Speech understanding and cognitive spare capacity

Sushmit Mishra[1,2], Mary Rudner[1,2], Thomas Lunner[1,2,3,4], Stefan Stenfelt[1,3], and Jerker Rönnberg[1,2]

1 Linnaeus Centre HEAD, The Swedish Institute for Disability Research, Linköping University, Sweden

2 Department of Behavioural Sciences and Learning, Linköping University, Sweden

3 Department of Clinical and Experimental Medicine, Linköping University, Sweden

4 Oticon A/S, Research Centre Eriksholm, Snekkersten, Denmark

Tests used in the audiological clinic for assessment of the outcome of rehabilitation with hearing aids do not take the individuals' cognitive abilities into account. Listening in effortful conditions has been related to working memory capacity. The complex relationship between working memory and language understanding can be understood in terms of the working memory model for Ease of Language Understanding (ELU) [Rönnberg *et al*., Int J Audiol **47**, S99-S105 (2008)]. The ELU model predicts that in challenging listening conditions, high explicit processing capacity is associated with better language understanding. In this study, we investigate the cognitive spare capacity, that is, residual cognitive capacity after successful listening has been achieved, and its relationship to working memory capacity. We achieve this by administering a battery of cognitive tests for assessing working memory capacity, including reading span, lexical access, phonological and inference-making tasks and a new test for assessing cognitive spare capacity (CSCT). Four factors are manipulated in the CSCT: memory load, executive function, presentation modality and noise level. We predict higher performance in CSCT with better working memory capacity, better inference making skills and easier listening conditions. This study will further our understanding of the role of cognition in listening and thus inform audiological rehabilitation.

INTRODUCTION

Work over the last few decades has established the connection between cognition and speech understanding. Twenty years ago, the Plomp group published a series of studies in which a battery of speech, psychoacoustic and cognitive tests were administered to younger adults with unimpaired hearing and elderly listener whose hearing was impaired. These studies showed that while progressive hearing loss with age accounts for approximately two thirds of the systematic variance in speech perception, a component of the general performance decrement is due to reduced mental efficiency (Van Rooij *et al*., 1989; Van Rooij and Plomp, 1990, 1992). Later on, Humes and his group established a relationship between various cognitive tests

Proceedings of ISAAR 2009: Binaural Processing and Spatial Hearing. 2nd International Symposium on Auditory and Audiological Research. August 2009, Elsinore, Denmark. Edited by J. M. Buchholz, T. Dau, J. Cristensen-Dalsgaard, and T. Poulsen. ISBN: 87-990013-2-2. The Danavox Jubilee Foundation, 2010.

and speech recognition (Humes, 2002; Humes *et al.*, 1994; Humes and Floyd, 2005; Humes *et al.*, 2006).

In particular, individual differences in working memory (WM) have been shown to reliably predict differences in language comprehension abilities in different modalities and settings in people with and without various functional impairments. Lunner and Sundewall-Thoren (2007) established the clear interaction between WM and the ability to benefit from fast compression in hearing aids, especially in modulated noise. Similarly, Lunner (2003) found that 30-40% of the variance in speech in noise performance could be attributed to WM capacity. Gatehouse *et al.* (2003, 2006) found a relationship between hearing aid benefit and cognitive function in different listening conditions. Akeroyd (2008) pointed out in a review article that whereas there appears to be a general link between cognitive ability and speech understanding, WM capacity in particular seems to be a reliable predictor of speech understanding under difficult conditions.

The WM model for Ease of Language Understanding (ELU) describes the relationship between cognition and language understanding and provides a framework for generating new hypotheses about the detailed structure of the cognitive system. Recent work suggests that one feature of the system may be cognitive spare capacity – residual cognitive capacity available once successful language understanding has taken place. The purpose of the present study is to investigate cognitive spare capacity in persons with hearing impairment and explore how spare capacity is allocated to WM and executive function.

Working Memory and Language Comprehension

WM has been conceptualized as a dual function cognitive system in which information can be temporarily stored and processed until the input is either forgotten or consolidated into long term memory (Baddely and Hitch, 1974). In general, WM models assume there is a limited resource capacity that constrains the amount of information that can be processed or stored (Miyake and Shah, 1999). Daneman and Carpenter (1980) contended that WM plays an important part in language comprehension. Because language processing occurs over time, the early part of any incoming message must be stored temporarily in WM while the reminder of the message is perceived, so that an integrated interpretation of the entire message can occur (Pichora-Fuller, 2006).

The WM model for ELU (Rönnberg *et al.*, 2008; 2010) focuses on the communicative role of WM and emphasizes its multimodal nature. The ELU is based on a wealth of data generated over the past three decades relating to language understanding in people with hearing impairment and deafness. It postulates that an incoming language signal is bound in an episodic buffer (Rapid, Automatic, Multimodal Binding of Phonology, RAMBPHO). The signal is processed implicitly, and understanding achieved as long as it can be matched rapidly enough to stored representations in long-term memory, at relevant linguistic levels. If mismatch occurs, explicit processing is required which may involve modality specific systems. The ELU model predicts that high explicit complex processing capacity gives good ease of language understanding, especially in challenging listening situations associated with a mismatch between the incoming language signal and representations in long term memory.

Hearing aid users may experience a mismatch between the incoming auditory signal and the stored representation in the long term memory due to various factors, including the hearing loss itself, noise, reverberation, and degraded or distorted signal. Phonological representations in the long-term memory of persons with hearing impairment may change as a result of degraded (Andersson, 2002) or distorted acoustic input (Rudner *et al*., 2009) and this may also lead to conditions of mismatch in accordance with the ELU model. Foo *et al*., 2007 found that when the compression release settings in the aids of experienced hearing aid users were adjusted to settings that were either slower or faster than the familiar settings, their aided speech recognition in noise performance with the new settings was significantly related to their performance on the reading span test (Daneman and Carpenter, 1980). Rudner *et al*. (2008) extended this finding to other data and Rudner *et al*. (2009) have shown that whereas aided speech recognition in noise performance with the new settings is reliably related to performance on the reading span test, speech recognition in noise performance with familiar settings is not.

The role of cognitive spare capacity

It has been shown that complex WM capacity correlates with aided speech recognition in noise performance (Foo *et al*., 2007; Gatehouse *et al*., 2003, 2006; Lunner, 2003, Lunner and Sundewall-Thorén, 2007; Rudner *et al*., 2009). Also, the ability to benefit from digital signal processing algorithms in hearing aids is associated with cognitive capacity (Gatehouse *et al*., 2003, 2006; Lunner, 2003; Lunner and Sundewall-Thorén, 2007). In other words, subjects with equal hearing impairment as measured by thresholds may have different speech reception in noise due to differences in cognitive capacity. However, simply measuring cognitive capacity does not give us enough information to optimize speech perception by altering signal processing parameters. In particular, different individuals may differ to the extent they engage cognitive resources in decoding a spoken message. Thus, two individuals with similar hearing thresholds and similar cognitive capacity may devote different levels of cognitive resources to decode different messages in different situations. The individual who devotes a high degree of cognitive capacity to decode a spoken message will have little capacity left to act adequately on the basis of the information, while the individual who can decode the message effortlessly will have a relatively high level of cognitive spare capacity to devote to other tasks.

We therefore suggest that it is important to measure not only general cognitive capacity but also cognitive spare capacity in a given situation. Cognitive spare capacity is a measure of residual processing capacity, i.e. the cognitive capacity available for solving other tasks such as problem-solving and decision-making once the meaning of the spoken message has been understood. In other words, the larger the cognitive spare capacity, the more capacity available for other cognitive processes. In clinical terms, when the hearing aid signal processing algorithms (e.g. amplification, wide dynamic range compression and noise reduction) are not optimally adjusted more cognitive resources will be devoted to decoding speech, particularly in taxing listening situations. A person with high cognitive capacity may score equally well on a speech-in-noise test with optimum and suboptimum hearing aid fittings, but with a suboptimum fitting, cognitive spare capacity will be lower, with less residual cognitive resources for solving other tasks and a greater risk of tiredness and fatigue.

Cognitive spare capacity, working memory and executive function

Where does cognitive spare capacity fit into the ELU model? The model postulates an implicit episodic processing buffer and explicit processing capacity. However, we do not know whether cognitive spare capacity is implicit, explicit or both. Whereas implicit processing is characterized by its automaticity, explicit processing is characterized by the engagement of executive function: mental resources are consciously engaged in different goal-directed processes. The executive functions of updating, shifting and inhibition are widely studied in the literature (e.g. Miyake *et al*., 2000) and it has been suggested that the relationship between executive function and WM is mediated by the ability to control irrelevant information (Carretti *et al*., 2005) and WM capacity may be regulated by inhibitory abilities (Conway *et al*., 2001). According to Miyake *et al*. (2000), updating is the process which keeps track of which information is old and no longer relevant; inhibition is concerned with one's ability to deliberately automatic responses when necessary; shifting is concerned with shifting back and forth between multiple task, operation or mental sets. Updating plays an important role in following a conversation, as the listener has to continually replace information stored in WM with new information. Similarly, inhibition enables a person to control interference from background noise. Shifting helps a person to select the conversation he wants to follow when multiple speakers are speaking, for example in a party situation. Thus, we note that the executive functions of updating, shifting and inhibition play an important role in listening and we hypothesize that they may be important factors in the explicit capacity postulated by the ELU model and help us understand the implicit/explicit nature of cognitive spare capacity. High cognitive capacity may allow the hearing impaired individual to score well on a speech-in-noise test with suboptimum hearing aid fittings. However, suboptimum fitting will lead to lower cognitive spare capacity which may be handicapping in a number of ways. Thus, it is important to develop a clinical test of cognitive spare capacity. However, before this step can be taken, we need to understand more about the phenomenon of cognitive spare capacity.

OBJECTIVE OF THE STUDY

The purpose of the present study is to further our theoretical understanding of the interplay between cognitive spare capacity, WM and executive function. One goal of the study is to devise a test of cognitive spare capacity that takes into account potential interaction between WM capacity, executive function, level and type of noise as well as modality of presentation. This test will be administered alongside a battery of established cognitive tests to assess its validity in terms of assessing different aspects of cognitive function relevant to speech understanding, including inference-making ability. The results of the study will allow us to develop the ELU model and a take step towards developing a clinical test of cognitive spare capacity.

COGNITIVE SPARE CAPACITY TEST (CSCT)

We hypothesize that the executive functions of updating, shifting and inhibition may be important factors in the explicit capacity postulated by the ELU model and help us understand the implicit/explicit nature of cognitive spare capacity. Thus, the key feature of the CSCT is that it taps different executive functions at different memory loads using a strong within subject factorial design with the factors: 1. Memory Load (low, high) and 2. Executive Function (Updating, Inhibition), 3. Modality (Auditory only, Audiovisual) and 4. Noise level (no noise, a positive signal-to-noise ratio (SNR), 0 dB SNR, a negative SNR). Updating and inhibition are selected because they constitute the lower level of executive functions compared to other executive functions and provide a basis for specifying what traditional executive function tests measure. We cannot include shifting because of its complexity, involving listeners in multiple tasking auditorily. The noise levels used in the test will be determined from a pilot study with five listeners. Steady state speech weighted noise will be used with the same long term average spectrum as the test material. Thus, the full design of the CSCT is 2x2x2x4.

Participants

20 university students will participate in the piloting study which will be carried out only in the quiet condition and will have 2x2x2 design with the factors of memory load, executive functions and modality of presentation. The main study will involve 20 elderly participants with hearing impairment and will include the four noise conditions. So the full design of the CSCT will be tested.

Materials

The stimulus material is based on audiovisual recordings of two digit numbers from 13 to 99 in Swedish by one male and one female native Swedish speaker. The recordings will be carried out in a sound treated recording chamber. Two digit numbers are chosen as they constitute a suitably large pool of material that is phonologically and semantically similar. The numbers 10, 11 and 12 are not included as they were considered to be phonologically dissimilar to the rest of the numbers with regard to number of syllables and duration. The numbers are arranged in 48 lists of twelve numbers each (24 each for the task of updating and inhibition). There will be no repetition of any number within any list and numbers are repeated up to seven times across lists. Talker gender will be randomized. The pronunciation of the numbers will be according to the standard set by the Swedish “Speaking clock” (Fröken Ur).

Procedure

The task throughout is to memorize two numbers. However, the instruction as to which two numbers to memorize differs between Updating and Inhibition conditions. In the Updating conditions, the subjects report either the two highest or the two lowest numbers in each list. In the Inhibition conditions, the subjects report two numbers of a particular parity (odd or even) except when spoken by a particular voice (male or female). The lists are presented one at a time in the appropriate modality and at the appropriate noise level in accordance with a predetermined randomized order. The appropriate instruction is given before each list. List stimuli are presented one at a time at a rate of one item per second in the low memory load conditions and two items per second in the high memory load conditions.

COGNITIVE TEST BATTERY

The cognitive test battery, to be included apart from the CSCT, consists of standardized tests to assess WM capacity (SVIPS; Hällgren *et al*., 2001) and inference making skills (Lyxell and Rönnberg, 1989).

SVIPS: Speech and Visual Information Processing System

The SVIPS battery taps WM, phonological processing and verbal information processing and is a modification of Text Information Processing System (TIPS) (Ausmeel, 1988).

WM is assessed by a reading span test in which the participant is presented with a set of sentences and asked to judge whether they are reasonable (e.g. *The girl brushed her teeth*) or unreasonable (e.g. *The train sang a song*). The words are presented in word-by word fashion and each word is shown on the screen for 0.8 seconds. After a sequence of sentences (three, four, five or six sentences), the experimenter indicates that the subject should recall either the first or the final word of each presented sentence in the sequence.

Phonological processing is evaluated by presenting a rhyme task in which the subject has to identify whether two given words rhyme with each other or not.

Verbal information processing is evaluated using the tasks of semantic decision making, lexical decision making and name matching. In semantic decision making the task is to decide whether a word belonged to certain predefined semantic category or not. In lexical decision making the task is to judge whether a three letter string is a real word or not. Finally, in the name matching task, the task is to judge whether two presented letters are same (e.g. A-A) or not (e.g. A-B).

Sentence Completion Test

The sentence completion test assesses inference making skills (Lyxell and Rönnberg, 1989). There are twenty four sentences divided into three blocks of eight sentences each. Each block consists of a different scenario; train, restaurant and clothes shop.

Each sentence consists of six to ten words and from each sentence four to six words are omitted. The task is to fill in the blank spaces within seven seconds. Scoring is based on accuracy.

PREDICTIONS

We predict that CSCT performance will be better in individuals with greater WM capacity and better inference making skills. CSCT performance will be better if stimuli are presented in the audio-visual mode than in the auditory mode and CSCT performance will be better when noise is lower. Furthermore we predict a pattern of interactions between CSCT factors that will indicate the relative effect on executive function in cognitive spare capacity of memory load, modality and noise.

IMPLICATIONS OF THE STUDY

The findings of this study will further our understanding of cognitive spare capacity and allow us to develop cognitive models. They will also provide a basis for developing a test of cognitive spare capacity for use in the clinic which will help us better predict the outcome of audiological rehabilitation.

ACKNOWLEDGEMENT

This work is supported by grant number 2007-0788 from the Swedish Council for Working Life and Social Research.

REFERENCES

Andersson, U. (**2002**). "Deterioration of the phonological processing skills in adults with an acquired severe hearing loss," Eur J Cogn Psychol. **14**, 335-352.

Akeroyd, M. A. (**2008**). "Are individual differences in speech perception related to individual differences in cognitive ability? A survey of twenty experimental studies with normal and hearing impaired adults," Int J Audiol **47**, S125-S143.

Ausmeel, H. (**1988**). *TIPS (Text-Information-Processing-System): A User's Guide.* (Linkoping Sweden: Department of Education and Psychology, Linkoping University).

Baddeley, A. D., and Hitch, G. (**1974**). "Working memory," in *The psychology of learning and motivation*, edited by G.A. Bower (London: Academic Press), pp. 47–89.

Carrretti, B., Cornoldi, C., De Beni, R., and Romano, M. (**2005**). "Updating in working memory: A comparision of good and poor comprehenders," J Exp Child Psychol. **91**, 45-66.

Conway, A. R. A., Cowan, N., and Bunting, M. F. (**2001**). "The cocktail party phenomenon revisited: The importance of working memory capacity," Psychonomic Bulletin and Review **8**, 331-335.

Daneman, M., and Carpenter, P. A. (**1980**). "Individual differences in working memory and reading," Journal of verbal learning and verbal behaviour **19**, 450-466.

Foo, C., Rudner, M., Rönnberg, J., and Lunner, T. (**2007**). "Recognition of speech in noise with new hearing instrument compression release settings requires explicit cognitive storage and processing capacity," J Am Acad Audiol. **18**, 553-566.

Gatehouse, S., Naylor, G., and Elberling, C. (**2006a**). "Linear and nonlinear hearing aid fittings. 1. Patterns of benefit," Int J Audiol. **45**, 130-152.

Gatehouse, S., Naylor, G., and Elberling, C. (**2006b**). "Linear and nonlinear hearing aid fittings. 2. Patterns of candidature," Int J Audiol. **45**, 153-171.

Gatehouse, S., Naylor, G., and Elberling, C. (**2003**). "Benefits from hearing aids in relation to the interaction between the user and the environment," Int J Audiol. **42**, S77-S85.

Hällgren, M., Larsby, B., Lyxell, B., and Arligner, S. (**2001**). "Evaluation of a cognitive test battery in young and elderly normal-hearing and hearing impaired persons," J Am Acad Audiol **12**, 357-370.

Humes, L. E. (**2002**). "Factors underlying the speech-recognition performance of elderly hearing-aid wearers," J. Acoust. Soc. Am. **112**, 1112-1132.

Humes, L. E., Watson, B.U., Christensen, L. A., Cokely, C. G., Halling, D. C., and Lee, L. (**1994**). "Factors associated with individual differences in clinical measures of speech recognition among the elderly," J. Speech Lang. Hear. Res. **37**, 465-474.

Humes, L. E., and Floyd, S. S. (**2005**). "Measures of working memory, sequence learning, and speech recognition in the elderly," J. Speech Lang. Hear. Res. **48**, 224-235.

Humes, L. E., Lee, J. H., and Coughlin, M. P. (**2006**). "Auditory measures of selective and divided attention in young and older adults using single-talker competition," J. Acoust. Soc. Am. **120**, 2926-2937.

Lunner, T., and Sundewall-Thorèn, E. (**2007**). "Interactions between cognition, compression, and listening conditions: Effects on speech-in-noise performance in a two-channel hearing aid," J Am Acad Audiol **18**, 604-617.

Lunner, T. (**2003**). "Cognitive function in relation to hearing aid use," Int J Audiol **42**, S49-S58.

Miyake, A., Friedman, N. P., Emerson, M. J., Witziki, A. H., Howerter, A., and Wager, T. (**2000**). "The unity and diversity of executive functions and their contribution to complex frontal lobe tasks: A latent variable analysis," Cognitive Psychology **41**, 49-100.

Pichora-Fuller (**2006**). "Audition and cognition: What audiologists need to know about listening," in *Hearing care for adults*, edited by C. Palmer and R. Seewald (Phonak: Stäfa, Switzerland), pp. 71-85.

Rönnberg, J., Rudner, M., and Foo, C. (**2010**). "The cognitive neuroscience of signed language: applications to a working memory system for sign and speech," in *Memory, aging and the brain: A Festschrift in honour of Lars-Göran Nilsson*, edited by L. Bäckman and L. Nyberg (London: Psychology Press), pp. 265-286.

Rönnberg, J., Rudner, M., Foo, C., and Lunner, T. (**2008**). "Cognition counts: A working memory system for ease of language understanding (ELU)," Int J Audiol **47**, S99-S105.

Rudner, M., Foo, C., Rönnberg, J., and Lunner, T. (**2009**). "Cognition and aided speech recognition in noise: specific role of cognitive factors following nine-week experience with adjusted compression setting in hearing aids," Scand J Psychol. **50**, 405-418.

Rudner, M., Foo, C., Sundewall-Thoren, E., Lunner, T., and Rönnberg, J. (**2008**). "Phonological mismatch and explicit cognitive processing in a sample of 102 hearing aid users," Int J Audiol **47** (suppl. 2), S163–S170.

van Rooij, J. C. G. M., Plomp, R. and Orlebeke, J. F. (**1989**). "Auditive and cognitive factors in speech perception by elderly listeners. I. Development of test battery," J. Acoust. Soc. Am. **86**, 1294-1309.

van Rooij, J. C. G. M., and Plomp, R. (**1990**). "Auditive and cognitive factors in speech perception by elderly listeners. II. Multivariate analyses," J. Acoust. Soc. Am. **88**, 2611-2624.

van Rooij, J. C. G. M., and Plomp, R. (**1992**). "Auditive and cognitive factors in speech perception by elderly listeners. III. Additional data and final discussion," J. Acoust. Soc. Am. **91**, 1028-1033.