provide superfluous information that causes distraction when target information is highly intelligible (Mishra *et al.*, 2013a; 2013b). However, in noisy conditions, visual cues do not reduce performance, probably because they help segregate the target signal, resulting in richer cognitive representations (Mishra *et al.*, 2013b). At high intelligibility levels, steady-state noise reduces CSCT performance when visual cues are not provided, but modulated noise does not reduce performance for adults with normal hearing (Mishra *et al.*, 2013b). Older adults with mild hearing loss demonstrate lower CSC than young adults, even with individualised amplification, and this effect is most notable in noise and when memory load is high (Rudner *et al.*, 2013b). Visual cues do not reduce performance for this group. Interestingly, although CSC and WM do not seem to be strongly related, there is evidence that age-related differences in WM and executive function do influence CSC (Rudner *et al.*, 2013b).

PHONOLOGICAL DISTINCTIVENESS

We have seen that the RAMBPHO component of the ELU model deals with phonological integration (Rönnberg *et al.*, 2013). Phonology refers to the sublexical structure of language and is manifest in the sound patterns of speech and corresponding cognitive representations in the mental lexicon. Equivalent representations based on the gestural patterning of sign language suggest phonology can be understood at an abstract level (MacSweeney *et al.*, 2013). Access to the mental lexicon is faster when the phonological representation is more distinct because of fewer phonological neighbours (Luce and Pisoni, 1998). Severe hearing impairment may lead to more diffuse representation of speech phonology in the long term reflected in poorer visual rhyme judgement ability (Andersson, 2002; Classon *et al.*, 2013c) and verbal fluency (Classon *et al.*, 2013a). Individuals with poor phonological representations due to severe long-term hearing impairment can compensate for this deficit by good WM capacity measured by reading span performance (Classon *et al.*, 2013c). An early ERP signature of hearing loss was recently found in just such a task, likely reflecting use of a compensatory strategy, involving increased reliance on explicit mechanisms (Classon *et al.*, 2013b). However, this compensation comes at the cost of poorer long-term storage (Classon *et al.*, 2013c).

SEMANTIC CONTEXT

Language understanding is about grasping the gist of the message. Use of available semantic context can facilitate speech understanding under adverse conditions and has been shown to recruit language processing networks in left posterior inferior temporal cortex and inferior frontal gyri bilaterally (Rodd *et al.*, 2005). Rudner *et al.*, (2011) found that although the role of WM in speech understanding with WDRC was clearly apparent with matrix-type sentences (Hagerman and Kinnefors, 1995) this was not the case with Swedish Hearing In Noise Test (HINT) sentences (Hällgren *et al.*, 2006). Although the Hagerman sentences are semantically coherent they have low ecological validity; the five-word syntactic structure is always identical and each individual word comes from a closed set of ten items, but no particular item can be predicted from sentence context. The HINT sentences, on the other hand, range in length and syntactic structure as well as semantic coherence. It was suggested that the low redundancy of the Hagerman sentences increases reliance on the details in the speech signal.

THE AGING BRAIN

Cognitive function declines with advancing age and the mechanisms behind this have been traced to both genetic and lifestyle factors (Nyberg *et al.*, 2012). Sensory functions also decline with age and there are several different theories explaining the relation between sensory and cognitive decline. The common cause hypothesis (Baltes and Lindenberger, 1997) suggests that a general reduction in the efficiency of physiological function drives both phenomena, while the information degradation hypothesis (Schneider *et al.*, 2002) suggests that cognitive processes function less efficiently when sensory input is less well defined due to declining sensory function. The Compensation-Related Utilization of Neural Circuits Hypothesis (Reuter-Lorenz and Cappell, 2008) suggests that older adults compensate for less effective use of neural resources, such as the prefrontal cortex, by engaging them at lower task loads than younger adults. However, potential activation levels in these regions are lower for older compared to younger individuals. This suggests that any factor that can reduce cognitive load during speech understanding under adverse conditions, including good hearing-aid fitting, phonological distinctness, and semantic context, is likely to become even more important with advancing age. This is supported by emerging results relating to CSC (Rudner *et al.*, 2013b).

It is important to gain an objective understanding of the link between sensory and cognitive function from a rehabilitation perspective. If hearing impairment drives cognitive decline then auditory rehabilitation becomes doubly important: satisfactory treatment of hearing loss may not only improve speech communication but also be able to prevent cognitive decline. There is accumulating evidence of a specific association between hearing impairment and cognition. Epidemiological studies show that individuals with hearing loss are at increased risk of cognitive impairment and that rate of cognitive decline as well as risk of cognitive impairment are associated with severity of hearing loss (Lin *et al.*, 2013). Analysis of data from hearing-aid users participating in the Betula study of cognitive aging (Nilsson *et al.*, 1997) showed that individuals with more hearing loss had poorer long term memory and that this cognitive deficit was not restricted to the visual domain (Rönnberg *et al.*, 2011). Importantly there was no significant association between loss of vision and cognitive function or between hearing loss and WM. These findings show that there is a link between sensory loss specifically in the auditory domain and cognitive decline that is limited to long-term memory without affecting WM.

MODALITY SPECIFICITY

We have seen that both acquired hearing impairment and hearing-aid use may result in changes in neurocognitive representation that may be susceptible to neuro-cognitive compensation. We have also seen that WM capacity modulates the neurocognitive processes involved in phonological processing and the integration of contextual information during speech understanding under adverse conditions. Further, there is a link between sensory and cognitive status with advancing age that seems to be specific in the sense that it is related to the auditory channel at a sensory level and to a modality-general long-term memory system. However, it is not clear how auditory deprivation and cognitive experience mediate this relation at the end of the lifespan. On the other hand, there is evidence that both auditory deprivation and cognitive experience drive neural plasticity during early development.

Parents of deaf children are faced by a set of critical choices. These include technical interventions influencing sensory input in the auditory domain and mode of communication. Hearing aids and cochlear implants can provide auditory input to facilitate development of speech communication but sign language provides a mode of communication that can develop independently of the auditory channel given adequate communicative input. Auditory deprivation as a result of congenital deafness results in recruitment of auditory cortex for visual processing (Fine *et al.*, 2005; Lomber *et al.*, 2010). However, it was not clear until very recently how auditory deprivation, on the one hand, and language choice, on the other, contribute to cortical plasticity. Cardin *et al.* (2013) dissociated these factors in a study that included two groups of congenitally profoundly-deaf adults: one group consisted of native sign-language users, that is, persons born into deaf families where signing was used as regular means of communication, and the other group who used speech communication and had no knowledge of sign language. Speakers with normal hearing constituted a reference group. All participants were scanned using fMRI while watching a model signing. The experimental design allowed separation of the effects of auditory deprivation and language experience. It was found that while sign-language experience drove recruitment of superior temporal cortex in both cerebral hemispheres, auditory deprivation drove recruitment of this region in the right hemisphere only. This shows that, although auditory deprivation from birth leads to a change in the sensory function of superior temporal cortex, the left lateralized cognitive function of language processing is preserved. Other evidence shows largely similar neural organization of cognitive function for sign and speech with some language-modality-specific differences that may be attributable to sensorimotor differences but also to modality-specific differences in the relationship between phonological and semantic processing (Rudner *et al.*, 2013a).

CONCLUSION

A wide range of factors conspire to make communication more or less successful across the lifespan. Hearing loss may hinder speech communication and this may be compounded by other adverse conditions. However, properly fitted hearing aids, phonological distinctness, and semantic context may all support speech understanding under adverse conditions. Limited cognitive resources are used in the very act of listening, and thus any factors supporting speech understanding may reduce cognitive load, effectively increasing cognitive spare capacity. Supporting speech understanding and thus reducing cognitive load is probably particularly important in older adults. Evidence suggests that given adequate experience, the neurocognitive organisation of congenitally deaf adults who are native signers is similar to that of adults with normal hearing who use speech communication. Neurocognitive organisation in deaf native signers, who do not experience age-related auditory decline, may provide a useful benchmark for understanding the complex interactions between age-related sensory and cognitive decline as well as audiological, cognitive, and social interventions aimed at supporting speech communication.

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