Original Article

Hearing impairment, cognition and speech understanding: exploratory factor analyses of a comprehensive test battery for a group of hearing aid users, the n200 study

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Abstract

O*bjective*: The aims of the current n200 study were to assess the structural relations between three classes of test variables (i.e. HEARING, COGNITION and aided speech-in-noise OUTCOMES) and to describe the theoretical implications of these relations for the Ease of Language Understanding (ELU) model. *Study sample*: Participants were 200 hard-of-hearing hearing-aid users, with a mean age of 60.8 years. Forty-three percent were females and the mean hearing threshold in the better ear was 37.4 dB HL. *Design*: LEVEL1 factor analyses extracted one factor per test and/or cognitive function based on a priori conceptualizations. The more abstract LEVEL 2 factor analyses were performed separately for the three classes of test variables. *Results*: The HEARING test variables resulted in two LEVEL 2 factors, which we labelled SENSITIVITY and TEMPORAL FINE STRUCTURE; the COGNITIVE variables in one COGNITION factor only, and OUTCOMES in two factors, NO CONTEXT and CONTEXT. COGNITION predicted the NO CONTEXT factor to a stronger extent than the CONTEXT outcome factor. TEMPORAL FINE STRUCTURE and SENSITIVITY were associated with COGNITION and all three contributed significantly and independently to especially the NO CONTEXT outcome scores ($R^2 = 0.40$). *Conclusions*: All LEVEL 2 factors are important theoretically as well as for clinical assessment.

Key Words: Hearing impairment, temporal fine structure, cognition, working memory capacity, executive functions, phonology, outcome, context

Introduction

Hearing loss (HL) affects approximately 15% of the general population, including every second person aged 65 and over (Lin et al, 2011). Recent advances in hearing aid technology benefit *some* persons with HL, but *far from all* can take advantage of the advanced signal processing available in modern hearing aids (Kiessling et al, 2003; Lunner & Sundewall-Thorén, 2007; Souza et al, 2015a,b for a review). These differences in benefit occur even when different individuals have similar audiograms. In addition, factors like

auditory temporal processing ability and specific cognitive functions explain some of these differences (Pichora-Fuller et al, 2007; Rönnberg et al, 2011a,b; Humes et al, 2013; Rönnberg et al, 2013, 2014; Schoof & Rosen, 2014; Füllgrabe et al, 2015).

Over the last decade, the research community has increasingly acknowledged that successful (re)habilitation of persons with HL must be individualized and based on a finer analysis of details of the impairment at all levels of the auditory system from cochlea to cortex in combination with individual differences in cognitive capacities

pertinent to language understanding (e.g., Souza et al, 2015; Wendt et al, 2015). Relevant cognitive capacities include working memory capacity (WMC; Lunner, 2003; Gatehouse et al, 2006; Foo et al, 2007; Arlinger et al, 2009; Stenfelt & Rönnberg, 2009; Arehart et al, 2013; Füllgrabe et al, 2015; Keidser et al, 2015; Souza et al, 2015; Wendt et al, 2015) and phonological skills (Lyxell et al, 1998; Lazard et al, 2010; Classon et al, 2013; Rudner & Lunner, 2014). Furthermore, these cognitive capacities underpin communicative and social competence, and this cognitive-social relationship is presumably reinforced among older people whose cognitive capacities are known to be variable and vulnerable (Danielsson et al, 2015; Pichora-Fuller et al, 2013; Rönnberg et al, 2013; Rönnlund et al, 2015; Schneider et al, 2010). There is also convincing evidence that sensory loss, including HL, is associated with age-related differences in cognition (Humes et al, 2013) and with incident dementia (Albers et al, 2015). Less well understood are the complex interactions among type of HL, aging and specific aspects of cognition, including phonological awareness, executive function and WMC (Harrison Bush et al, 2015). In addition to the associations between pure-tone threshold elevation and cognitive decline, there is evidence that decline in central auditory processing abilities is associated with cognitive declines, including specific executive function deficits (Gates et al, 2002, 2010, 2011; Idrizbegovic, 2011).

Recent cross-sectional data suggest that HL is associated with poorer long-term memory (LTM; both semantic and episodic), but only to a lesser degree with short-term or working memory (Rönnberg et al, 2011a,b, 2014). This is also true when age is accounted for (the Betula database, Nilsson et al, 1997; Rönnberg et al, 2011a,b), and even when episodic LTM is assessed using *visuo-spatial* materials (Rönnberg et al, 2014; the UK Biobank Resource). The use of hearing aids may interact with the relationship between memory and hearing (Amieva et al, 2015). For example, Rönnberg et al (2014) were also able to show that hearing aid users performed slightly better than non-users on a *visual* working memory task. This cross-modal effect of auditory intervention on visuo-spatial processing suggests that in the long-term, HL may also impair central (or multi-modal) WMC, not only modality-specific working memory abilities (see also Dupuis et al, 2015; Verhaegen et al, 2014).

However, what is still lacking is a more comprehensive and longitudinal account (cf. Lin et al, 2011, 2013) of the mechanisms underlying the correlations between HL and cognition, including the transitions between healthy and pathological functioning such as in incident dementia. Also lacking is a more detailed and theoretically driven description of cognitive and perceptual predictors of speech-in-noise criterion variables.

Purpose

The current study is the first investigation in a series of studies based on the n200 database. The name n200 reflects the fact that the number of participants in each of three groups will be around 200. The data collection for the first of those three groups has been completed; it forms the basis for a cross-sectional study of 200 participants with HL who use hearing aids in daily life (age range: 37–77 years). It has also been extended to include a longitudinal study with three test occasions (T1–T3, with 5 years between test occasions) and two control groups of around 200 persons each. The two control groups, one comprised of individuals with normal hearing and the other of individuals with HL who do not use hearing

aids, are matched for age and gender. The current paper is based on data collected from the 200 participants with HL who use hearing aids.

The aim of the current paper is threefold: (1) to present a test battery which is based on well-established tests as well as new, theoretically motivated (cognitive) experimental measures belonging to three classes of tests: hearing, cognitive and speech-in-noise outcome test variables, (2) to statistically examine how the test variables from the three classes of tests are structurally related to each other, taking age into account and (3) to address theoretical and clinical implications from the overall picture of the data.

The focus of the current study was to present the overall pattern of data, which means that detailed analyses of specific hearing and cognitive predictor variables and specific outcome test conditions, subjective or objective, are not included this study. These kinds of studies, where we, for example, relate different kinds of working memory tests to certain signal processing conditions, or where we (as is typically done) analyse subjective ratings into their component scales (i.e. the SSQ, see below), are planned for subsequent reports.

The research and the overall rationale for the selection of the types of cognitive tests have been generally driven by the fact that the tests have been found to be associated with communicative outcomes, primarily with speech understanding under adverse or challenging conditions (for reviews, see Mattys et al, 2012; Rönnberg et al, 2013; Schmulian Taljaard et al, 2016). More specifically, the tests included in the battery tap into different operationalisations of the components of and the predictions by the Ease of Language Understanding (ELU) model (Rönnberg, 2003; Rönnberg et al, 2008, 2011a,b, 2013). The research and the overall rationale for the selection of the types of cognitive tests have also been driven by accounts of speech processing involving measures of executive function (Mishra, 2014; Rudner & Lunner, 2014).

Hearing tests

The hearing tests were selected for their ability to identify different aetiologies of the hearing impairment based on the reasoning in Stenfelt and Rönnberg (2009, see also Neher et al, 2012). The hearing thresholds were measured to obtain the hearing sensitivity of the participant and together with the bone conduction thresholds conductive hearing losses could be identified. The distortion product oto-acoustic emissions (DPOAEs) were tested to determine the function of the outer hair cells and Threshold-Equalizing Noise – Hearing Level (TEN HL) for the integrity of larger areas of inner hair cells. Phonetically balanced (PB) words in quiet together with pure tone thresholds can be used to estimate the influence of any auditory neuropathy. The Spectro-Temporal Modulation (STM) test by Bernstein et al (2013) was used as a general test of modulation detection and the Temporal Fine Structure Low Frequency test (TFS-LF), developed by Hopkins and Moore (2010), was used to test the general ability to use pitch information.

Cognitive mechanisms and ELU

The ELU-model is primarily defined at a linguistic-cognitive level. It assumes that processing of spoken input involves *Ra*pid *M*ultimodal *B*inding of *PHO*nology (called RAMBPHO, Rönnberg et al, 2008), completed around 150–200 ms after stimulus presentation (Stenfelt & Rönnberg, 2009). The RAMBPHO component is assumed to contain short-lived phonological information

in a buffer that binds and integrates multimodal information (typically audiovisual) about syllables, which in turn feed forward to semantic LTM in rapid succession. If the RAMBPHO-delivered sub-lexical information matches a corresponding syllabic phonological representation in semantic LTM, then lexical access will be successful, including speed of access, both of which are crucial to speech understanding success (Ng et al, 2013b; Rönnberg, 1990, 2003). In its most general form, the ELU-model encompasses phonological information mediated by the tactile sense, lip-reading and sign language (Rönnberg, 2003). In the current study, only auditory and audiovisual speech are studied.

RAMBPHO concerns automatic and implicit processing. Lexical activation is compromised if there is a mismatch between the incoming RAMBPHO-processed stimuli and phonological representations in semantic LTM; i.e. when there are too few overlapping (matching) phonological and semantic attributes, immediate lexical entry is denied (Rönnberg et al, 2013 for details; cf. Luce & Pisoni, 1998). In such cases, the basic prediction is that explicit, elaborative and relatively slower WMC-based inference-making processes are invoked to aid the reconstruction of what was said. Mismatches may be due to one or more variables, including the type of HL, adverse signal-to-noise ratio conditions, competing talkers, unfamiliar output from signal processing in the hearing aid or excessive demands on cognitive or lexical processing speed. The relative effects of these variables on recovery from a mismatch in the ELU model can be evaluated and estimated with the current test battery.

WMC: In the Rönnberg et al (2013) version of the ELU-model, WMC plays two different roles: a post-dictive role that supports communication repair (cf. above) and a predictive role that involves priming or pre-tuning of RAMBPHO processing. Evidence of the latter role is based on the findings that WMC affects early attention processes in the brainstem (cf. Sörqvist et al, 2012; Anderson et al, 2013; Kraus &White-Schwoch, 2015; cf. the early filter model by Marsh & Campbell, 2016), which propagates to the cortical level, especially under conditions where memory load is high and concentration is demanded (Mattys et al, 2012; Sörqvist et al, 2016). Higher levels of linguistic predictions also involve WMC (Huettig & Janse, 2016).

Hearing impairment: The post-cochlear input to the linguistic-cognitive level of analysis is assumed to consist of neural patterns that can be recognized as particular phonemes (cf. Stenfelt & Rönnberg, 2009). These neural patterns will presumably be altered depending on the type of impairment (damage to the inner and/or outer hair cells and/or auditory nerve pathology, see Stenfelt & Rönnberg, 2009) and by temporal fine structure functions (suprathreshold measures) of the auditory system (e.g., Neher et al, 2012; Füllgrabe et al, 2015; Marsh & Campbell, 2016). In order to better understand the interplay between the auditory and cognitive systems, including speech perception and understanding abilities, we have collected the first wave of data on 200 participants with respect to degree and type of impairment, tapping into suprathreshold properties of the auditory system. This group was fitted with hearing aids.

The current study is an ELU-based comprehensive first account of how the impairment, RAMBPHO-related phonological skills, WMC and executive and inference-making functions, as well as speech understanding in noise (with and without signal processing) relate and interact. The extensive test battery and the large number of participants enable unique comparisons. Thus, the cognitive components that have been grouped conceptually in the current analyses may be found to have hitherto unexpected

interrelationships and factor structures (latent variable constructs), as well as new kinds of relationships with the speech-in-noise outcome constructs. In addition, and as noted previously, we have observed associations between degree of HL and episodic LTM (Rönnberg et al, 2011a,b) and we have claimed that the effect is multi-modal and represents a potential link to dementia (Lin et al, 2011; Rönnberg et al, 2014). In a recent paper, Waldhauser et al (2016) suggested a mechanism that fits with the above claim: episodic memory retrieval is dependent on the ability to generate short-lived sensory representations of the encoding experience. In the study by Waldhauser et al (2016), the fidelity of the original sensory representation was reflected by lateralized alpha/beta (10–25 Hz) power of the electroencephalographic (EEG) signal. This mechanism agrees with the suggested ELU-mechanism behind episodic memory loss in people with HL (Rönnberg et al, 2011a,b): due to a less than optimal auditory input, short-lived RAMBPHO-related information will mismatch more frequently with representations in semantic LTM, hence causing poorer encoding and subsequent retrieval from episodic memory. This in turn causes a relative disuse of episodic LTM compared to WM, which in turn is occupied with reconstructing and predicting what is to come in a dialogue, and hence, would be used more frequently than episodic LTM.

Therefore, partly for the purposes of the cross-sectional analyses but also for longitudinal reports to come, examining putative links between HL and cognitive impairment in aging (e.g., Lin et al, 2011), tests of general cognitive function were added to the battery. Also, semantic, but not episodic memory tests, were included together with the on-line storage and processing tests related to the ELU-model, to make a conservative evaluation of the existence of negative relationships between HL and cognition.

The test descriptions below are brief, with the purpose of relating and conceptually organizing the tests according to the ELU model components. The detailed test descriptions can be found under Methods in Supplementary materials.

Phonological processing mechanisms and ELU
Gating: The ELU model proposes that sub-lexical phonological functions as represented by RAMBPHO are crucial. We tested the participants' phonological abilities by using the gating paradigm (Grosjean, 1980; Moradi et al, 2013, 2014a,b, 2016). This paradigm measures the duration of the initial portion of the signal that is required for correct identification of speech stimuli (in this case *vowel* and *consonant* identification). Phonological, sub-lexical representations were also assessed by means of *vowel duration discrimination* (Lidestam, 2009) and *rhyme* (e.g. Classon et al, 2013).

Semantic LTM access speed and ELU
Physical matching (PM) and *lexical* decision (LD) speed measures, as well as *rhyme* decision speed were included (cf. Rönnberg, 1990). Speed of phonologically accessing the lexicon in semantic LTM is a crucial factor in the ELU model (Rönnberg, 2003).

Working memory mechanisms and ELU
The choice of WM tasks was guided by two principles: first, the emphasis was on storage and processing, and second, stimulus modality. Regarding the first principle, we used one task that emphasized storage only (i.e. a *non-word serial recall task* (NSR); Sahlén, 1999; Baddeley, 2012), and three tasks that in different

ways demanded both storage and semantic processing (i.e. the *reading span* (*RST*)*, semantic word-pair span* (*SWPST*) *and the Visuo-Spatial Working Memory test* (*VSWM*)*;* Rönnberg et al, 1989; Lunner, 2003; Foo et al, 2007, see details under Methods section). Two of the latter three tasks required the participant to recall target words in sentences/word-pairs (storage aspect) and to make semantic verification judgments of the content of sentences (*RST*) or by means of semantic classification into pre-defined semantic categories (*SWPST*). The semantic judgement/classification decisions thus represent the processing aspect of the tasks.

Second, while the NSR, the reading span and SWPST tasks were text-based, we also included the VSWM. In this task, ellipsoids are shown in spatial locations in a matrix. Participants make decisions regarding the visual similarity of pairs of ellipsoids in a given cell of the matrix while having to remember the order of locations of the pairs of ellipsoids (cf. Olsson & Poom, 2005). The dual task requirement is analogous to the requirements for the RST and SWPST.

Executive and inference-making mechanisms and ELU

The selection of executive tests was based on the subdivision of executive functions into *shifting*, *updating* and *inhibition* proposed by Miyake and Shah (1999, see also Diamond, 2013) Executive functions (EF) are important in speech perception, e.g. when tracking a talker in a cocktail party situation while inhibiting other voices (Sörqvist & Rönnberg, 2012). EF may also interact with WM when there is a need for storage to support explicit executive processing demands (cf. Sörqvist & Rönnberg, 2012; Rudner & Lunner, 2014). Verbal inference-making tests represent another explicit mechanism that interacts with WMC (here operationalised as the *sentence completion test, SCT,* Lyxell & Rönnberg, 1987, 1989; and the *Text-Reception Threshold, TRT*, Zekveld et al, 2007), and were, therefore, included in the battery.

Shifting was tested by the speed of categorizing items (e.g. digit–letter pairs presented on a screen) according to a relevant dimension (whether it is an odd/even number or a Capital/small letter). Depending on the position of the stimuli on the screen, shifting between dimensions is necessary.

Updating was operationalised as a memory task and concerns monitoring and keeping track of information according to some criterion and then appropriately revising the items held in working memory by replacing old, no longer relevant information with newer, more relevant information (keeping in mind the last word of four pre-defined semantic categories, e.g. fruits).

Inhibition errors were measured in a simple fashion: the participants watched a sequence of random digits and their task was to press the ''space bar'' every time they saw a digit, unless it was the digit 3.

The SCT (Lyxell & Rönnberg, 1987) was employed as another verbal inference-making test administered under time pressure, *with* prior contextual cues offered.

The TRT test (Zekveld et al, 2007) is based on an adaptive procedure that determines the percentage of unmasked text needed to read 50% of the words in a sentence correctly. The TRT is based on inference making from the sentence *without* use of prior contextual cues. Both the TRT and SCT have been proven to predict speech in noise understanding (Zekveld et al, 2007) and contextually driven speechreading (Lyxell & Rönnberg, 1987, 1989).

A Hannon–Daneman (2001) type of test was employed to assess the participant's ability to combine information about real and imaginary worlds from several written statements and to draw related inferences, here denoted Logical Inference-making Test (LIT).

General cognitive functioning

The standard *Mini Mental State Examination test* (*MMSE*, Folstein et al, 1975) was used for cognitive screening along with a *Rapid Automatised Naming test (RAN)* test. RAN is a quickly administered cognitive speed test (e.g. Wiig & Nielsen (2012)) which has also been shown to be sensitive to Alzheimers disease (Palmqvist et al, 2010). *Raven's* matrices (Raven, 1938; Raven, 2008) were used as a basic non-verbal IQ estimate.

Outcome variables and ELU

The Hagerman sentences (Hagerman, 1982; Hagerman & Kinnefors, 1995), which are Swedish matrix-type sentences, were used to test speech understanding in noise. The speech signal was presented using an experimental hearing aid that allowed us to assess and compare the effects of linear amplification, compression and noise reduction in different noise backgrounds on speech understanding and their interactions (Foo et al, 2007; Lunner & Sundewall-Thorén, 2009; Souza et al, 2015; Ng et al, 2015; Souza & Sirow, 2015). For the purpose of this overview paper, we will statistically treat all Hagerman conditions together. Details of the interactions between signal processing conditions and specific cognitive functions will be analysed in papers to come. In addition to the Hagerman sentences, we also employed other outcome variables where modality, contextual and semantic components were emphasized and manipulated (Samuelsson & Rönnberg, 1993; Hannon & Daneman, 2001; Sörqvist et al, 2012).

The general prediction from previous research is that there are speech understanding situations (e.g. in mismatch conditions; Foo et al, 2007; Rudner et al, 2009, 2011) in which the dependence on WMC (and WMC-related cognitive functions) increases when there is less contextual support (i.e., comparing context-free Hagerman with daily Swedish HINT sentences, Hällgren et al, 2006). By implication, we predict weaker associations between WMC and understanding of contextually rich (cued) spoken sentences in noise (e.g. Samuelsson & Rönnberg, 1993). We also expected that the understanding of audiovisual sentences compared to auditory-only would be less dependent on WMC (cf. previous sentence and phoneme-based gating data, Moradi et al, 2013).

An auditory version of the Hannon and Daneman (2001) materials was used to provide an indicator of the predictive nature of Auditory Inference-Making (here denoted AIM) ability in relation to speech understanding (see Supplementary materials).

In addition to the objective criterion variables, ratings were obtained using the Swedish version of the Speech, Spatial and Qualities of Hearing Scale (SSQ) questionnaire developed by Gatehouse and Noble (2004, see website: http://www.ihr.mrc.ac.uk/pages/products/ssq).

Summary of expectations and predictions

In sum, with the current test battery of hearing, cognitive and outcome variables, the following general predictions were made:

First, since the ELU-model consists of independent, but interacting cognitive components (e.g. Rönnberg et al, 2013), one general expectation is that all cognitive variables would be subsumed under one factor in an overall exploratory factor analysis.

Second, because of the different hearing and cognitive functions they tap into, one expectation was that the outcome variables would result in one context-driven factor (mainly the HINT, Hällgren et al, 2006, and Samuelsson & Rönnberg test, 1993) and one where context is less important (mainly the Hagerman, 1982). The hearing variables would also be split up into sensitivity (i.e. thresholds) on one hand and suprathreshold, temporal fine structure tests on the other hand (mainly STM and TFS-LF).

Third, we predicted that performance on the outcome tests that are relatively context-independent (e.g. the Hagerman sentences) would be associated to a higher degree with the hearing and cognition factors than would performance on the context-dependent tests (e.g. Rönnberg et al, 2013; Samuelsson & Rönnberg, 1993).

Fourth, we expected the measures of inner/outer hair cells and temporal fine structure to be related to speech understanding in noise, via relations to cognitive components (Stenfelt & Rönnberg, 2009).

Fifth, we expected that hearing sensitivity (i.e. thresholds) would relate to the cognitive functions, but less so than in previous work because the current test battery included on-line cognitive processing and excluded episodic memory functions (Rönnberg et al, 2011, 2014).

Methods

All tests were conducted by two clinical audiologists. In Table 1, we provide executive summary test descriptions and measurement objectives for all tests variables included. Table 2 gives the descriptive statistical information for each test. For detailed test descriptions, see Supplementary materials at http://tandfonline.com/doi/suppl.

Hearing-impaired participants

Two-hundred and fifteen experienced hearing aids users with bilateral, symmetrical mild to severe sensorineural HL were recruited from the patient population at the University Hospital of Linköping. Out of the 215 consenting participants, 15 dropped out at either Session two or three (see below). All participants fulfilled the following criteria: they were all bilaterally fitted with hearing aids and had used the aids for more than 1 year at the time of testing. Audiometric testing included ear-specific air-conduction and bone-conduction thresholds. Participants with a difference of more than 10 dB between the bone-conduction and air-conduction threshold at any two consecutive frequencies were not included in the study.

The 200 included participants were on average 61.0 years old ($SD = 8.4$, range: 33–80) and 86 were females. They had an average four-frequency pure-tone average (PTA4 at .5, 1, 2 and 4 kHz) in the better ear of 37.4 dB HL ($SD = 10.7$, range: 10–75). They reported having had hearing problems for an average of 14.8 years ($SD = 12.4$, range: 1.5–67) and they had used their hearing aids on average for 6.7 years ($SD = 6.6$, range: 1–45). They had on average 13.4 years of education ($SD = 3.4$, range: 6–25.5) and 168 were married or co-habiting. All participants gave informed consent. All participants had normal or corrected-to normal vision, and they were all native Swedish speakers.

Aetiology of the impairment varied in this sample. Therefore, inner and outer hair cell integrity and auditory processing abilities were measured to unveil the possible effects of different types of distorted auditory neural signals on the linguistic-cognitive level of cortex-based processing (see Stenfelt & Rönnberg, 2009). To study how inner ear damage is related to auditory and cognitive performance, DPOAE (Neely et al, 2003) were obtained to measure outer hair cell integrity, and a threshold-equalizing noise test with calibrations in dB HL, or TEN(HL) (Moore et al, 2004), was applied to estimate inner hair cell integrity.

Two experimental tests assessed the ability to detect spectro-temporal modulations (STM), which is predictive of speech in noise (Bernstein et al, 2013). The second test examines the ability to detect changes in temporal fine structure for low frequencies (TFS-LF, Hopkins & Moore, 2010; Neher et al, 2012). Finally, an unaided word recognition accuracy score (in quiet) was also collected using phonemically balanced (PB) word-lists (see Methods section in Supplementary materials for detail).

Results and discussion

Descriptive data

First, we present the descriptive data for all tests below (see Table 2 for the mean, *SD* and range for each variable). Where there are other published data collected under similar circumstances, we compare them with the current data set to check for similarities and replication. Note that the variables selected for the purpose of this overview of the database are main variables or composites for each test. Later reports will deal with the details of each test and with multivariate statistical modelling.

In Table 2, we have organized the data according to the order of the three classes of test variables presented in the Methods section, which is also the basis for subsequent factor analyses.

Hearing variables

The current sample is within the mild to severe hearing impairment range, measured with air conduction thresholds, here averaged over four frequencies (PTA4 = 0.5, 1, 2 and 4 kHz), with 39.09 dB HL ($SD = 10.88$ dB) for the left ear and 38.91 dB HL ($SD = 11.27$ dB) for the right ear. Bone conduction thresholds were on average 1.7–1.9 dB lower for the two sides, indicating that participants with conductive losses were successfully excluded from the study (see Figure 1 for audiometric thresholds across the whole frequency range measured).

The *TEN HL* was scored for number of dead regions identified. A masked threshold value of 15 dB SL or more was used here as the limit for an identified dead region. Four frequencies (0.5, 1, 2 and 4 kHz) were tested for each ear meaning that the possible scores ranges from 0 (no dead region) to 8 (dead regions at all tested frequencies). Most of the tested participants ($n = 155$, 77.1%) had no indication of any dead region (score 0), 30 participants had one dead region (14.9%) and 16 had two or more dead regions (8.0%).

The *DPOAEs* were scored as either present (SNR >= 6 dB) at some level (40–60 dB SPL) or absent (SNR < 6 dB) at all levels (40–60 dB SPL) for the three test frequencies (1, 2 and 4 kHz) and for each ear. This gives a maximum score of 6 (1 score given for presence of DPOAEs at each frequency and each ear and 0 for the absence) and the average score here was 2.12 ($SD = 1.14$). This means that the participants had, on an average, detectable OAEs at two of the six tested frequencies.

TFS-LF: The average result of the TFS-LF test was 59.3° ($SD = 75.13°$). This result is markedly larger than the data in

Table 1. Summary test descriptions and measurement objectives for all tests variables.

Name (abbreviation)	Description	Measurement objective
Hearing tests		
Pure-tone audiometry	Obtained air- and bone-conduction thresholds at 0.125 through 8 kHz	To measure hearing acuity
Threshold-equalizing noise – hearing level (TEN HL)	Obtained masked thresholds at 0.5, 1, 2 and 4 kHz	To identify dead regions of inner hair cells
Distortion product oto-acoustic emissions (DPOAE)	Assessed oto-acoustic emissions at 1, 2 and 4 kHz and at 40, 50 and 60 dB SPL	To measure integrity of outer hair cells
Temporal fine structure low frequency test (TSF-LF)	Judged which one of the two tones contained an interaural phase shift	To measure interaural phase difference thresholds for pure tones/general ability to use pitch information
Spectro-temporal modulation (STM) test	Judged which one of the two sound intervals contained spectro-temporal modulations	To measure modulation detection
Phonetically balanced (PB) word lists	Repeated verbally consonant-vowel-consonant monosyllabic words heard in quiet	To measure speech perception
Cognitive tests		
Phonological tests		
Consonant gating	Identified the consonants in vowel–consonant–vowel syllables	To assess individual skill in early identification of phonetic information
Vowel gating	Identified the vowels in consonant–vowel syllables	To assess individual skill in early identification of phonetic information
Vowel duration discrimination	Judged which one of the two sound tokens in each pair was longer	To assess individual ability to discriminate duration
Rhyme judgment	Judged whether or not two visually presented words rhymed	To assess phonological processing abilities
Semantic long-term memory access speed		
Physical matching (PM) test	Judged whether or not two visually presented letters were identical	To measure long-term memory access speed
Lexical decision making (LD) test	Judged whether a string of three letters constituted a real word or not	To measure lexical access speed
Working memory		
Non-word serial recall (NSR)	Repeated verbally lists of non-words shown on a screen	To measure phonological processing based on working memory for phonological information devoid of semantic information
Reading span test (RST)	Judged whether or not each visually presented sentence was sensible, and after a sequence of sentences, recalled either the first or the last word of all sentences in the sequence	To measure working memory, a test taxing memory storage and processing simultaneously
Semantic Word-Pair Test (SWPST)	Judged which one of the two visually presented words (word-pairs) was a living object, and after a sequence of word-pairs, recalled either the first or the second words of all word-pairs	To measure working memory that does not include syntactic elements in the processing and storage components
Visuo-spatial working memory test (VSWM)	Judged whether the two ellipsoid shapes visually presented in one of the squares in a 5×5 grid were identical, and after a sequence, recalled where in the grid the ellipsoid-pairs were presented	To measure non-verbal working memory
Executive and inference-making functions		
Shifting test	Specified whether a number-letter pair contained an odd or even number in half of the trials and contained a capital or small letter in the other half of the trials	To measure shifting ability
Updating test	Recalled the last word presented in 4 out of 6 pre-defined categories	To measure updating ability
Inhibition test	Responded to any digit presented on a screen except when digit 3 appeared	To measure the ability to deliberate responses
Text reception threshold (TRT)	Repeated orally visually presented sentences, masked by bars	To measure reception threshold of masked text
Sentence completion test (SCT)	Filled in the missing words in each incomplete sentence	To assess context-bound verbal inference-making ability
Logical Inference-making test (LIT)	Answered to a question with help of two statements presented on screen simultaneously	To measure text-based inference-making ability

(continued)

Table 1. Continued

Name (abbreviation)	Description	Measurement objective
General cognitive functioning		
Mini mental state examination (MMSE)	Eleven questions probing different mental or cognitive functions such as orientation to time and place, immediate recall, and attention	A screening test for dementia
Rapid automatized naming (RAN)	Named the shapes, colours, or shapes and colours of visual stimuli	A quick test of cognitive speed and dementia
Raven	Chose one out of the 6 alternatives to complete an overall visual pattern	To measure non-verbal reasoning ability (fluid intelligence)
Outcome tests		
Swedish Hearing In Noise Test (HINT)	Repeated verbally sentences heard in noise	To measure speech recognition in noise threshold (50%) in noise
Hagerman sentences	Repeated verbally sentences heard in different conditions of noise and noise reduction settings	To measure speech recognition in noise threshold (50% and 80%) in noise
Samuelsson & Rönnberg	Repeated verbally sentences heard in noise in auditory only and audiovisual modalities, with or without contextual cues	To measure contextually cued speech recognition in noise
Auditory interference making (AIM)	Answered to a text-based question with help of a statement presented auditorily in noise	A text- and auditory-based test, measuring inference-making ability
Speech, Spatial and Qualities of hearing scale	Self-reported aided performance and abilities in speech perception, spatial hearing and qualities of hearing (50 questions in total)	Self-assessment of speech perception, spatial hearing and qualities of sound and hearing

Hopkins and Moore (2011) where they report an average TFS-LF of just below 20° in a group of hearing impaired participants. Those participants had PTA4s that were lower than in the present study (PTA4, right ear: 31.2 dB HL), but the average age was similar to our study (62.8 years). Consequently, our participants seemed to have a significantly worse ability to process low-frequency fine structure information than people with normal hearing or persons with slightly milder HL. One possible reason for the higher means here than in the Hopkins and Moore (2011) study is that the distribution of the variable is rather skewed. This has larger effects for larger sample sizes since the extreme values could be so much higher. In our data, 163 participants had measures with the normal procedure and the rest had measures with the non-adaptive percent-correct procedure described in the method section. The participants in the latter group had much higher TFS values, indicating that the standard procedure for this calculation might need a revision. The first group had a mean of 29 but a median of 22 which indicates that the distribution is somewhat skewed even in this group. Twenty-two is relatively close to the Hopkins and Moore mean so we conclude that the data here are in line with Hopkins and Moore (2011).

STM: The modulation depth was around −3 dB SNR in the current study and around −9 dB SNR in the Bernstein et al (2013) study. However, that study did not use a low-pass filter, which we did (the low-pass filter was 2 kHz, which could explain at least some of the difference). Rather than employing a broadband carrier in the current study, we used the low-pass filter at 2 kHz for two reasons. First, Mehraei et al (2014) investigated the effects of carrier-frequency on the relationship between STM sensitivity and speech-reception performance in noise and found that the relationship was strongest with a low-frequency STM carrier. Second, the goal of the study was to identify a psychophysical test that could account for variance in speech-performance not accounted for by the audiogram, and the high-frequency components of the audiogram (i.e. 2 kHz or greater) that are typically most highly correlated with speech perception (see also Bernstein et al, 2015).

The *PB word test* scores were at 95% ($SD = 5.92\%$) showing a high performance on word recognition in quiet.

Cognitive variables
Some of the test parameters presented below are collapsed into one main variable and can be directly compared with previous data, whereas other experimental tests that consist of several manipulated variables, especially those which are relatively new, were analyzed with *t*-tests or ANOVAs for future reference.

PHONOLOGICAL TESTS

Consonant gating: The mean IP for correct consonants for A presentation was 288 ms ($SD = 102$ ms) and, for AV presentation, it was 196 ms ($SD = 54$ ms), $t(198) = 13.64$, $p < 0.001$, $d = 0.97$, showing that AV identification occurs earlier than A identification. The present results replicate earlier research (Munhall & Tohkura, 1998; Moradi et al, 2014a,b) reporting a mean percentage correct for correct consonants for A presentation to be 81% ($SD = 22\%$, range 20–100%) and for AV presentation 96% ($SD = 9\%$, range 60–100%), $t(199) = 9.67$, $p < 0.001$, $d = 0.68$, showing also better accuracy for AV identification.

Vowel gating task: The mean IP for entirely correct vowels was, for A presentation, 222 ms ($SD = 85$ ms), and, for AV presentation, 208 ms ($SD = 81$ ms), $t(198) = 2.60$, $p = 0.01$, $d = 0.18$, thus showing a small but significant benefit of AV vowel identification in terms of identification speed. The mean percentage correct for A presentation was 71% ($SD = 21\%$, range 20–100%), and, for AV presentation, it was 77% ($SD = 20\%$, range 20–100%), $t(199) = 4.20$, $p < 0.001$, $d = 0.30$, meaning that AV identification was more accurate.

Table 2. Summary of means and SDs for all the main dependent variables used in the factor analyses.

|		*M*	*SD*	*Range*
Hearing variables				
Air-conduction PTA4 (left) (dB HL)		39.09	10.88	11.25–75.00
Air-conduction PTA4 (right) (dB HL)		38.91	11.27	10.00–82.50
Bone-conduction PTA4 (left) (dB HL)		37.11	10.07	8.75–63.75
Bone-conduction PTA4 (right) (dB HL)		37.17	10.21	10.00–70.00
Threshold-Equalizing Noise and Hearing Level		0.39	0.90	0–7
(TEN HL at 2 and 4 kHz in both ears, number of dead regions)				
Distortion Product Oto-Acoustic Emissions		2.12	1.14	0–5
(DPOAEs at 1, 2 and 4 kHz and at all levels in both ears, number of emissions present)				
Temporal Fine Structure sensitivity (TFS LF)		59.30	75.13	5.30–487.96
STM_threshold1_left (dB SNR)		−2.71	4.12	−14.33 to 0.97
STM_threshold2_left		−2.95	4.16	−13.00 to 0.93
STM_threshold3_left		−2.77	3.87	−13.33 to 0.90
STM_threshold1_right		−3.77	4.26	−14.67 to 0.97
STM_threshold2_right		−3.77	4.20	−15.00 to 0.96
STM_threshold3_right		−3.91	4.45	−16.00 to 0.97
Phonetically Balanced word test (PB, % correct)		94.75	5.92	68–100
Cognitive variables				
Consonant gating (auditory) (average IP, in ms)		289	105	96–640
Vowel gating (auditory) (average IP, in ms)		223	86	112–376
Consonant gating (audiovisual) (average IP, in ms)		196	54	48–456
Vowel gating (audiovisual) (average IP, in ms)		208	81	64–432
Vowel duration discrimination (auditory, errors)		7.17	4.63	0.00–21.00
Vowel duration discrimination (audiovisual, errors)		7.09	4.93	0.00–26.00
Rhyme judgment (% correct)		87.27	11.20	47–100
Rhyme judgment (response time, in ms)		1685	404	985–3204
Physical matching (PM, response time, in ms)		976	207	552–1575
Lexical decision making (LD, response time, in ms)		969	187	652–1675
Non-word serial recall (NSR, max score = 42)		24.33	5.62	10–39
Reading span (RST, max score = 28)		16.07	3.83	5–26
Semantic word-pair span test (SWPST, max score = 42)		17.49	5.39	3–38
Visuo-spatial working memory (VSWM, max score = 42)		29.34	6.10	9–42
Shifting cost (in ms)		760	592	−837 to 2982
Updating task (max score = 16)		10.15	2.87	0–16
Inhibition task (error rates)		1.82	2.04	0–17
Text Reception Threshold (TRT, % unmasked text)		55.23	5.32	39.67–77.23
Sentence completion (SCT, % correct)		83.25	14.98	28.95–100.00
Logical Inference-making Test (LIT, % correct)		64.34	16.80	12–88
Mini Mental Test (max score = 30)		28.63	1.50	20–30
Rapid Automatised Naming (difference, in sec)		5.36	6.60	−13.40 to 32.85
Rapid Automatised Naming (RANCS, average response time, in sec)		60.35	10.95	37.80–110.63
Raven total score (max score = 24)		15.47	4.66	2–24
Outcome variables				
Hearing-In-Noise Test (HINT, dB SNR)		−1.43	1.85	−4.82 to 12.00
Hagerman test (dB SNR)				
Stationary noise				
Linear amplification, no noise reduction	50%	−6.23	1.59	−10.78 to −1.89
	80%	−1.93	2.95	−8.00 to 9.56
Linear amplification, with noise reduction	50%	−11.22	1.66	−15.11 to −3.22
	80%	−5.67	3.12	−10.67 to 5.22
Fast-acting compression, no noise reduction	50%	−5.91	1.61	−10.00 to −1.67
	80%	−0.48	3.58	−7.11 to 13.44
Four-talker babble				
Linear amplification, no noise reduction	50%	−0.94	1.69	−8.11 to 3.22
	80%	3.83	2.84	−1.78 to 12.89
Linear amplification, with noise reduction	50%	−7.93	1.57	−12.22 to −0.89
	80%	−2.33	3.10	−7.78 to 9.22
Fast-acting compression, no noise reduction	50%	−0.31	1.88	−6.78 to 6.11
	80%	4.88	2.87	−0.44 to 14.00
Samuelsson & Rönnberg (% correct)				
Auditory, no contextual cues		22.99	16.83	0–83
Auditory, with contextual cues		26.25	17.63	0–96
Audiovisual, no contextual cues		59.04	19.28	0–96
Audiovisual, with contextual cues		61.85	18.83	0–93
Auditory Inference-Making (AIM, max = 16 correct)		70.97	17.96	25–100
Speech, Spatial and Qualities of hearing scale (SSQ, max = 500)		324.66	78.21	137.23–493.15
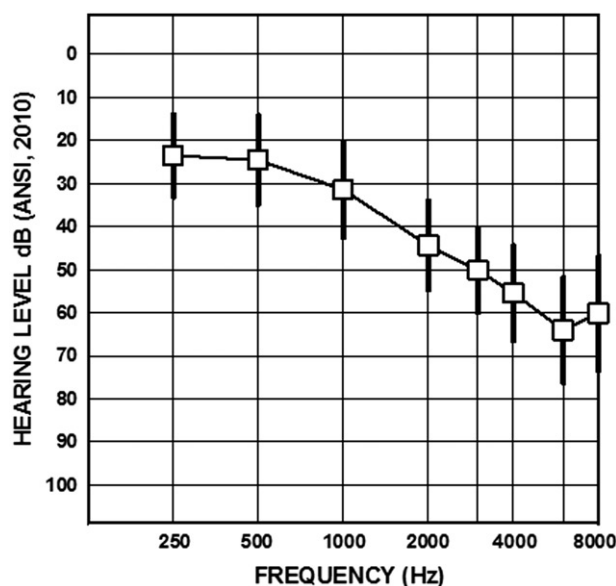
Figure 1. Hearing thresholds, means and SDs for the entire frequency range measured for the 200 hearing-impaired participants.

Vowel duration discrimination task: For A presentation, the mean was 7.18 errors ($SD = 4.62$ errors, range 0–20 errors), while AV presentation resulted in 7.05 errors ($SD = 4.77$ errors, range 0–20 errors), $t(198) = 0.39$, $p = 0.70$, thus revealing no significant benefit of AV over A presentation.

The *rhyme judgment test* is a phonological representation test (Lyxell et al, 1996; Classon et al, 2013), where the matching and mismatching conditions are not analysed separately in this overview paper. Since most conditions produce high proportions correct in this sample (i.e. 87%) compared with samples with more pronounced hearing impairment (e.g. Lyxell et al, 1996; Classon et al, 2013), we here focus on the latency data for correct responses (showing a mean of 1685 ms, $SD = 404$), which is in line with previous studies (Lyxell et al, 1996, 1998).

SEMANTIC LTM ACCESS SPEED
The *PM* and *LD* tasks replicate very closely the results of previous independent studies (i.e. with access speeds just below one second; cf. Perfetti, 1983; Hunt, 1985; Rönnberg, 1990). There seems to be good agreement across studies for our computer-based applications of the tasks (e.g. Rönnberg et al, 1989; Rönnberg, 1990), with the current sample being around 0.1 s slower than the earlier samples, but the current sample is also around 10 years older.

WORKING MEMORY
NSR: The level of performance ($24/42 = 57\%$) is comparable with other independent data on adults (Majerus & van der Linden, 2010).

RST: The RST has been used in many studies from our research group and the average score from all these studies is just below 45% for participants with hearing loss and long versions of the test (cf. Besser et al, 2013; Ng et al, 2014). When a short version of the task is used (with 24 or 28 items), the accuracy goes up 10–15% percent (see Hua et al, 2014; Ng et al, 2014), which is quite comparable with our 57% performance in the current sample (16 out of

max = 28). Other independent labs show comparable scores with the long versions (e.g. Besser et al, 2013; Keidser et al, 2015; Souza et al, 2015a).

SWPST: Since the SWPST is lacking the grammatical component that is included in the RST, but similar to the RST in terms of a semantic processing task and post-cuing of recall, we expected performance levels to be lower than for the RST, which was found to be the case (41% vs. 57%).

VSWM: The data (29/42, 69% in total score) suggest a span size of close to 4, which is quite comparable with the data reported in Olsson and Poom (2005).

EXECUTIVE AND INFERENCE-MAKING TASKS
Shifting: The shifting cost was 760 ms, which is slightly greater than in a younger hearing-impaired sample (Hua et al, 2014).

Updating: The current sample performed at a 63% level (i.e. 10/16, $SD = 2.87$), which again would be compatible with the 70% obtained in the Hua et al (2014) study.

Inhibition: The error rate in the inhibition task was 3.1 in the Hua et al (2014) study and in the current sample it was 1.72 ($SD = 2.04$), which actually is relatively low, but still within 1 SD compared with the Hua et al (2014) study.

TRT: The current mean value in percentage of unmasked text, i.e. 53%, to reach the criterion of 50% correct responses, agrees very well with previous studies. These showed that the average TRT (in percentage unmasked text) is around 54% (Zekveld et al, 2007; Kramer et al, 2009) for younger participants (mean age around 35 years) and around 56% for somewhat older participants (mean age around 45 years, in Besser et al, 2012).

SCT: In a similar test version, Andersson et al (2001) found that mean SCT performance was 71%, but that level of performance applied to a sample with more profound hearing impairment. The current high performance level (0.83) is still within one SD of the Andersson et al. studies.

LIT: The average score was 64.50, with an SD of 16.81.

GENERAL COGNITIVE FUNCTIONING
Mini Mental State Examination Test (*MMSE*): The current sample scored on average 28.4/30 on the MMSE. This average score is similar to a previous sample of 160 hearing-aid wearers (Rönnberg et al, 2011), who scored 27.3/30, thus within 1 SD of the current sample. Only 16 participants scored below 27.

Rapid Automatised Naming test (*RAN*) *Test*: The RAN time for the colour and form naming combined (RANCS) was 60 s. This result is comparable with other samples (Wiig & Al-Halees, 2013). The difference score between RANCS and the sum of RANC + RANS is also positive and similar in magnitude to previous research (Warkentin et al, 2005; Wiig et al, 2010).

Raven test: The Raven test score on sets D and E of Raven was 64%, and it was 81% on set D. These results are very close to independent and recent data by Kilman et al (2015), where performance for a slightly younger adult hearing impaired sample was 83% for set D.

Outcome variables
THE SWEDISH HINT
The 50% threshold was −1.43 ($SD = 1.85$), which is comparable with an average of −1.9 ($SD = 2.2$) in a study by Kilman et al (2015) on another sample of hearing impaired participants.
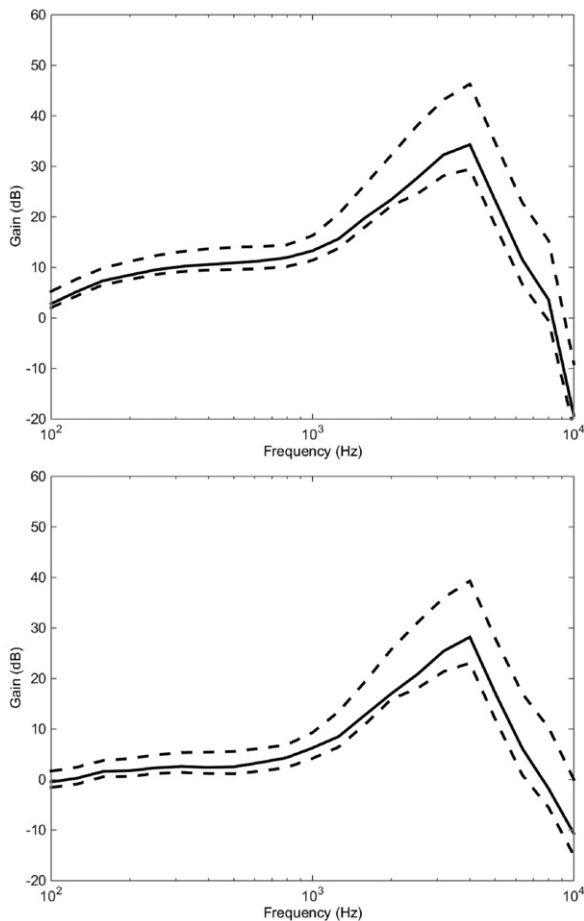
Figure 2. Insertion gain response curves for the linear amplifications (upper panel) and amplification with fast-acting compression (lower panel). Curves in solid lines represent insertion gain based on the average hearing thresholds at 125 through 8000 Hz. Curves in dotted lines represent insertion gain response based on hearing thresholds one standard deviation above/below average.

THE HAGERMAN TEST CONDITIONS

To give an overview of the test results, an analysis of variance (ANOVA) with three within-subject factors, background noise (unmodulated stationary noise, 4-talker babble), signal processing (linear amplification with NR, linear amplification without NR, fast-acting compression without NR) and SNR (50% and 80%) was performed (overall result $= -2.87$ dB SNR ($SD = 1.77$), but see Table 2 for means in each condition, and Figure 2 for insertion gain response curves). Overall, there was a main effect of SNR, indicating that the average SNR obtained at 50% was lower than that at 80%, $F(1, 199) = 2295.55$, $p < 0.001$ (e.g. Foo et al, 2007). The main effect of background noise was significant, $F(1, 199) = 3864.86$, $p < 0.001$, demonstrating that 4-talker babble had a stronger masking effect than stationary noise. The magnitude of this effect is comparable with that in previous studies (cf. Figure 3, Wang et al, 2009; Ng et al, 2013b). There was also a significant main effect of signal processing, $F(2, 398) = 2233.67$, $p < 0.001$. The post hoc *t*-tests (Bonferroni adjusted for multiple comparisons) showed that test performance with linear amplification with NR was better (i.e. with a lower average SNR) than test performance with the linear amplification without NR ($p < 0.001$) (Wang et al, 2009),

which again was better than the performance found in the fast-acting compression without NR condition ($p < 0.001$). In other words, linear amplification generally resulted in better speech recognition performance than non-linear amplification with fast-acting compression.

Compared with the original test results in a study by Hagerman and Kinnefors (1995), the current sample produced somewhat flatter slopes (ranging from 5.33 to 6.98%/dB in the six test conditions). Slightly worse hearing sensitivity in the sample tested in the present study (average PTA4 $= 39$ dB HL vs. 34 dB HL for the sample in the study of Hagerman and Kinnefors) and different configurations of HL (*slight* sloping HL in the present study versus sloping HL in the Hagerman and Kinnefors study) could have contributed to flatter psychometric functions (see e.g. Takahashi & Bacon, 1992). As a final general observation, the standard deviations (SDs) in the present study were larger in the harder 80% condition (SDs from 2.95 to 3.58) than in the 50% condition (SDs from 1.59 to 1.88), which makes sense from the perspective of individual differences that play out with the higher cognitive load in the 80% condition.

THE SAMUELSSON & RÖNNBERG SENTENCES

For reasons of simplicity in this overall analysis, we focused on the context and modality manipulations only. The modality manipulation was not present in the original Samuelsson and Rönnberg (1993) study, as the study focused on lip-reading only. An ANOVA with two within-subject variables, namely context (with, without) and modality (auditory, audiovisual), was performed. As was the case in the original experiment, we observed a main effect of context, $F(1, 199) = 17.16$, $p < 0.001$. The main effect of modality was also significant, $F(1, 199) = 989.61$, $p < 0.001$, such that test performance in the audiovisual modality was better than that in the auditory modality. No significant interaction was present.

We did not analyse the effects of sentence type (typical vs. atypical), (abstract vs. detailed), temporal order (early or late event in the script) and type of script (three scripts) in this overall context, but all data are retained at that level of scoring for future reports.

THE AIM

The average accuracy in terms of percent correct was 71% and the average reaction times were 6.68 s for the AIM.

THE SSQ

The total score used for the present overall purpose was 324 out of 500. These results are comparable (within 1 SD) to previous studies on experienced hearing aid users (e.g. Gatehouse & Noble, 2004; Ng et al, 2013a).

Factor analyses

First, all variables were investigated for potential outliers. However, we believe that it is important to reflect as much variability as possible in this initial n200 paper. Therefore, we used a liberal criterion: Only values more than four standard deviations from the mean were removed. This resulted in the removal of four data points from the HINT, and one data point from the MMSE and inhibition tests, respectively. All analyses were first conducted for the results of the participants who had no missing data and then re-computed with imputed values for those with missing data. Imputation was
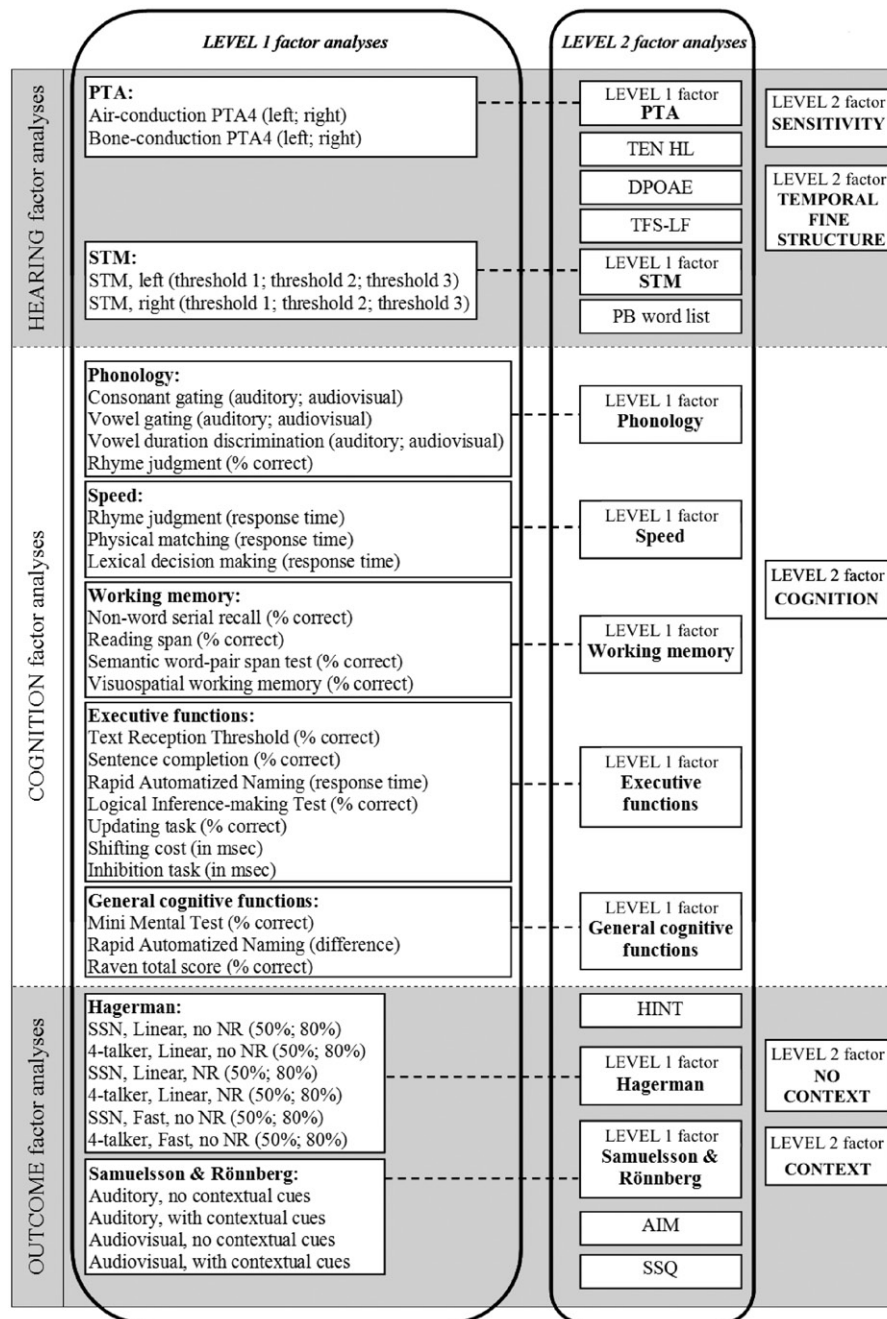
Figure 3. Overview of the exploratory factor analyses.

done using the data imputation module in the AMOS software version 23 for each factor separately. No differences in the pattern of results were found between the analyses with or without imputed data and, therefore, only the analyses on the imputed data are reported in this article.

Data from the tests were analysed with exploratory factor analyses using maximum likelihood extraction and direct oblimin rotation using SPSS version 23 (see Figure 3 for an overview of the steps involved in the factor analyses). Factors were saved using the regression method. The factor analyses followed the a priori conceptualizations and categorizations of the tests included in the overall battery. For tests with many variables, we computed what is

here called LEVEL 1 factor analyses to determine one score per test which then were used in the next level of factor analyses. LEVEL 1 factor analyses were computed for the following tests including several sub-scores: Audiograms, STM sensitivity, Hagerman sentences, and Samuelsson & Rönnberg sentences. LEVEL 1 factor analyses were also computed for the cognitive sub-functions Phonology, Semantic LTM access speed, WM, Executive and Inference-making functions, and General Cognitive Functioning. After the LEVEL 1 factor analyses, the individual factor scores were saved for the next level. In the LEVEL 2 factor analyses, HEARING, COGNITION and speech understanding OUTCOMES were analysed separately and here the number of factors extracted

Table 3. Summary of all factor analyses.

		KMO	Explained variance (%)
HEARING factor analyses			
LEVEL 1			
	PTA	0.76	94.2
	STM	0.87	73.2
LEVEL 2			
	Hearing global	0.57	32.1
COGNITION factor analyses			
LEVEL 1			
	Phonology	0.60	34.3
	Speed	0.62	70.6
	Working memory	0.74	53.0
	Executive functions	0.68	30.8
	General Cog. Function	0.50	43.7
LEVEL 2			
	Cognition global	0.76	51.0
OUTCOME factor analyses			
LEVEL 1			
	Hagerman	0.91	57.1
	Samuelsson & Rönnberg	0.68	66.4
LEVEL 2			
	Outcome global	0.52	43.8

Table 4. Summary of LEVEL 2 Factor analyses. The scale has been reversed for some variables (marked with *) such that higher values on all variables represent better HEARING, COGNITION, and speech in noise OUTCOME abilities. This was done to make the interpretations of the factors easier.

	Factor	
	SENSITIVITY	TEMPORAL FINE STRUC
HEARING factor analyses		
LEVEL 1 Factor PTA*	0.91	0.05
TEN HL*	0.06	0.16
DPOAE*	−0.29	0.03
TFS-LF*	−0.29	0.92
LEVEL 1 Factor STM*	0.10	0.48
PB word test	0.37	0.34
COGNITION factor analyses	COGNITION	
LEVEL 1 Factor Phonology*	0.59	
LEVEL 1 Factor Speed*	0.53	
LEVEL 1 Factor Working Memory	0.63	
LEVEL 1 Factor Executive Functions*	0.92	
LEVEL 1 Factor General Cog. Func.	0.43	
OUTCOME factor analyses	CONTEXT	NO CONTEXT
HINT*	0.87	0.32
LEVEL 1 Factor Hagerman*	0.25	0.83
LEVEL 1 Factor Samuelsson & Rönnberg	−0.52	0.08
Hannon & Daneman	−0.05	0.40
SSQ	−0.02	0.41

was determined by an Eigenvalue larger than 1 (see Table 4). Finally, a correlation matrix was constructed based on the factor scores of the LEVEL 2 factors in the overall matrix (see Tables 5 and 6).

The overall results of all factor analyses are seen in Table 3. Data were promising for the factor analyses as indicated by the fact

Table 5. Correlations among the LEVEL 2 components.

Variables	SENSITIVITY	TEMPORAL	CONTEXT	NO CONT.
COGNITION	0.17	0.37	0.20	0.44
SENSITIVITY		0.32	0.24	0.44
TEMPORAL			0.24	0.45
CONTEXT				0.36

All correlations are significant, the COGNITION-SENSITIVITY correlation is significant at $p < 0.05$ and the remaining correlations are significant at $p < 0.001$.

Table 6. Correlations among the LEVEL 2 components, with age partialled out.

Variables	SENSITIVITY	TEMPORAL	CONTEXT	NO CONT.
COGNITION	0.13	0.30	0.16	0.37
SENSITIVITY		0.29	0.22	0.42
TEMPORAL			0.20	0.38
CONTEXT				0.33

All but the COGNITION–SENSITIVITY correlation are significant; the 0.16 coefficient is significant at $p < 0.05$ level; the 0.20–0.22 coefficients are significant at $p < 0.01$, and the remaining coefficients are significant at $p < 0.001$.

that all analyses had significant results on Bartlett's test of sphericity (all $ps < 0.001$) and most Kaiser–Meyer–Olkin measure (KMO) values were 0.60 or higher. The analyses of *Executive and inference-making* tests and *Phonological processing mechanisms* (see under Cognitive Mechanisms and ELU for tests included under these conceptual headings) would have resulted in two and three factors, respectively, meeting the Eigenvalue criteria, but since we used the a priori conceptualization of one factor per sub-function, only 31% and 34% of the variance was explained by the first factor in those cases. The *General Cognitive Functioning* factor also explained a relatively small amount of variance, which is reasonable since the sample is relatively well functioning at this point in time.

For the remaining LEVEL 1 cases, the factor solutions were clear-cut and strong (see Table 3). All factor analyses are discussed in more detail below. For a *summary* of all LEVEL 1 factor analyses, again see Table 3. For *the interested reader,* each of the LEVEL 1 factor analyses with factor loadings is presented in the Supplementary materials (in Tables 1–3).

HEARING
LEVEL 1: The first large class of variables is based on the hearing tests. Here, we computed one separate factor analysis for the PTA, based on air- and bone-conduction thresholds, for the left and the right ear, giving four parameters. Each parameter was pooled over the values for 0.5, 1, 2 and 4 kHz. The results show unequivocally that the four parameters load on one factor with factor loadings of 0.93 and higher (denoted PTA). We also computed a separate factor analysis of the STM test based on the three frequencies used, for the left and the right ear, giving six parameters. The analysis resulted in a one-factor solution, with factor loadings of 0.78 and higher (denoted STM). These two LEVEL 1 analyses thus indicate that the test variables converge on the same hearing mechanism for each test in a very clear-cut way (see Table 1 in Supplementary materials).

LEVEL 2: As a LEVEL 2 factor analysis of the HEARING variables, the factor scores from LEVEL 1 for PTA and STM

(which best represent these tests) were further factor analysed together with the remaining HEARING parameters: TEN HL, DPOAE, TFS LF and PB. A two-factor solution was obtained and only factor loadings above .40 will be interpreted (see Table 4). It is clear that the PTA loads heavily (0.91) on factor 1 (here labelled SENSITIVITY), the TFS-LF and STM tests load on factor 2, here labelled TEMPORAL FINE STRUCTURE (cf. Bernstein et al, 2015, submitted). The inner (TEN HL) and outer hair cell measures (DPOAE) do not seem to build on any of the other two factors (the factor loading is lower than .40 for each of the two tests, respectively), at least not with the current pooled measures.

COGNITION

LEVEL 1 factor analyses were run separately for the *Phonological tests* (i.e. the four summary variables of gating, i.e. the auditory or audiovisual conditions for vowels and consonants, rhyme accuracy and the auditory/audiovisual vowel durations), *Long-term Memory Access* indices (i.e. PM speed, LD speed, Rhyme reaction time, and the RANCS), *the Working memory tests* (i.e. NSR, RST, SWPST and VSWM span tests), the *Executive and Inference-making tests* (i.e. Shifting, Updating, Inhibition, TRT, SCT and LIT) and finally a separate factor analysis on the *General Cognitive Functioning* tests (i.e. the MMSE, RAN diff and Raven tests). See Table 2 in Supplementary materials for details of factor loadings.

The results showed that the *Phonological* tests yielded a one-factor solution where only the vowel gating conditions (A/AV) load above the .40 traditional criterion (AV = 0.73 and A = 0.69). Therefore, vowel processing (CV syllabic format in the test) is presumably the most indicative of the syllabic RAMBPHO processing for this hearing-impaired sample. The results are in line with previous research attesting to the importance for participants with hearing loss to be able to perceive vowels (Richie & Kewley-Port, 2008).

The *Long-term Memory Access* one-factor solution resulted in factor loadings above 0.58, for all three tests, with LD speed having the highest factor loading (1.00), hence being in line with a conceptualization of a more general speed factor for Long-Term Memory (e.g. Salthouse, 2000).

The *Working Memory* factor also produced an interesting domain-general factor across the four tests, with loadings between 0.57 and 0.68 (see Sörqvist et al, 2012, for comparable domain-general composites).

For the *Executive and Inference-making* factor the TRT, SC and RANC came out with reasonable loadings, the TRT and SCT having the highest (0.76 and −0.70, respectively). It thus seems like they both draw on some general linguistic closure ability (Besser et al, 2013).

The *General Cognitive Functioning* tests resulted in one factor with the MMSE predictably being the test with the highest factor load 1.00.

LEVEL 2: Finally, we computed a LEVEL 2 factor analysis and found an interesting one-factor solution with all LEVEL 1 factors loading higher than 0.43, and the *Executive and Inference-making* factor loading the highest (0.92), and with the LEVEL 1 Working memory factor loading the second highest (−0.63) (see Table 4). Interestingly, both these factor constructs belong to the explicit part of the ELU model (Rönnberg et al, 2011, 2013), which in turn suggests that the global COGNITION factor should be interpreted from that perspective (see under Correlations among the LEVEL 2 factors, Tables 5 and 6).

OUTCOMES

LEVEL 1: In the LEVEL 1 analyses, we tested whether all 12 Hagerman conditions loaded on one factor only. We found this to be the case, with loadings from 0.57 to 0.85 (see Table 3, Supplementary materials). Similarly, we tested whether the Samuelsson and Rönnberg main conditions (with/without context, combined with the auditory/audiovisual test modalities) also loaded on one single factor, and again, this was the case, with factor loadings from 0.56 to 0.89. At a general level, this is very reassuring because the basic mechanisms that each of the two tests measures seem reliable and valid across conditions (see Table 3 in Supplementary materials).

LEVEL 2: Our aim was to test the hypothesis that the OUTCOME variables tap into two conceptually different categories of OUTCOME variables, that is, the context-free and stereotypical Hagerman sentences and the more context-bound and naturalistic HINT and Samuelsson and Rönnberg sentences. To accomplish this, we computed a LEVEL 2 analysis together with the remaining OUTCOME variables (SSQ, the HINT and the AIM). According to our prediction, the analysis resulted in two factors, with the HINT and the Samuelsson & Rönnberg sentences loading on the first factor (here denoted the CONTEXT outcome). The Hagerman, the AIM and SSQ loaded on the second factor (here denoted NO CONTEXT, because the Hagerman sentences constituted the variable that loaded the highest on this second factor, and, therefore, must determine the interpretation of this factor; see Table 4). This means that the hypothesis was confirmed in the sense that the Hagerman sentences tap an outcome dimension that is different from that tapped by the HINT and Samuelsson and Rönnberg materials (cf. Foo et al, 2007; Rudner et al, 2009, 2011). Furthermore, this finding is vital to future studies of intervention or rehabilitation outcomes because the most sensitive OUTCOME seems to be the NO CONTEXT type of materials. It is interesting that the AIM also loaded on this factor, but in the same way as for the LIT, it taps into logical thinking rather than the use of context for its solution. SSQ total loads on the Hagerman factor as well. However, we refrain from interpretation as the factor loading for the SSQ was very low and a future study will analyze how the subscales relate to the CONTEXT–NO CONTEXT outcomes.

In all, the two expectations regarding factorial structure were confirmed (see also Figure 3): first, the LEVEL 2 analysis revealed that a global COGNITION factor could be established, and that the explicit functions (executive and working memory) that have proven to be good predictors of speech understanding under adverse conditions also demonstrated the highest loadings on this ELU-factor. Second, the prediction of a division of the HEARING variables into threshold (i.e. SENSITIVITY) and suprathreshold factors (i.e., TEMPORAL FINE STRUCTURE) was also confirmed. Although not explicitly predicted, neither the cochlear measures of inner (TEN HL) and outer hair cells (DPOAE) loaded on any of the two hearing factors nor did they contribute to a separate third factor. Future studies will go deeper into potential subgroups of inner/outer hair cell damage.

With respect to the COGNITION factor, further evidence for the argument that WMC and Executive/inference-making components play important roles in the explicit part of the ELU-model can be found in the results of studies that have combined the executive component (especially inhibition) and WMC in one test. One such example is the size comparison span test (SIC span), which, in some cases, has been shown to be a better predictor of speech perception than the RST (Rönnberg et al, 2011; Sörqvist & Rönnberg, 2012).

The same logic applies to the TRT test (Besser et al, 2013), which was the test with the highest load on the Executive-Inference-making factor in the LEVEL 1 analysis. This research track, where new tests are based on theoretically motivated components and then combined together, seems to be an important area on which future studies should focus.

Correlations among the LEVEL 2 factors

Pearson correlations were used to analyse the relations between the LEVEL 2 factors. Differences between correlations were analysed using the Fisher r-to-z transformation. As shown in Table 5, the global COGNITION factor is positively and significantly related to the NO CONTEXT OUTCOME factor, and also to the CONTEXT OUTCOME factor, albeit it to a lesser degree. The difference between the strengths of the correlation coefficients was significant ($Z = 3.12$, $p < 0.01$, one-tailed). This pattern of data generally replicates that found in a number of independent studies, both from within our laboratory (Lunner, 2003; Foo et al, 2007; Rudner et al, 2009, 2011; Zekveld et al, 2013) and from other independent laboratories (e.g., Akeroyd, 2008; Arehart et al, 2013; Besser et al, 2013; Souza & Sirow, 2014; Souza et al, 2015a,b, see also Füllgrabe et al, 2015).

The significant difference in the strength of the relationships supports the hypothesis that when speech processing in noise is contextually driven, fewer explicit cognitive resources are required to resolve ambiguity than when contextual information is lacking (Moradi et al, 2013; Meister et al, 2016). Other independent studies suggest that the strength of correlations may vary depending on the type of WMC test (Sörqvist & Rönnberg, 2012; Smith & Pichora-Fuller, 2015) and the complexity of sentence materials (Heinrich et al, 2015; DeCaro et al, 2016). The strength of the current study is the sample size, and the fact that these correlations are based on abstract, general factors, which in turn are based on several test conditions (LEVEL 1) and tests (LEVEL 2). Even after statistically removing the effects of chronological age, the COGNITION–NO CONTEXT association and the COGNITION–CONTEXT associations remain significant (see Table 6). This allows us to demonstrate that the strength of correlations between cognition and speech recognition in noise varies with context and knowledge. Thus, the third prediction was confirmed, a finding further supported by the final multiple regression analyses.

The TEMPORAL FINE STRUCTURE factor was positively and significantly related to the global COGNITION factor (see Tables 5 and 6). The existence of a relationship between temporal fine structure and cognition has been the subject of relatively little research, but has been reported in recent studies by Lunner et al (2012), Neher et al (2013) and Füllgrabe et al (2015), and replicated in this study. This is in line with the general fourth prediction by Stenfelt and Rönnberg (2009) about how distorted neural output from the cochlea and brainstem may affect linguistic and cognitive functions at the cortical level. However, the above studies have not pinpointed exact mechanisms as to why this is the case. How the DPOAE and TEN HL parameters relate to cognitive subfunctions such as phonology (Stenfelt & Rönnberg, 2009) has also yet to be determined.

One possible cognitive hearing science interpretation of this relationship relates to the cognitive task demands of the STM and TFS-LF tests. In both cases, sounds have to be kept in mind before internal temporal fine structure comparisons and decisions are made: that is, there is also an *auditory memory component* involved here. This memory component may well relate to some of the core components of the ELU-system (i.e. Phonology (RAMBPHO), which is a bottleneck of WM; parts of the Speed component (especially rhyme speed), but certainly also WM per se).

Another alternative interpretation relates to a general temporal processing ability that may support all components in the COGNITION factor (cf. Pichora-Fuller, 2003). This kind of reasoning is based on the fact that fine structure is dependent on the resolution in coding of the supra-threshold spectro-temporal speech sound patterns in the cochlea as well as from the auditory nerve and upwards. This may in turn be related to the SENSITIVITY aspect of hearing impairment. Both aspects are dependent on cochlear integrity. We also found that TEMPORAL FINE STRUCTURE was significantly and positively correlated with SENSITIVITY, even after partialling out for age (Tables 5 and 6). Temporal fine structure information can be important for pitch perception and for the ability to perceive speech in the dips of fluctuating background noise (Quin & Oxenham, 2003; Moore, 2008), the latter ability also being modulated by WMC (as part of the COGNITION factor, e.g., Lunner & Sundewall-Thorén, 2007; Rönnberg et al, 2010; Füllgrabe et al, 2015). Here, we again come back to the first interpretation, namely that our TFS tests actually place demand on an element of WM. Thus, the inter-correlations among COGNITION, SENSITIVITY and TEMPORAL FINE STRUCTURE factors suggest interesting theoretical and experimental possibilities that must be pursued to reach firm conclusions.

Of the two interpretations we have suggested, one is a cognitive more of a top-down, WM interpretation and the other is primarily a sensorineural, cochlear, or bottom-up interpretation. Presumably, there are other levels of interaction in the auditory system that are related. Two examples from brain research illustrate the complexity.

The first example relates to the possibility that at least part of the effects of temporal fine structure are finally determined at the cortical level. It has been proposed (e.g. Yonelinas, 2013) that hippocampal binding is important for the rapid computation of evolving percepts, as well as for working memory and LTM. Even more specifically, recent data suggest that the human brain (at least in the case of listeners with normal hearing) is extremely efficient in picking up temporal patterns within rapidly evolving sound sequences, presumably serving to aid the prediction of upcoming auditory events. Again, the hippocampus interacts with the primary auditory cortex and the *inferior frontal gyrus* to accomplish this feat (Barascud et al, 2016). The role played by the inferior frontal gyrus in sentence-based speech-in-noise tasks has recently been demonstrated by Zekveld et al (2012). The findings show that the inferior frontal gyrus and mid temporal regions interact such that participants with low WMC activate these areas more than participants with high WMC do when they use semantic cues to aid speech perception in noise (see also Hassanpour et al, 2015).

Another example can be found at the level of the brainstem. Attending to a sound (counting deviants in a sequence of tones) increases the amplitude of the brainstem response. However, the brainstem response decreases when attention is shifted from the auditory modality to a visually based, n-back WM task, based on letter sequences. The brainstem response is further suppressed when the cognitive load of the n-back task increases, especially for participants with a high WMC (Sörqvist et al, 2012, see also Anderson et al, 2013; Kraus & White-Schwoch, 2015). Recent conceptualizations of a top-down governed, subcortical, early auditory filter model are in line with these results and account for

the WMC data and interpretation referred to above (Marsh & Campbell, 2016).

The common denominator in these examples is that the temporal (Pichora-Fuller, 2003; Vaughn et al, 2006) and sensitivity aspects of the cochlear/brainstem output may be modulated both sub-cortically and cortically by cognitive factors such as WMC. The inter-correlation matrix supports that kind of inter-action, but the level(s) at which the crucial interactions take place and the specific cognitive subcomponent(s) of the COGNITION factor that are the most influential in this process remain to be determined. According to an ELU-perspective (Rönnberg et al, 2013), it may be argued that WMC can serve a *pre-dictive* function, affecting brainstem processing of sound (Marsh & Campbell, 2016; Sörqvist et al, 2012). The arguments and data supporting a *post-dictive* and reconstructive function of WMC have already been presented by Rönnberg et al (2013), and emphasize the role that WMC plays when there are conditions that for some individuals cause a mismatch between input and semantic LTM representations.

SENSITIVITY (dominated by PTA4) was positively and significantly related to COGNITION. The difference in strength between the COGNITION–SENSITIVITY and COGNITION–TEMPORAL FINE STRUCTURE correlations was significantly different, $Z = 2.45$, $p < 0.05$. After partialling out for age, the association became non-significant for the SENSITIVITY correl-ation (cf. Humes, 2007; Humes et al, 2013), but the TEMPORAL FINE STRUCTURE correlation with COGNITION remained significant (see Table 6). The finding of a significant association between SENSITIVITY and COGNITION is in line with previous studies (Lin et al, 2011; Deal et al, 2015; Harrison Bush et al, 2015), but the relatively weak correlation that vanishes when age is partialled out seems to give partial support only to the fifth prediction. Nevertheless, as already stated we have employed a conservative test of the prediction in the sense that the majority of studies have typically targeted one cognitive function or memory system at the time instead of using a composite COGNITION score, as is the case in the current study (e.g. Tun et al, 2009; Rönnberg et al, 2011; Rönnberg et al, 2014; Verhaegen, 2014).

Also, as most of the components of the current COGNITION factor are related to the on-line processing of speech (especially the Executive/Inference-making and WMC components), we should expect smaller or non-existent effects relative to other memory systems such as episodic LTM, which is known to be more sensitive to hearing loss (Rönnberg et al, 2011; Rönnberg et al, 2014; Leverton, 2015). It may also be the case that episodic memory loss, not WMC, is coupled to the heightened risk of developing Alzheimer's dementia (Lin et al, 2011, 2014; Rönnberg et al, 2014; Leverton, 2015). However, as the present study did not take a memory systems approach to cognition, and as episodic LTM indices were not employed, we can only partially evaluate this proposition. Additionally, the current sample (at this point in time) did not show very much variability on the MMSE, and hence, we expect that later data collections (when SENSITIVITY and MMSE scores are lower), and when we have included episodic LTM indices, will show greater impact on the COGNITION factor.

The fact that both the SENSITIVITY and the TEMPORAL FINE STRUCTURE factors both predict the NO CONTEXT outcome factor is very much in line with the results reported by Bernstein et al (2013), where both factors account for variance

independently. SENSITIVITY and TEMPORAL FINE STRUCTURE also significantly influence the CONTEXT outcome factor, albeit to a lesser extent than they influence the NO CONTEXT outcome factor.

Finally, to get a more general handle on how the factors relate to each other and how they collectively predict outcomes, we computed two regression analyses (one for each OUTCOME LEVEL 2 factor). This approach is in many ways similar to the approach taken by Humes et al (1994) in their classic paper, where they used auditory (e.g. thresholds, suprathreshold discrimination tests), cognitive (i.e. Wechsler Adult Intelligence Scale-Revised measure) and speech perception measures, e.g. ranging from recognition of nonsense syllables to final words in sentences, combined with noise-no noise conditions. They also factor analyzed their battery and did subsequent prediction analyses. However, we have used other kinds of tests in each of the three categories, which might explain why thresholds (i.e. SENSITIVITY) dominated as a predictor construct in the Humes et al (1994) study, while we have reached a somewhat different conclusion.

We used stepwise linear regression with backward elimination to predict the CONTEXT and NO CONTEXT outcomes from age, COGNITION, SENSITIVITY and TEMPORAL FINE STRUCTURE. CONTEXT was significantly predicted by COGNITION ($\beta = 0.12$, $t(195) = 1.69$, $p = 0.09$), SENSITIVITY ($\beta = 0.18$, $t(195) = 2.25$, $p = 0.02$) and TEMPORAL FINE STRUCTURE ($\beta = 0.14$, $t(195) = 1.83$, $p = 0.07$), $R^2 = 0.10$, $F(3, 196) = 7.33$, $p < 0.001$. Age was not a significant predictor ($p = 0.39$). Note that common practice with a backward elimination strategy is to view predictors as significant when $p < 0.10$. The NO CONTEXT was significantly predicted by COGNITION ($\beta = 0.26$, $t(195) = 4.18$, $p < 0.001$), SENSITIVITY ($\beta = 0.31$, $t(195) = 5.23$, $p < 0.001$), TEMPORAL FINE STRUCTURE ($\beta = 0.21$, $t(195) = 3.26$, $p = 0.001$), and age ($\beta = -0.15$, $t(195) = -2.43$, $p = 0.02$), $R^2 = 0.40$, $F(4, 196) = 31.73$, $p < 0.001$.

Thus, we obtain a robust prediction of variance especially for the NO CONTEXT outcome factor, where all three LEVEL 2 factors contribute independently with roughly equal beta weights in the equation, i.e., the HEARING factors and COGNITION contribute to performance. This is different from the Humes et al (1994) study, one possible reason being that the COGNITION factor was motivated in the on-line ELU-context and not from a general intelligence test. Nevertheless, SENSITIVITY – similar to the Humes study – is an important general predictor variable for both of our outcome factors as well.

Conclusions

Taken together, the present overall and introductory study of the n200 database generally shows that LEVEL 1 and LEVEL 2 factorial structures are clear-cut, and replicate findings observed in previous studies that have been based on much smaller samples. The results indicate theoretically and clinically challenging LEVEL 2 inter-correlations.

First prediction: The fact that all cognitive tests significantly load on one factorial structure (i.e. COGNITION) gives general support for the unity, integration and interaction among the subcomponents (especially executive and WM functions) of the ELU-system.

Second prediction was also confirmed in the sense that we obtained two-factor solutions for both the HEARING and OUTCOME LEVEL 2 scores.

Third prediction: we demonstrated that the COGNITION factor predicts the NO CONTEXT outcome scores more than it predicts the CONTEXT outcome scores and that for the NO CONTEXT outcome, all three LEVEL 2 factors independently predicted the NO CONTEXT factor more than they predicted the CONTEXT factor and the difference was similar for all three factors.

Fourth prediction: TEMPORAL FINE STRUCTURE plays an interesting role relative to SENSITIVITY, COGNITION and to both OUTCOME factors and was given a cognitive hearing science interpretation in terms of WM (Stenfelt & Rönnberg, 2009). Recent brain-based findings pertinent to cognitive modulation of both subcortical and cortical levels of processing in the auditory system were discussed, and in line with a new early filter model (Marsh & Campbell, 2016).

Fifth prediction: SENSITIVITY was weakly correlated to COGNITION. Possible reasons for the weakness of the relation were discussed and it was suggested that the most likely explanation was that we did not use episodic memory tests during this test occasion.

Future studies using data from the n200 database will focus on the more detailed relationships between the subcomponents of the LEVEL 2 factors and their specific test contributions.

Acknowledgements

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