Even though the present study cannot provide a clear recommendation for binaurally linked hearing aids to improve speech intelligibility, the binaural link might still be useful to improve sound quality in terms of naturalness and spatial awareness, as was shown in previous studies (Sockalingam *et al.*, 2009; Behrens, 2008).

The independent hearing aid research platform in combination with a loudspeaker setup as used in the present study are versatile tools to further develop outcome measures that show the benefit of hearing aids for hearing-impaired listeners.

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Testing listening effort for speech comprehension

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When listening in noise, an individual's cognitive capabilities seem to play an important role. The individual's limited working memory capacity will gradually be consumed by processing the auditory information in increasing background noise, leading to less spare capacity. Good fitting of hearing aids can be seen as a way to ease listening effort, and therefore an objective measure of listening effort would be a useful tool when fitting hearing aids. The aim of the present study was to develop a test of cognitive spare capacity to assess if worse signal-to-noise ratio (SNR) would result in greater objectively measured listening effort. In the Auditory Inference Span Test (AIST) sentences were presented in stationary speech-shaped noise, at three SNRs, and then questions generating different memory load levels were asked about the content of the sentences. Listeners with normal hearing showed decreasing accuracy with increasing cognitive load and slower responses at maximum cognitive load. However, no relation between SNR and cognitive spare capacity could be established in this study.

INTRODUCTION

Hearing-aid fittings are essentially based on the audiograms of the hearing impaired individuals. Evaluating the fitting using SNR thresholds is not sufficient since individuals with similar hearing impairments, as measured by the audiograms, might perform significantly different (Rudner *et al*., 2011). There are probably many reasons for this, but it has been shown that differences in the individuals' cognitive capabilities may play an important role when hearing in noise (Gatehouse *et al*., 2003; Lunner, 2003; Edwards, 2007; Akeroyd, 2008; Stenfelt and Rönnberg, 2009).

Studies have shown significant correlations between working memory performance and speech recognition in noise (Lunner, 2003; Foo *et al*., 2007; Rudner *et al*., 2009). When speech perception is degraded by background noise, speech comprehension requires more cognitive resources (Larsby *et al*., 2005; Pichora-Fuller and Singh, 2006; Edwards, 2007). Every individual has a limited working memory capacity, which is gradually consumed by increasing background noise (Pichora-Fuller and Singh, 2006; Schneider, 2011). An individual with higher

Proceedings of ISAAR 2011: Speech perception and auditory disorders. 3rd International Symposium on Auditory and Audiological Research. August 2011, Nyborg, Denmark. Edited by T. Dau, M. L. Jepsen, J. Cristensen-Dalsgaard, and T. Poulsen. ISBN 87-990013-3-0. EAN 9788799001330. The Danavox Jubilee Foundation, 2012.

working memory capacity is therefore likely to better cope in a noisy environment, than an individual with lower working memory capacity (Lunner, 2003; Larsby *et al*., 2005; Foo *et al*., 2007; Pichora-Fuller, 2007; Rudner *et al*., 2009). As background noise increases, even more cognitive capacity needs to be used to discern the desired information leading to less spare capacity (Pichora-Fuller, 2007). This in turn causes a greater perceived listening effort (Pichora-Fuller and Singh, 2006; Tun *et al*., 2009).

From this it is derived that in an advantageous signal-to-noise-ratio (SNR), when the noise is less intense, there will be less perceived effort. This would theoretically manifest in more cognitive spare capacity, the residual cognitive capacity once successful listening has taken place (Mishra *et al*., 2010), which in turn can be used for other cognitive tasks such as storage and processing of information. Therefore it is hypothesized that cognitive spare capacity can be used as a measure of listening effort, and measured with a dual-task test that assess speech perception in noise and working memory span simultaneously. In the test, more working memory capacity would be needed to discern speech when the SNR becomes more problematic, which would lead to less cognitive spare capacity and, as a consequence, poorer performance on the memory task. Measuring listening effort as performance on a secondary task is, however, not sufficient, since an individual might successfully compensate for increased task demand by increasing the amount of effort (Hicks and Tharpe, 2002; Zekveld *et al*., 2010). This means that two individuals that perform equally well on the secondary task might have utilized different levels of effort. Theoretically the person with lower working memory capacity would experience more effort. It is therefore hypothesized that a test of cognitive spare capacity should be designed to tap into different levels of memory load. At a low level of memory load two individuals might perform equally well, but as background noise increases in amplitude the lower working memory capacity individual needs to invest more effort to be able to perform as well as the higher working memory capacity individual. At a high level of memory load the higher working memory capacity individual will perform better, and this difference will be more evident in a worse SNR.

The use of hearing aids and the process of fitting a hearing aid can be seen as ways to ease an individual's listening effort (Sarampalis *et al*., 2009). This could also be viewed from the other angle, that the less perceived effort the better the fitting of the hearing aid. Therefore an objective measure of listening effort would be a useful tool when fitting hearing aids.

The aim of the study was to develop a test of cognitive spare capacity, the Auditory Inference Span Test (AIST), to assess if a worse SNR, would result in a greater perceived listening effort and less cognitive spare capacity objectively measured by worse accuracy and longer response times on a memory task.

METHOD

Participants

Forty participants, mainly students or employees at Linköping University, that met the inclusion criteria of hearing thresholds better or equal to 20 dB HL (frequencies 500 Hz to 4000 Hz), normal visual acuity (after correction), no tinnitus problems, and native Swedish speaking, participated in the study. Twenty-two of these were women and 18 were men, and they had an average age of 31.8 years (SD = 6.5, range 22 to 45). The regional ethics committee approved the study.

Materials

All speech in noise tests used the same speech material, the Hagerman sentences (Hagerman, 1982; Hagerman and Kinnefors, 1995). These are Swedish five word matrix sentences, with a closed set of 50 words, ordered in a structured sequence: name, verb, number, adjective, item. The noise used in all tests was steady-state speech-shaped noise with the same long-term average frequency spectrum as the corresponding speech material (Hagerman, 1982). The same three SNRs were used for all tests: -2 dB, -4 dB, and -6 dB, respectively.

Speech in noise tests

The speech recognition test used eight lists with ten sentences each. The first two lists were practice lists, and then each SNR was tested twice. The participants' task was to repeat the sentence orally after the recorded speech material had finished. Each incorrect repeated word was recorded as an error. The speech recognition score was measured as the percentage of words that were correct repeated for each SNR.

The Auditory Inference Span Test (AIST) is a dual-task hearing-in-noise test, that combines auditory and memory processing (Rönnberg *et al*., 2011). The test used ten lists of three sentences each, and the first list was a practice list. The participants' task was to recall and process the information from the sentences by giving button-press responses to multiple-choice questions. These questions, termed information questions, were designed to tap three levels of memory load, where a level 1 question was a simple memory question, a level 2 question was a complex memory question, and a level 3 question a complex memory and cognitive processing question. Only one memory load level was tested at a time, and each memory load level was tested once in each SNR. Responses and response time were recorded, and the AIST score was measured as the average of information questions that were correctly answered.

The listening effort test used six lists of five sentences each, testing each SNR twice. The participants' task was to listen to one list of sentences and then state the effort needed to hear all of the words in all of the sentences. Responses were given by moving a horizontal slider, stating the effort on a visual analogue scale between "No efforts at all" via "Moderate effort" marked in the middle, to "Maximum possible effort". The listening effort was measured as the average rated effort for each SNR.

Cognitive tests

The reading span test is a working memory test that loads on memory storage and processing at the same time (Daneman and Carpenter, 1980; Daneman and Merikle, 1996). The participants' task was to read and comprehend sentences, and to recall either the first or the final words of a presented sequence of sentences depending on instruction given after a sequence of sentences (Baddeley *et al*., 1985; Baddeley, 2000). The test was in Swedish (Rönnberg *et al*., 1989), but shortened from the original version. Sequences were two to five sentences long, two sequences of each length, and presented in ascending order, with an additional two-sentence practice sequence in the beginning of the test. The reading span score was measured as the percentage of the totally presented words that were correctly recalled.

The letter memory test is a test that examines the executive function of updating in working memory (Miyake *et al*., 2000). The participants' task was to read lists of capital letters presented one at a time on the computer screen and memorize the last four letters, to be able to type these letters in the right order on the computer keyboard. A list of letters could be five, seven, nine, or eleven letters long, and the order of these was randomized. The letter memory score was measured as the percentage letters that were correctly recalled in the right order.

Set up and test procedure

All stimuli were presented on the computer screen, with an application developed in Matlab (R2010b), and with a pair of Sennheiser HDA 200 headphones with a calibrated output level of 65 dB A. All test material, written instructions as well as those given by the test supervisor, were presented in Swedish. Answers were given orally, by key presses, or with the computer mouse depending on the sub-test. The participants visited Linköping University Hospital at one occasion each, and the testing took at maximum 1.5 hours and was performed without any pause.

RESULTS

The main results are presented in table 1. A median split divided the cognitive measurements in two groups of cognitive capacity, High and Low. Five participants with the median reading span score (60.7%) were excluded from the two groups. No participants were excluded from the two letter memory groups.

Analysis of variance was performed for the speech recognition test and showed a main effect of SNR (F(2,117) = 30.41, $p < 0.001$), where, as shown in table 1, the speech recognition score was significantly poorer at worse SNR. There was a significant main effect of reading span groups on speech recognition score ($p < 0.05$) where the High RS group performed significantly better than the Low RS group, but there was no effect of letter memory groups.

A repeated measures analysis of variance was performed on AIST accuracy scores with two within group factors, memory load levels (1, 2, 3) and SNR (-2 dB, -4 dB, -6 dB) and one between group factor, working memory capacity (High, Low). There was a main effect of memory load levels (F(2,66) = 22.86, $p < 0.001$), see table 1. There was a significant difference between memory load level 1 and memory load level 2, as well as between memory load level 1 and memory load level 3, but there was not between memory load level 2 and memory load level 3. There was a main effect of reading span groups (F(1,33) = 4.93, $p < 0.05$), where the High RS group performed better than the Low RS group. The same main effect was found for letter memory groups (F(1,38) = 5.24, $p < 0.05$). There was no effect of SNR. A similar repeated measures analysis of variance was performed on AIST response time. There was a main effect of memory load level (F(2,76) = 52.53, $p < 0.001$) where questions on memory load level 3 had significantly longer response times, as shown in table 1. There was no effect of reading span groups or of letter memory groups, and there was no effect of SNR.

Speech in noise tests			
Speech recognition test			
SNR	-2 dB	-4 dB	-6 dB
Speech recognition score	97.5% (SD: 2.5%)	95.9% (SD: 3.1%)	90.9% (SD: 5.5%)
AIST			
SNR		-2 dB	
Memory load level	Level 1	Level 2	Level 3
Accuracy (max = 3)	2.4 (SD: 0.8)	1.8 (SD: 0.9)	1.4 (SD: 1)
Response time (seconds)	5 (SD: 2)	5.4 (SD: 2.3)	8.5 (SD: 4.4)
SNR		-4 dB	
Memory load level	Level 1	Level 2	Level 3
Accuracy (max = 3)	2.4 (SD: 0.6)	1.8 (SD: 1.1)	1.6 (SD: 1)
Response time (seconds)	5.1 (SD: 2.2)	5.5 (SD: 2.8)	7.7 (SD: 3.4)
SNR		-6 dB	
Memory load level	Level 1	Level 2	Level 3
Accuracy (max = 3)	2.3 (SD: 0.8)	1.6 (SD: 1)	1.4 (SD: 0.9)
Response time (seconds)	5.3 (SD: 1.9)	5.5 (SD: 2.2)	8.7 (SD: 3.1)
Listening effort test			
SNR	-2 dB	-4 dB	-6 dB
Listening effort	2.1 (SD: 2.2)	3.7 (SD: 2.3)	5.9 (SD: 2.3)
Cognitive tests			
Reading span test			
Reading span score	60.1% (range 28.6% to 82.1%, SD: 12.2%)		
High RS group	n = 17 (>= 64.3%)		
Low RS group	n = 18 (<= 57.1%)		
Letter memory test			
Letter memory score	75.8% (range 47.9% to 95.8%, SD: 11.7%)		
High LM group	n = 20 (>= 79.2%)		
Low LM group	n = 20 (<= 77.1%)		

Table 1: Main results

Analyses of variance showed a main effect of SNR on the listening effort test (F(2,117) = 29.30, $p < 0.001$), where -2 dB was rated as significantly less effortful than -6 dB, as can be seen in table 1. There were no significant effects of reading span groups or of letter memory groups.

DISCUSSION

In this study, the average speech recognition score for -4 dB was 95.9%. This is a slightly lower noise level than the one that generated a performance level of approximately 90% in Hagerman (1982). This difference may derive from differences in the test set-ups. In the Hagerman study stimuli were presented monaurally, while in the current study stimuli were presented binaurally. There were also differences in headphones and number of practice lists. There was a ceiling effect at -2 dB where 62.5% of the participants performed 98% or better, but there were no ceiling effects at -4 dB or -6 dB and the speech recognition score was poorer with worse SNR in accordance with the psychometric function for the speech material (Hagerman, 1982). Still, the speech recognition score at all of these rather undemanding SNRs was high, which might have reduced the effects of SNR on the tests. It might be debatable what role working memory capacity plays in speech recognition when steady-state noise is used as masker (Rudner *et al.*, 2009). However, the data showed an effect of working memory capacity as measured by the reading span test, where the participant with higher working memory capacity performed better. The letter memory test evaluated the executive function of updating in working memory, but the data did not suggest that this was important for speech recognition in stationary noise.

AIST accuracy was insensitive to SNR. The reason for this might have been how AIST was constructed. Only three questions at each memory load level were asked for each SNR, making the test rather sensitive to inattention and disturbances. The poor results on memory load level 3 questions, just above chance level, indicated that these questions might have been too cognitive demanding to give reliable results. The data showed nevertheless that having a higher cognitive capacity improved the AIST accuracy irrespective of memory load level. AIST response time was not affected by changes in SNR, but by memory load levels. The longer response time for memory load level 3 questions may be due to a greater amount of processing before an answer was given or that it took a longer time to read and comprehend the more complicated questions.

No scale normalization was done of the results from the listening effort test. Therefore the variance in listening effort ratings was great. This diversity in stated listening effort indicated that factors other than SNR only, played an important role when stating the perceived listening effort. The data showed that there were no significant correlations between the subjectively stated listening effort and AIST accuracy, even if the average AIST accuracy tended to decrease with worse SNR and the average subjectively stated listening effort increased with worse SNR. It might also be questionable what the participants were actually rating; the rather undemanding SNRs might have tested how well the participants could distinguish between different SNRs.

CONCLUSION

It was found that when speech recognition was tested with steady-state speech-shaped noise in undemanding SNRs, speech recognition score was a function of noise level and working memory capacity. When AIST was tested under the same non-challenging conditions, AIST accuracy was a function of memory load level and working memory capacity, but not noise level. Since AIST performance showed no effect of SNR, no difference in cognitive spare capacity as a measure of listening effort could be demonstrated in relation to SNR in the present study.

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Auditory and cognitive contributions to hearing-impaired listeners' spatial speech recognition performance

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This study investigated the auditory and cognitive processes affecting speech recognition in spatially complex, multi-talker situations. Twenty-three elderly hearing-impaired (HI) listeners were tested on a number of competing-speech tasks, a measure of monaural spectral ripple discrimination, a measure of binaural temporal fine structure (TFS) sensitivity, and two cognitive measures indexing working memory and attention. All auditory test stimuli were spectrally shaped to restore (partial) audibility for each listener on each listening task. Eight younger normal-hearing (NH) listeners served as a control group. Data analyses revealed that the chosen auditory and cognitive measures were unable to predict speech recognition when the target and maskers were separated along the front-back dimension. When the competing talkers were separated along the left-right dimension, however, speech recognition was correlated with the measures of attention and binaural TFS sensitivity as well as with low-frequency hearing thresholds. Altogether, these results support the notion that both bottom-up and top-down deficits are responsible for the impaired functioning of elderly HI listeners in cocktail party-like situations.

INTRODUCTION

Spatial hearing is an important capacity of the auditory system, which is mediated by different acoustic cues: interaural phase and level differences are crucial for left-right (L-R) spatial hearing, while monaural spectral cues introduced by pinna filtering are crucial for front-back (F-B) spatial hearing (e.g. Blauert, 1997). The benefits offered by spatial hearing are particularly large in noisy environments where considerable speech recognition improvements can occur, especially if the interferers are also speech signals. Compared to NH listeners, however, HI listeners generally obtain much less spatial hearing benefit in such situations, especially if they are also older (e.g. Marrone *et al.*, 2008).

Previous research has been concerned with the supra-threshold deficits that might be responsible for HI listeners' poorer speech-in-noise performance. For example, reductions in TFS sensitivity (e.g. Strelcyk and Dau, 2009) and working memory capacity (e.g. Akeroyd, 2008) have been ascribed a role. However, in none of these studies was the speech target presented against a background of spatially separated speech maskers, and so it is unclear if these effects also apply to such situations.

Proceedings of ISAAR 2011: Speech perception and auditory disorders. 3rd International Symposium on Auditory and Audiological Research. August 2011, Nyborg, Denmark. Edited by T. Dau, M. L. Jepsen, J. Cristensen-Dalsgaard, and T. Poulsen. ISBN 87-990013-3-0. EAN 9788799001330. The Danavox Jubilee Foundation, 2012.