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Interactions between Cognition, Compression, and Listening Conditions: Effects on Speech-in-Noise Performance in a Two-Channel Hearing Aid

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Abstract

This study which included 23 experienced hearing aid users replicated several of the experiments reported in Gatehouse et al (2003, 2006) with new speech test material, language, and test procedure. The performance measure used was SNR required for 80% correct words in a sentence test. Consistent with Gatehouse et al, this study indicated that subjects showing a low score in a cognitive test (visual letter monitoring) performed better in the speech recognition test with slow time constants than with fast time constants, and performed better in unmodulated noise than in modulated noise, while subjects with high scores on the cognitive test showed the opposite pattern. Furthermore, cognitive test scores were significantly correlated with the differential advantage of fast-acting versus slow-acting compression in conditions of modulated noise.

The pure tone average threshold explained 30% of the variance in aided speech recognition in noise under relatively simple listening conditions, while cognitive test scores explained about 40% of the variance under more complex, fluctuating listening conditions, where the pure tone average explained less than 5% of the variance. This suggests that speech recognition under steady-state noise conditions may underestimate the role of cognition in real-life listening.

Key Words: Speech recognition in noise, fast-acting compression, slow-acting compression, pure-tone audiogram, modulated noise, unmodulated noise, visual letter monitoring score, cognitive function, working memory

Abbreviations: WDRC = wide dynamic range compression, AVC = automatic volume control, SII = speech intelligibility index, VLM = visual letter-monitoring score, ML = maximum likelihood, SNR = speech-to-noise ratio, SRT = speech recognition threshold, PTA(6) = average of the pure-tone hearing threshold levels at 250, 500, 1000, 2000, 4000, and 6000 Hz, HSD test = Tukey honestly significant difference test

Sumario

Este estudio, que incluyó a 23 usuarios con experiencia en auxiliares auditivos, replicó varios de los experimentos reportados por Gatehouse y col. (2003, 2006) con nuevas pruebas de habla y lenguaje, y procedimientos de evaluación. La medida de desempeño utilizada fue el SNR requerido para un resultado de 80% de palabras correctas en una prueba de frases. En forma consistente con Gatehouse y col., este estudio indicó que los sujetos que mostraban un bajo puntaje en una prueba cognitiva (monitoreo visual de letras) se desempeñaban mejor en la prueba de reconocimiento del lenguaje y en constantes lentas de tiempo más que en constantes rápidas de tiempo, y también rindieron mejor en medio de ruido no modulado que en ruido modulado, mientras que los sujetos

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con puntajes altos en las pruebas cognitivas mostraron el patrón opuesto. Más aún, los puntajes de las pruebas cognitivas se correlacionaron significativamente con la ventaja diferencial en la compresión de acción rápida vs. la compresión de acción lenta, en condiciones de ruido modulado.

El promedio de umbrales tonales puros explicó el 30% de la varianza en el reconocimiento amplificado del lenguaje en medio de ruido, bajo condiciones relativamente simples de escucha, mientras que los puntajes de las pruebas cognitivas explicaron cerca del 40% de la varianza bajo condiciones auditivas fluctuantes y más complejas, donde el promedio tonal puro explicó menos del 5% de la varianza. Esto sugiere que el reconocimiento del lenguaje bajo condiciones de ruido de estado estable puede subestimar el papel de la cognición en la audición en la vida real.

Palabras Clave: Reconocimiento del lenguaje en ruido, compresión de acción rápida, compresión de acción lenta, audiograma tonal puro, ruido modulado, ruido no modulado, puntaje de monitoreo visual de letras, función cognitiva, memoria activa

Abreviaturas: WDRC = compresión de rango dinámico amplio; AVC = control automático de volumen; SII = índice de inteligibilidad del lenguaje; VLM = puntaje de monitoreo visual de letras; ML = mayor posibilidad; SNR = tasa de señal/ruido; SRT = umbral de reconocimiento del lenguaje; PTA (6) = promedio de los niveles umbrales auditivos para tonos puros a 250, 500, 1000, 2000, 4000 y 6000 Hz; HSD test = prueba turca de diferencias honestamente significativas

Emerging evidence indicates the importance of acknowledging the role of individual cognitive function when developing new signal processing schemes and fitting rules for hearing aids (Gatehouse et al, 2003; Gatehouse et al, 2006; Lunner, 2003; Pichora-Fuller and Singh, 2006).

In a clinical hearing-aid fitting context it is important to choose the best possible set of signal-processing parameters for the individual. Results by Gatehouse et al (2003, 2006) suggest that the individual choice of fast-acting wide dynamic range compression (WDRC) versus slow-acting automatic volume control (AVC) fittings in a two-channel WDRC device is associated with patterns of variation in cognitive capacity. The Gatehouse data show that hearing aid users with high cognitive capacity benefit in terms of speech recognition in noise from fast-acting compared to slow-acting compression, while those with poor cognitive capacity benefit from slow-acting compared to fast-acting compression. However, also according to Gatehouse et al (2003, 2006), it is important to note that if measures other than speech intelligibility are used (i.e. Listening Comfort), then different patterns of results might emerge.

Furthermore, since the introduction of digital signal processing hearing instruments there is a continually growing spectrum of available signal-processing schemes. In addition to multi-channel compression schemes, adaptive noise reduction and adaptive directional microphones are used in many commercial hearing aids. Since these adaptive systems by definition are time-varying, the adaptive functions may lead to further interactions between individual cognitive abilities and signal processing characteristics in the light of the Gatehouse et al (2003, 2006) results. The complexity of the signal processed by an adaptive hearing instrument may be cognitively demanding to different degrees for different persons, and therefore, specific signal processing characteristics may need to be tailored to the individual user's cognitive ability.

The test conditions under which different signal-processing schemes are evaluated may also be of importance for an individual hearing impaired person's apparent ability to utilize the signal processing. Some studies indicate that pure tone hearing threshold elevation is the primary determinant of speech recognition performance in quiet conditions and in situations using linear hearing aid signal processing in unmodulated noise (Dubno et al, 1984; Schum et al, 1991; Magnusson et al, 2001). Generally, these studies used relatively simple stimuli, such as words or sentences presented in quiet conditions or in steady-state background noise conditions. This indicates that under relatively steady-state conditions, performance is rather well predicted by the Speech Intelligibility Index (SII; ANSI S3.5-1997 [American National Standards Institute, 1997]). However, SII fails to predict speech intelligibility accurately in the case of fluctuating noise maskers (Festen and Plomp, 1990; Houtgast et al, 1992; Versfeld and Dreschler, 2002) and under informational masking conditions, e.g. masking by another talker (Versfeld and Rhebergen, 2005). This suggests the importance of cognitive functions, such as attention and working memory, in more complex and natural listening situations.

A reasonable hypothesis is that working memory (Jarrold and Towse, 2006; Baddeley and Hitch, 1974; Baddeley, 2000; Daneman and Carpenter, 1980) may be involved in speech recognition in complex listening situations, since working memory includes both storage and processing aspects of incoming stimuli. Working memory is thought of as a capacity-limited system that both stores recent visual-spatial, phonological and episodic information and at the same time provides a computational mental workspace in which the just stored information can be manipulated and integrated with knowledge stored in long-term memory (Baddeley, 1986, 2000; Just and Carpenter, 1992; Repovš and Baddeley, 2006). Working memory is one of the mechanisms or processes that are involved in the control, regulation, and active maintenance of task-relevant information in the service of complex cognition, including novel as well as familiar, skilled tasks (Miyake and Shah, 1999), and has shown large individual differences (e.g. Jarrold and Towse, 2006).

In Lunner (2003), 71 hearing aid users, recruited from the ordinary clinical database at the hearing clinic in Linköping, were tested for working memory performance using the (visual) reading span test (Daneman and Carpenter, 1980; Baddeley et al, 1985). The results showed a large spread in working memory performance across test subjects, and that about 30-40 percent of the variance in speech-in-noise performance was explained by their working memory performance. In a follow-up analysis (Lunner, 1999), individual aided SII was calculated and correlated with the working memory performance, and again about 30-40 percent of the variance in aided SII was explained by the working memory performance, suggesting that factors other than pure audibility contributed to the individual speech recognition performance.

The cognitive test in the Gatehouse et al (2003, 2006) study was a visual letter-monitoring test where the task was to hit a key when three consecutive letters formed recognized words in the English language (Gantz et al, 1993; Gfeller et al, 2005). The cognitive test resembles to some extent the more well-known *n*-back task working memory test (Braver et al, 1997). Specifically, the 2-back task (n=2) is a variant where sequential letters are visually presented and the task is to indicate when the target letter is identical to the letter *two* trials back. It can be argued that the visual letter-monitoring task includes aspects of working memory since both information processing and memory aspects are included, and this is also confirmed in the accompanying paper in this issue (Foo et al).

Since the Gatehouse et al (2003, 2006) studies have interesting clinical implications with regard to prescription of time constants in hearing aids, it seemed reasonable to perform a study to confirm the Gatehouse et al (2003, 2006) results. In this new study, the same cognitive test procedure, hearing aids, time constants, and background noises (unmodulated and modulated speech-weighted noise) were used as in the Gatehouse et al (2003, 2006) study. However, to test the applicability of the findings in new contexts, the outcome measures were different with regard to language (Danish versus English) and speech-in noise test (sentence test versus single word test) and speech-in-noise assessment procedure (adaptive noise adjustment versus fixed speech-to-noise ratio).

Furthermore, to investigate the relative importance of pure-tone hearing thresholds versus cognitive performance with respect to prediction of aided speech recognition in noise, several analyses were made from relatively steady-state to more fluctuating test conditions.

METHODS

Visual Letter Monitoring Score

The Visual Letter Monitoring Test (VLM) is a test developed at the Medical Research Council (MRC) Institute of Hearing Research by Quentin Summerfield and John Foster (see Gatehouse et al, 2003) as an analog to a previously developed test (digit letter monitoring; Gantz et al, 1993; Knutson et al, 1991). A translation of the test (from English to Danish) was made at the Oticon Research Centre Eriksholm. The VLM-test is a test of attention, reaction time, continuous performance and working memory (Gfeller et al, 2005). The test requires that the subject sits in front of a computer screen on which one letter at a time is presented. The letters presented alternate between Vowels and Consonants in a continuous stream without pauses. The subjects were instructed to press the space bar on the computer's keyboard every time three consecutive letters (Consonant-Vowel-Consonant) formed a correct Danish CVC-word ('Yes'-response). The correct words were always constructed by Consonant-Vowel-Consonant (e.g. "BAD"). Abbreviations were not considered to be correct words. Before the test started the subject had the opportunity to read the written instructions, and to do a practice run of the test. The letters were presented with two different inter-stimuli-intervals of two seconds and one second. Individual cognitive performance was expressed as one *d'* value, in correspondence with the Gatehouse et al study (2003, 2006). To calculate the d' from the subjects' hit-rates (H) and false-alarm rates (F), Equation 1 was used (see e.g. Stanislaw and Todorov, 1999),

$$d' = \Phi^{1}(H) - \Phi^{1}(F) \qquad \text{(Equation 1)}$$

where Φ^{-1} ("inverse phi") converts normal distributed probabilities to z-scores and thus *d'* is found by subtracting the z-score that corresponds to the false-alarm rate from the z-score that corresponds to the hit rate. Extreme values of hit-rate and false-alarm rate (zero or one) were adjusted according to Hautus (1995). Although the d' assumptions were probably not entirely fulfilled (normal distribution of false-alarm rate and hit rate, as well as false-alarm rate and hit rate having the same standard deviation) since the test subjects had a limited time for response and the task was not a pure yes-no task, we chose to use the same *d'* calculation method as Gatehouse et al to be able to compare the results from the two studies.

Speech Recognition Test

Speech Material

The speech material was recorded sentences by a female speaker. The sentences were five-word, low redundancy, low context sentences with a regular structure (noun, verb, numeral, adjective and noun), e.g. "Michael had five new plants" (Dantale II, Wagener et al, 2003).

Noise

The unmodulated noise was constructed from the original speech material (Wagener et al, 2003) to have the identical long-term spectrum as the speech signal, while minimizing the modulations and thus the informational content in the noise signal.

The modulated noise was the two-talker modulated noise from ICRA track 6 (Dreschler et al., 2001), and was constructed to preserve speech-like modulations, while minimizing the informational content in the noise signal.

Adaptive Methods and Calculation of Psychometric Functions

The sentences were presented in noise. The percentage of correctly recalled words from each sentence at the corresponding speech-to-noise ratio (SNR) were considered as one data point. Individual psychometric functions were estimated by adaptively adjusting the SNR after each presented sentence, the adjustment being dependent on the number of correctly recalled words. To obtain a fair distribution of the data points across the whole range of the psychometric function, adaptations were made towards three different targets of performance; 80% correct, 50% correct, and 20% correct (20 sentences per target). Thus, the adaptation towards each target would result in a number of data points around this target, which were used for the estimation of the psychometric function. Two adaptive procedures were used, the standardized Dantale II method for the 50% target (Wagener et al, 2003), and the method proposed by Brand (2000) for the 20% and 80% targets. Sixty sentences with corresponding percent correct scores and SNRs were thus used for the estimation of one psychometric function. The individual psychometric function was fit using the maximum likelihood (ML) method. As generator function for the ML optimization (and thus as model for the psychometric function) we used the logistic discrimination function, see Equation 2 below, known from signal detection theory (Green and Swets, 1966, 1988);

$$p = \frac{1}{1 + \exp\left(4s_{50}(SRT_{50} - SNR)\right)} \quad \text{(Equation 2)}$$

where p is the cumulative probability for word recognition as a function of speech-to-noise ratio (SNR). SRT_{50} is the SNR at which 50% of the speech is understood, and s_{50} represents the slope of the psychometric function at the 50%-point. Thus, the individual psychometric functions were fitted from the observed data points with SRT_{50} and s_{50} as parameters.

Setup and Test Procedure

The test was carried out in a soundproof booth. The sentences and noise were both initially presented at 65 dB(A) from a loudspeaker (Genelec 1031A) one meter in front of the test subject and the level of the noise was adaptively varied as described above. The speech material was presented to the subject with the background noise continuously presented (i.e. no interruptions of the noise, e.g. Wagener and Brand, 2005) and the subject's task was to recall as many words as possible after each presented sentence. Before the test started the subjects had the opportunity to read the written instructions and to do a practice run of the test.

Subjects

Subjects that met the inclusion criteria of symmetrical, mild to moderate hearing loss, were enrolled from the test subject pool at the Eriksholm clinic. Twenty-three subjects, nine women and 14 men, with an average age of 65.6 years (SD 12.8, range 32 to 87) were invited to participate. All subjects accepted the invitation. Figure 1 shows the average hearing threshold for the subjects and range.

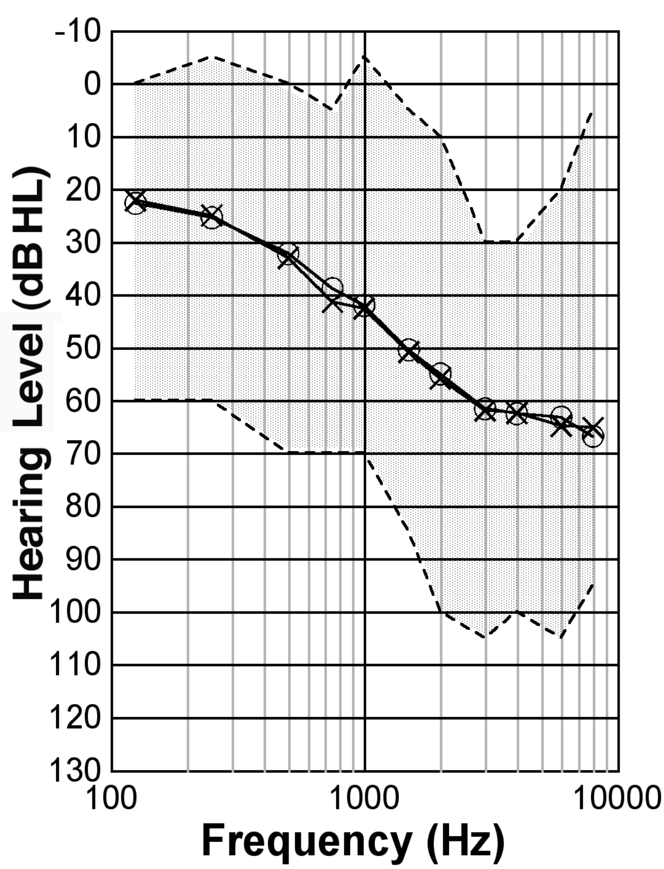

Figure 1. Average hearing loss left and right ears and range.

Table 1. Overview of Experimental Program

Visit 1		Visit 2		Visit 3
Cognitive test		*Time Constant 1*		*Time Constant 2*
Visual Letter Monitoring	10 weeks	*Speech recognition test*	10 weeks	*Speech recognition test*
Time Constant 1		Training		Training
		Unmodulated noise		Unmodulated noise
		Modulated noise		Modulated noise
		Time Constant 2		

Hearing Aids

The test subjects were experienced hearing aid users with digital, non-linear, two-channel hearing aids (Oticon Digifocus I and II), nine were fitted with behind-the-ear instruments and fourteen were fitted with in-the-ear instruments. Twelve of the participating subjects wore hearing aids bilaterally, eleven unilaterally. In the experiment, new time constants (Fast and Slow) were programmed in their own hearing aids. Fast was a two-channel WDRC amplification strategy and used an attack time of 10 ms and a release time of 40 ms, both in the low frequency channel (LF) and in the high frequency channel (HF). Slow was a two-channel AVC amplification strategy, with attack times of 10 ms and release times of 640 ms in both channels. During the experiment the subjects retained all the fine-tuning settings they used at the time of the experiment, but any manual volume controls or directional microphones were inactivated throughout the duration of the experiment.

Experimental Procedure

The subjects visited the Eriksholm hearing clinic three times, with ten weeks between each visit. At each visit the subjects underwent a battery of speech recognition tests and cognitive testing as shown in Table 1. At the first visit the subjects were fitted with one set of experimental time constants (time constant 1). Half of the subjects used Fast for the first test period and half used Slow. [After the experiment was finalised, the subjects were grouped into three cognitive groups (see results section). Within each cognitive group it turned out that about equal numbers of subjects started with Fast in the first test period.] At the second visit the subjects were tested for speech recognition in noise with time constant 1 and afterwards switched to the other time constant (time constant 2). The experiment was finalized at the third visit 3 by measuring speech recognition in noise with time constant 2. Thus, all testing with hearing aids was made after 10 weeks of usage with the current time constant.

Statistical Analysis and Power

During the planning phase of the study, the experiment was powered to detect a within-subject between-fitting difference of 0.5 dB on the mean scores across conditions on the speech recognition test described subsequently for $p < 0.05$ at 80% power. This required at least 23 complete data sets. Furthermore, subgroups of 8 subjects or more could detect a subject between-fitting difference of 1.5 dB on the mean scores for $p < 0.05$ at 80% power. A mixed design analysis of variance was used to investigate interaction effects. Simple correlations were calculated through Pearson product-moment correlations. However, if test variables could not be clearly assumed to be normally distributed, simple correlations were also calculated through Spearman Rank order correlations. Multiple linear regression analyses were performed to investigate partial correlations and explained variance. *K*-means clustering was used as clustering method to divide the subjects into three subgroups. All statistics were performed using STATISTICA version 7 (www.statsoft.com).

RESULTS

Cognitive Grouping

The results from the visual letter monitoring (VLM) cognitive test indicated an average VLM score of 2.0 (N = 23, SD =

0.9). We formed three cognitive subgroups for further statistical analysis. The grouping into subgroups was made through k-means clustering. The clustering resulted in three subgroups; Low performance (n = 8, M = 1.2, SD = 0.2), Medium performance (n = 9, M = 2.0, SD = 0.3), and High performance (n = 6, M = 2.9, SD = 0.3).

Psychometric Functions Derived from the Speech-in-Noise Test

Four psychometric functions were fitted for each test subject representing each test condition; a) slow time constants and unmodulated noise (Slow and Unmodulated), b) slow time constants and modulated noise (Slow and Modulated) c) fast time constants and unmodulated noise (Fast and Unmodulated), and d) fast time constants and modulated noise (Fast and Modulated).

Figure 2 shows the psychometric functions for each test condition where the individual psychometric functions were averaged (i.e. the parameters SRT_{50} and s_{50} in Equation 2 were averaged) across the subjects in each cognitive group.

It is interesting to note the difference in performance across cognitive groups and across test conditions. Inspection of Figures 2a to 2d suggests that the cognitively High performing group tends to perform better than cognitively Medium and Low performing groups (i.e. lower SNR for a given percent correct score) for all test conditions, and that the cognitively High performing group tends to perform at their best in the fast and modulated condition compared to the slow and unmodulated condition. Furthermore, the cognitively Medium and Low performing

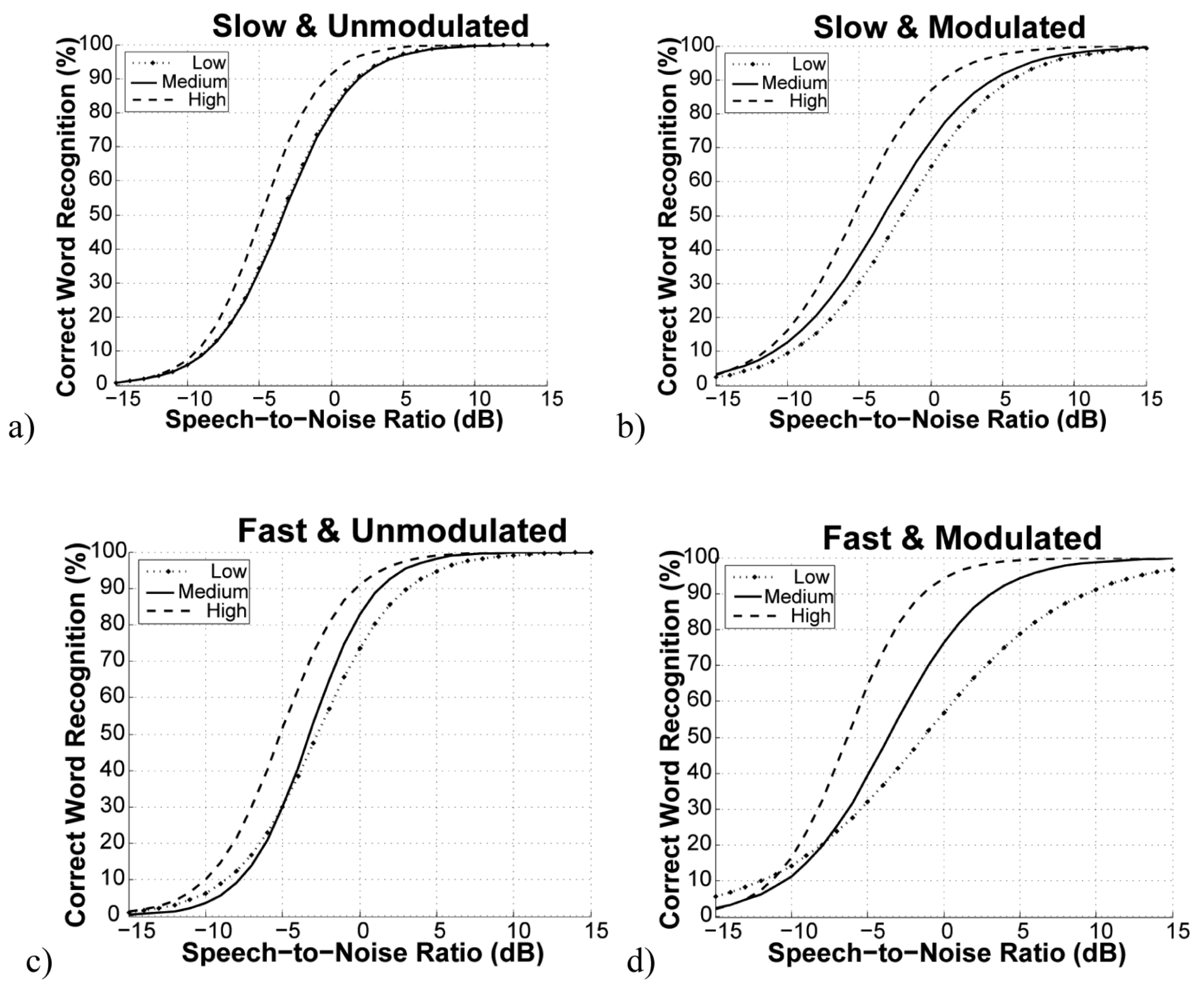

Figure 2. Average psychometric functions for cognitively High, Medium and Low performing subjects: (a) Slow time-constant and unmodulated noise; (b) Slow time-constant and modulated noise; (c) Fast time-constant and unmodulated noise; (d) Fast time-constant and modulated noise.

groups tend to perform worse in the modulated condition compared to the unmodulated. In addition, the cognitively Low performing group tends to perform at their worst in the fast and modulated condition. If we consider Figures 2a and 2d, some interesting patterns emerge. In the slow and unmodulated test condition (Figure 2a) the three cognitive groups tend to perform rather similarly, except for a somewhat better overall performance for the cognitively High performing group, while in the fast and modulated condition (Figure 2d), the difference in performance across cognitive groups is large. Consider Figure 2d. For the cognitively High performing group it seems as if an SNR of around 0 dB is necessary to elicit a 5 percent performance drop from 100 percent correct, while the same performance drop occurs at an SNR of about 12 dB for the cognitively Low performing group. As can be seen in Figures 2a to 2d, the largest SNR-variability across cognitive groups and across test conditions appears around a correct word recognition score of about 80 percent. For further statistical analysis we therefore chose to sample the SNR-performance for 80% correct words from the individual psychometric functions in each test condition.

Analysis of Variance

Table 2 shows the cognitive group means of the sampled SNR-performance data for the four test conditions, as well as the post hoc analysis. Note the more negative SNR, the better performance.

Table 2. Mean Aided SNRs (dB) at 80% Correct Words for Cognitive Groups with Fast and Slow Time Constants in Unmodulated and Modulated Noise

	Time constant	
Cognitive Group	*Slow*	*Fast*
Low performance		
Unmodulated noise	-0.1_a	1.0_a
Modulated noise	2.8_b	5.4_c
Medium performance		
Unmodulated noise	0.0	-0.4
Modulated noise	1.5	0.6
High performance		
Unmodulated noise	-2.0_d	-2.1_d
Modulated noise	-1.5_d	-3.2_d*

Note: Means that do not share subscripts differ at p < 0.05 in the Tukey HSD test (*differ at p < 0.08). Note that the more negative the SNR, the better the performance.

Analysis of variance was made with a mixed design where time constant and noise type were entered as repeated measures (dependent variables) and the cognitive group was regarded as the categorical predictor (factor). The analysis revealed a main effect of cognitive group, where the cognitively high performing group obtained generally better performance than the cognitively low performing group, $F(1,12)= 7.2$, $p < 0.05$. Furthermore, the analysis showed several interaction effects. Firstly, an interaction between cognitive group and time constant indicated that the cognitively low performing subjects on average performed better with the slow time constants, while the cognitively high/mid performing subjects performed better with the fast time constants, $F(1,20) = 3.6$, $p < 0.05$. However, in the subgroup post hoc analysis with rather low n, only the difference for the cognitively low performing group was significant (LSD, $p < 0.05$). Secondly, an interaction between the cognitive group and noise type, indicated that the cognitively low/mid performing subjects on average performed better in the unmodulated noise, while the cognitively high performing subjects performed better in the modulated noise $F(1,20) = 4.2$, $p < 0.05$. In the post hoc analysis with subgroups, only the difference for the cognitively low performing group was significant (LSD, $p < 0.05$).

Thus it seems as though cognitive performance influenced the speech-in-noise performance differently in the four test conditions. It appears that fast and slow time constants give rise to different performance across cognitive groups. In a clinical context it is important to know the result of switching from one time constant to the other for the *individual* hearing aid user. Therefore, the following analysis is directed towards individual hearing aid user predictions of time constants, as opposed to group means.

Benefit of Fast versus Slow

To qualify the clinical applicability of the results, i.e. would a given individual hearing aid user benefit from switching from Slow to Fast (or vice versa), we

Table 3. Correlations between Slow Minus Fast Difference in SNR at 80% Correct in Two Noise Types and Cognitive Performance

	Slow minus Fast difference	
	Unmodulated noise	Modulated noise
Cognitive score		
Pearson correlation	.16	.47*
Spearman correlation	.24	.49**

*p < .05, **p < .01

derived a new variable, benefit of Fast versus Slow as the performance with slow *minus* performance with fast (SNR for 80% correct performance). Thus, a positive value of this variable indicated benefit of Fast over Slow, while a negative value indicated benefit of Slow over Fast. We correlated the score from the cognitive test with this benefit of Fast versus Slow variable. Table 3 shows the correlations for the unmodulated and modulated test conditions.

As shown in Table 3, a significant correlation was found for the modulated test condition. Figure 3 shows a scatter plot of the individual data as well as the regression line for the prediction of the SNR-difference from the cognitive score. The regression line indicates that in modulated noise the subjects with high results on the cognitive test are those who have an advantage of fast-acting compression over slow-acting compression, while those with poor cognitive capacity have an advantage of slow-acting compression over fast-acting compression.

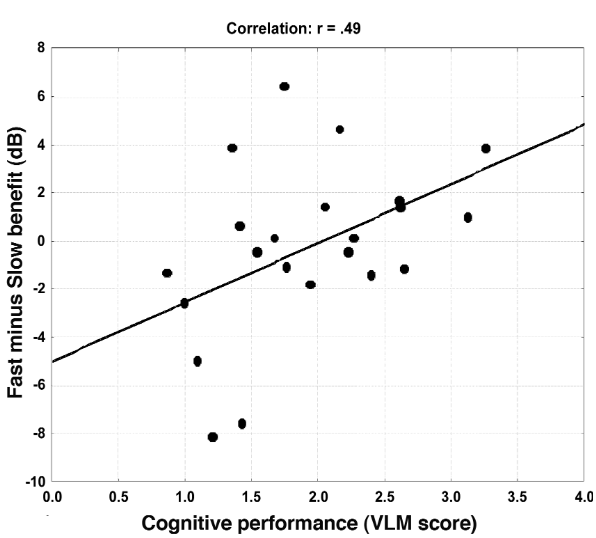

Figure 3. Scatter plot and regression line showing the Pearson correlation between the cognitive performance score and differential benefit in speech recognition in modulated noise of Fast versus Slow time-constants

Table 4. Multiple Regression Results for Prediction of Aided Speech Recognition in Noise (SNR) Performance from PTAs and Cognitive Performance

	β	*B*
Slow and Unmodulated noise		
Intercept		-6.08
PTA	.53**	0.14**
Cognitive score	-.19	-0.73
Slow and Modulated noise		
Intercept		-6.29
PTA	.50*	0.23*
Cognitive score	-.29	-1.97
Fast and Unmodulated noise		
Intercept		0.35
PTA	.20	0.05
Cognitive score	-.44*	-1.67*
Fast and Modulated noise SNR		
Intercept		7.03
PTA	.14	0.08
Cognitive score	-.62**	-4.84**

*p < .05, **p < .01
Note: β:s are the partial correlation coefficients and *B:s* are the raw coefficients in the multiple regression equation.

Prediction of SNR Performance and Explained Variance

Multiple regression analysis was made to investigate whether the pure tone average, PTA(6), and cognitive score contributed to predict aided SNR-performance. The multiple regressions were also used to investigate how much of the variance in aided SNR-performance could be explained by the pure tone average, PTA(6), and by the cognitive score in the four test conditions. Table 4 and Figure 4 summarize the results.

As can be seen in Table 4 the partial correlations were only significant for PTAs when using slow time constant conditions, while only the cognitive scores resulted in significant partial correlations for the fast time constant conditions. As seen in Figure 4, the explained variance differed across test conditions. About 30 percent of the variance was explained by the PTAs in the slow time constant test conditions, while around 5 percent or less was explained in the fast time constant condition. The cognitive score explained some variance (5%) in the slow and unmodulated condition and somewhat more in the slow and modulated

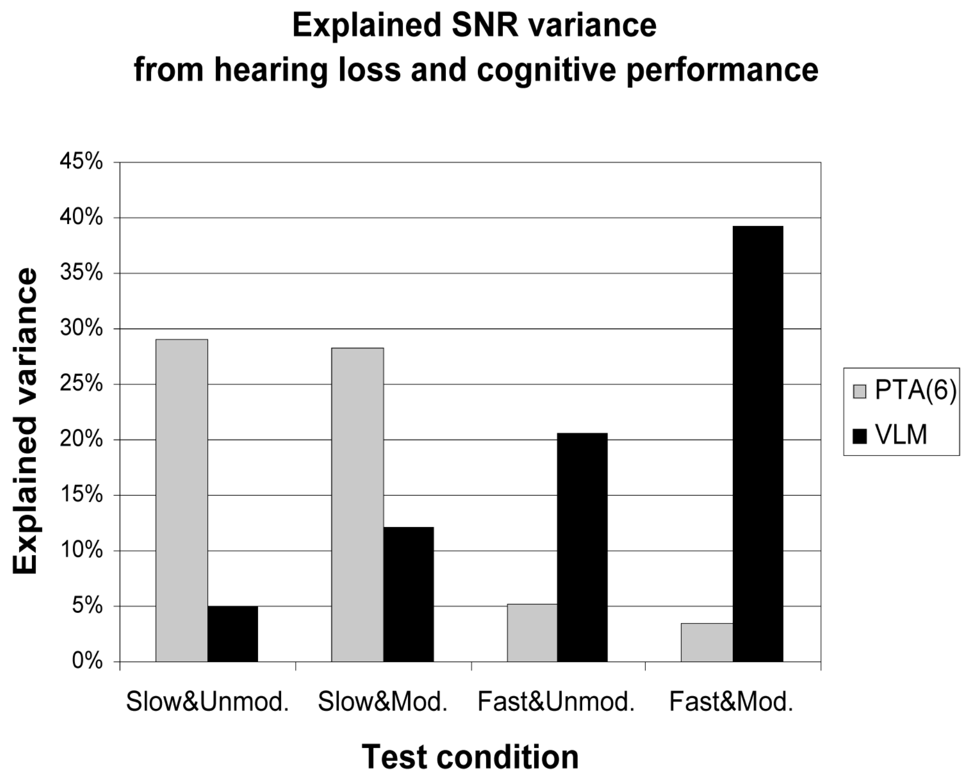

Figure 4. Explained speech recognition in noise variance for different test conditions of background noise and hearing aid time constants. VLM=Cognitive test. PTA(6)=hearing loss.

condition (12%). However, in the fast time test conditions the cognitive score explained substantially more variance than PTA(6). In the fast and modulated test condition 39 percent of the variance was explained by the cognitive score and only 3 percent by PTA(6). Thus, PTA(6) explained most variance in the slow and unmodulated condition, while the performance in the cognitive test explained most variance in the fast and modulated test condition.

In summary, the results indicated an interaction effect between cognitive group and time constants as well as an interaction effect between cognitive group and noise type. Furthermore, the results indicated a correlation between cognitive test score and differential benefit of fast versus slow compression in modulated noise. In addition, multiple regression results showed that PTA(6) only explained variance of aided speech recognition performance when using slow time constants, while the cognitive test only explained variance of aided speech recognition performance in fast time constant conditions. Lastly, the PTA(6) explained most variance in the slow and unmodulated condition, while the cognitive test explained most variance in the fast and modulated test condition.

DISCUSSION

The results of this study indicate that the cognitively low performing subjects performed better with the slow time constants in unmodulated noise, while the cognitively high performing subjects performed better with the fast time constants in modulated noise, as indicated by the correlation between cognitive test score and differential benefit of fast versus slow compression time constants in modulated noise (Figure 3 and Table 3) and indicated by the interaction effects found in the analysis of variance. These results are consistent with the results seen by Gatehouse et al (2003), where the direction of the interaction was that test subjects with greater cognitive capacity derived greater benefit from temporal variations in the background noise for fast time constants, and consistent with the results from Gatehouse et al (2006, table 13), where a positive correlation was seen between the cognitive function prediction factor and the speech test benefit factor, indicating an increased advantage for the fast over the slow time constants with increasing cognitive performance. These similar results were obtained in spite of the differences between the two studies, i.e. testing in different languages (Danish versus English), different speech in noise test methods (sentence test versus Four Alternative Auditory Feature, FAAF, word test), and different speech in noise assessment procedures (adaptive noise adjustment versus fixed speech-to-noise ratio). Thus, this study together with the Gatehouse et al studies give further evidence of the importance of cognitive performance for aided speech recognition in noise with different time constants and background noises. However, both the present study and the Gatehouse et al (2003, 2006) studies were based on similar two-channel hearing instruments. Thus, it remains to be investigated if the findings are possible to generalize to any *n*-channel hearing instrument.

Cognition Is Important in Complex Listening Situations

The partial correlations for the PTA(6) in Table 4 indicate poorer speech recognition performance in noise (greater SNR required) for more severe hearing loss. This is in accordance with the findings in several studies (e.g. see the review by Plomp 1994; Magnusson, 2001).

Furthermore, partial correlations for the cognitive score indicate that a higher cognitive performance is likely to lead to better (lower SNR required) speech recognition in noise performance. This is in accordance with the findings by Lunner (2003), where the working memory performance was correlated with aided speech in noise performance.

However, most interesting and most clinically relevant is the fact that the PTA(6) had no predictive contribution at all for the SNR-performance with fast time constants in modulated noise, while the cognitive test explained up to 40 percent of the variance. This was indeed an unexpected result. The largest partial correlation was actually seen for the cognitive score in the fast and modulated condition.

The results are consistent with a hypothesis that peripheral hearing loss explains performance under relatively simple listening conditions (unmodulated background noise and slowly varying compression) while cognitive abilities explain performance under complex listening conditions with large fluctuations in background noise and hearing aid signal processing (fast acting compression in modulated noise).

It is natural to pose the question of why cognition seems to be important for aided speech recognition in complex listening situations. Working memory is thought of as a capacity-limited system that both stores recent visual-spatial, phonological and episodic information and at the same time provides a computational mental workspace in which the just-stored information can be manipulated and integrated with knowledge stored in long-term memory (Baddeley, 1986, 2000; Repovš and Baddeley, 2006; Just and Carpenter, 1992). The major hypothesis of these models is that there is a limited pool of operational resources available to perform computations, and when demands exceed available resources, the processing and storage of information are degraded. Furthermore, models of poorly perceived or degraded auditory speech signals (e.g. delivered through hearing instruments, cochlear implants, in noise, or as visual or tactile signal only) have been proposed which imply involvement of cognitive operations/processing to facilitate inference-making (Rönnberg, 2003).

With reference to these models, the working memory can be assumed to be highly involved in realistic hearing and communication in complex natural conditions, especially for hearing impaired persons where the auditory input is degraded. For example, in a conversation in a noisy background (or when being tested in a speech recognition in noise task), information must be stored in working memory in order to make sense of subsequent information. At the same time some words or fragments are possibly missed as a consequence of both the hearing loss and the interfering noise, and thus some of the limited cognitive processing resources need to be allocated to what is being said.

This reasoning suggests that individual working memory performance may correlate to (hearing) aided speech recognition in noise. Thus, it is likely that the *individual* cognitive capacities are stretched to the limit (and thus determine the performance) when the rate of speech is fast, the message is complex, or the input signal is degraded by hearing impairment, external distortion (reverberation) or interference (noise). Although the hearing aid may make speech sounds audible, the consequences of cochlear damage (see e.g. Moore, 1996) such as broadening of auditory filters, loss of nerve-fibre synchrony through absent phase-locking are not compensated by the hearing aid. Furthermore, the hearing aid itself may introduce new, possibly cognitively demanding, distortions due to compression, noise reduction scheme, switching in and out of directional microphones, or other signal processing algorithms.

Thus the results in this study may be explained in the way that in a condition with slow-acting compression and unmodulated noise the test subjects' cognitive capacities are active, but without exceeding the capacity limit of most individual listeners. Thus, the individual peripheral hearing loss restrains the performance and the performance may be explained by audibility. Possession of greater cognitive capacity confers relatively little benefit. However, in the complex situation with fast-acting compression and varying background noise, much more cognitive capacity is required for successful listening. Thus, the individual cognitive capacity restrains the performance and the speech-in-noise performance may, at least partly, be explained from individual working memory capacity.

The results suggest that laboratory testing under steady-state conditions may underestimate the role of cognition. Thus, we argue for the evaluation of hearing aids in more complex listening situations. Speech recognition testing on hearing impaired test subjects may then include natural variations in rate of speech (Tun and Wingfield, 1999; Wingfield, 1996), messages with different levels of context (Pichora-Fuller et al, 1995), different levels of comprehension (Hannon and Daneman, 2001), including natural variations in reverberation and background noise, as well as natural spatial listening conditions (Blauert, 1997; Li et al, 2004, Freyman, 1999). Testing under complex listening conditions may for example be used to further investigate target release times for patients with varying cognitive levels, and to examine whether the interaction between time constants and cognition as found in this study and the Gatehouse study holds under such complex conditions.

Lastly, it should be noted that the cognitive tests referred to in this article (VLM and reading span) by no means are thought of as being optimal for understanding the role of cognition with regard to speech recognition in noise. These cognitive tests have been developed for other purposes. In future studies it may be necessary to develop cognitive tests that are more directly intended to assess the role of cognition under complex listening circumstances.

CONCLUSIONS

The results in this study, using other speech test material, language and test procedure, confirmed the speech recognition in noise findings by Gatehouse et al (2003, 2006) where an interaction was seen between the results on a visual letter monitoring cognitive test and the time constants in two-channel hearing instruments, as well an interaction between the cognitive capacity and type of background noise. The results in the present study indicated that the cognitively low performing subjects performed better with the slow time constants in unmodulated noise, while the cognitively high performing subjects performed better with the fast time constants in modulated noise.

The pattern of explained variance was in line with a hypothesis that peripheral hearing loss explains aided speech recognition in noise under relatively simple listening conditions, while cognitive capacity explains performance under more complex, fluctuating, listening conditions. This suggests that laboratory testing of speech recognition under steady-state conditions may underestimate the role of cognition in real-life listening.

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