

COGNITIVE DEAFNESS

The deterioration of phonological representations in adults with an acquired severe hearing loss and its implications for speech understanding

Ulf Andersson

Akademisk avhandling

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Abstract

The aim of the present thesis was to examine possible cognitive consequences of acquired hearing loss and the possible impact of these cognitive consequences on the ability to process spoken language presented through visual speechreading or through a cochlear implant.

The main findings of the present thesis can be summarised in the following conclusions: (a) The phonological processing capabilities of individuals who have acquired a severe hearing loss or deafness deteriorate progressively as a function of number of years with a complete or partial auditory deprivation. (b) The observed phonological deterioration is restricted to certain aspects of the phonological system. Specifically, the phonological representations of words in the mental lexicon are of less good quality, whereas the phonological system in verbal working memory is preserved. (c) The deterioration of the phonological representations has a negative effect on the individual's ability to process speech, either presented visually (i.e., speechreading) or through a cochlear implant, as it may impair word recognition processes which involve activation of and discrimination between the phonological representations in the lexicon. (d) Thus, the present research describes an acquired cognitive disability not previously documented in the literature, and contributes to the context of other populations with

phonological disabilities by showing that a complete or partial deprivation of auditory speech stimulation in adulthood can give rise to a phonological disability. (e) From a clinical point of view, the results from the present thesis suggest that early cochlear implantation after the onset of an acquired severe hearing loss is an important objective in order to reach a high level of speech understanding with the implant.

Keywords: Acquired hearing loss, phonological processing, cochlear implants, speechreading.

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PREFACE

This thesis is based on the following four studies, which will be referred to in the text by Roman numerals.

- I. Andersson, U., & Lyxell, B. (1998). Phonological Deterioration in Adults with an Acquired Severe Hearing Impairment. Scandinavian Audiology, 27(suppl. 49), 93-100.
- II. Andersson, U. (in press). Deterioration of the phonological processing skills in adults with an acquired severe hearing loss. European Journal of Cognitive Psychology.
- III. Lyxell, B., Andersson, J., Andersson, U., Arlinger, S., Bredberg, G., Harder, H. (1998). Phonological representation and speech understanding with cochlear implants in deafened adults. Scandinavian Journal of Psychology, 39, 175-179.
- IV. Andersson, U., Lyxell, B., Rönnerberg, J., & Spens, K-E. (2001). Cognitive correlates of visual speech understanding in hearing impaired individuals. Journal of Deaf Studies and Deaf Education, 6, 103-115.

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Linköping, April, 2001

Ulf Andersson

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1. INTRODUCTION

The present thesis deals with individuals who have acquired a severe hearing loss or deafness in adulthood. The effect of an acquired hearing impairment is fundamentally a communication disability that affects not only the hearing impaired individuals, but also those around them (Meadow-Orlans, 1985; Rutman, 1989; Rutman, & Boisseau, 1995; Thomas, Lamont & Harris, 1982). The hearing impairment makes spoken communication laborious, stilted and exhausting because of things like the need to constantly stay focused, the frequent misunderstandings and the need to ask to repeat (Cowie & Stewart, 1987; Héту, Lalonde & Getty, 1987; Kerr & Cowie, 1997). Several studies show that the communicative malfunctions and restrictions following hearing loss often produce feelings of social insecurity, anxiety and embarrassment, which eventually may lead to the hearing impaired individual avoiding social interaction (Eriksson-Mangold & Carlsson, 1991; Knutson & Lansing, 1990; Luey, 1980). Thus, individuals with an acquired hearing loss might not experience sufficient social interaction of the kind that gives life meaning. As such, the overriding social effect of an acquired hearing loss is social isolation, which in turn may produce feelings of depression (Knutson & Lansing, 1990; Stevens, 1982; Thomas & Gilhome-Herbst, 1980).

The interactive nature of a hearing loss produces a number of disadvantages for the relatives (i.e., family members) of the hearing impaired individual (Hallberg, 1996; Héту et al., 1987; Héту, Jones, & Getty, 1993). For example, loud TV and radio listening and speaking with a loud voice are perceived as serious inconveniences for the family of hearing impaired individuals. Another inconvenience experienced by the family members is that the hearing impaired family member is unreliable as regards noticing warning signals and taking telephone messages (Héту et al., 1987).

A number of studies have provided evidence that individuals with an acquired hearing loss experience problems at work (Backenroth & Ahlner, 1998; Thomas & Gilhome-Herbst, 1980; Thomas et al., 1982). They obviously have problems with all social aspects of work, such as conversation with colleagues and telephone conversation. In addition, hearing loss has an adverse affect on the individuals' opportunity to be promoted (Héту & Getty, 1993; Lalande, Lambert, & Riverin, 1988;

Thomas et al., 1982), actually, they are frequently faced with the need to change jobs due to their hearing problem (Thomas et al., 1982).

In contrast to the rather well recognised social and psychological problems following an acquired hearing loss, the overall aim of the present thesis was to examine cognitive effects of acquired hearing loss and the possible impact of hearing loss related cognitive changes on speech processing. Although medical professionals working with deafened adults have some implicit knowledge regarding cognitive effects based on their clinical observations, only a few studies have actually addressed this issue (Conrad, 1979; Lyxell et al., 1996; Lyxell, Rönnerberg, & Samuelsson, 1994). Based on these few previous studies, the focus of the present thesis is on phonological processing in individuals with an acquired severe hearing loss and its relation to visual speechreading and hearing with cochlear implants.

The outline of the thesis, which is divided into eleven sections, is as follows. Section two (2) defines and discusses different populations of hearing impaired and deaf individuals. The next section (3), focuses on three different ways to perceive, process and understand spoken language. Section four (4) reviews the research on cognitive and phonological processing in three specific populations; congenitally deaf, deafened adults and adult dyslexics. Section five (5) discusses the concept of phonological processing and provides a definition of this important concept. Taken together the first five sections are intended to provide the relevant theoretical and empirical background to the overall purpose of the thesis and to the empirical questions addressed in the four studies. The general and specific purposes of the present thesis are stated in section six (6). Methodological problems related to the present research is discussed in section seven (7). The next two sections (8 & 9) present the specific purposes and a summary of each empirical study. Section ten (10) summarises the main empirical findings of the four studies. In the final section (11) the empirical findings of the thesis are discussed in the context of a descriptive conceptual framework. This is followed by the main conclusions and suggestions for further research.

2. POPULATIONS OF HEARING IMPAIRED AND DEAF INDIVIDUALS

Hearing impairment constitutes one of the most common disabilities of adulthood (Jones, Kyle & Wood, 1987; Ries, 1982; Wilson et al., 1999). In spite of this, it is difficult to give an exact estimate of the prevalence

of this impairment, as only a small number of epidemiological studies exist that have been performed on the general population and that include actual audiological assessment of the participants (e.g., Davis, 1989; 1995; Quaranta, Assennato & Sallustio, 1996; Wilson et al., 1999). The few studies conducted on representative samples and with audiological assessment are usually difficult to compare, as different studies report the evaluation of hearing loss in different ways (Quaranta et al., 1996). Studies performed in Great Britain by British researchers report the amount of hearing loss as an average over four frequencies (i.e., .5, 1, 2, and 4 kHz), whereas studies performed in the USA report a three frequency average (i.e., .5, 1, and 2 kHz). However, the combined empirical picture of the available international epidemiological research suggests that 5-10 % of the general adult population have a hearing impairment that exceeds 34 dB for the "better ear" calculated as a pure tone average over four frequencies (i.e., .5, 1, 2, and 4 kHz; Davis, 1989; 1995; Quaranta et al., 1996; Wilson et al., 1999). No reliable data on the prevalence of hearing impairment is available for Sweden, but a rough estimate would be that 10% of the Swedish general population (adults and children) have a hearing loss greater than 40 dB (S. Arlinger, personal communication, August 21, 2000; Backenroth & Ahlner, 1997).

The populations of hearing impaired and deaf individuals are heterogeneous, varying in many aspects such as aetiology, degree of hearing loss, and type of hearing loss (i.e., conductive or sensorineural; Cowie & Douglas-Cowie, 1992; Davis, 1995; Parving, Sakihara & Christensen, 2000). Degree of hearing loss is usually described by using a few verbal categories that represent specific dB value intervals. The most common verbal categories employed in Sweden are displayed in Table 1 (Arlinger, 1991; Liden, 1985).

Table 1.
Classification of different degrees of hearing loss

| Verbal category | Hearing loss in dB |
|-----------------|--------------------|
| mild | <35 |
| moderate | 35-64 |
| severe | 65-89 |
| profound | ≥90 |

For the purpose of the present thesis, the most important distinction between individuals with hearing impairment concerns the time of onset of hearing loss. The time when the hearing loss occurs is critically important for the impact it has on the individuals' life (Cowie & Douglas-Cowie, 1992; Rutman, 1989). Therefore, a clear distinction is made between individuals who have a hearing impairment from birth or the first few years of life, and those who have acquired a hearing impairment in adulthood (David & Trehub, 1989; Rutman, & Boisseau, 1995). In the present thesis, focus is on the latter group of hearing impaired individuals. There are at least three important differences between these two populations of hearing impaired or deaf individuals. As a prelingual severe hearing impairment makes the acquisition of spoken language via the aural mode practically impossible, sign language is the first and preferred mode of communication for most prelingually deaf individuals. In contrast, individuals who have become deaf after developing normal language skills will not, in general, learn and use sign language. They want to continue to use the spoken language that they have learned when growing up and used until their hearing capacity deteriorated (Cowie & Douglas-Cowie, 1992; Öhngren, 1992). Even if some hearing impaired individuals may consider learning and using sign language, one obstacle is that individuals close to them may not be willing to learn sign language. Neither are individuals with an acquired hearing loss likely to become members of the deaf community, which most congenitally deaf individuals are. Instead, their preference is to continue to be a member of the hearing mainstream community (David & Trehub, 1989). A third important difference concerns how the hearing impairment or deafness is perceived by the individuals of these two populations. As a consequence of not experiencing the actual loss of their hearing, the prelingually deaf tend to experience deafness as a cultural difference rather than a deficit (Glass, 1985). This difference constitutes an important and fundamental part of the individuals' self-image (Becker, 1980; Rutman, 1989). An acquired hearing impairment, on the other hand, constitutes a traumatic loss to its victims as they are acutely aware of the differences between their pre- and postmorbid life situation (David & Trehub, 1989).

It is apparent from the previous discussion that acquired hearing loss is a complex phenomenon that impacts on multiple domains. The International Classification system of Impairments, Disabilities and Handicaps (ICIDH) proposed by The World Health Organisation (WHO, 1980)

is therefore a useful tool when describing and studying different aspects of auditory dysfunction (Davis, 1983; Hyde & Riko; 1994; Stephens & Héту, 1991). This classification system consists of four basic concepts; disease (or disorder), impairment, disability and handicap. When applied to hearing dysfunctions the term disease/disorder refers to anatomical or physiological damage in the hearing organ (Davis, 1983; Thomas, 1988). Hearing impairment is the defective function of the auditory system as a result of the pathology of the hearing organ and is usually measured by a pure-tone audiogram (Davis, 1995; 1983; Stephens & Héту, 1991). Hearing disability refers to the hearing problems, caused by the hearing impairment, which the hearing impaired individual experiences in his or her real life situation. The hearing disability is not only determined by the nature and magnitude of the hearing impairment, but also by the social situation of the affected individual (Davis, 1983; Stephens & Héту, 1991). Different measures of speech discrimination and recognition are commonly used to assess this domain of auditory dysfunction (Davis, 1995). The term handicap represents the non-auditory problems (e.g., social isolation, loss of promotion and family disharmony) caused by the hearing disability (Hallberg & Carlsson, 1991; Stephens & Héту, 1991). Thus, this term refers to the socialisation of the disability as it comprises the psychosocial experiences of the affected person, which result from the interaction between the sociocultural and physical context and the disability (Hallberg & Carlsson, 1991). The handicapping effects of a hearing disability are usually measured by means of different types of self-assessment instruments (Giolas, 1990; Schow & Gatehouse, 1990). According to this framework, the overall aim of the present thesis – to examine cognitive effects of acquired hearing impairment and the possible impact of hearing loss related cognitive changes on speech processing – is concerned with issues that are connected to the disability level of acquired hearing loss.

In sum, deafness and hearing loss constitute a common phenomenon in the general population that covers many dimensions. It is important to realise that not all hearing impaired or deaf individuals perceive the hearing loss as an impairment or a disability. How the hearing loss is perceived and what kind of effect it has on the individuals' daily life is to a large part a function of when the hearing loss occurs (i.e., prelingually or postlingually), but is also determined by the social and physical environment of the hearing impaired individual.

3. SPEECH PROCESSING

Spoken language is the primary mode of communication for most human beings. In the present section, three different ways of perceiving and processing speech are reviewed. In the first part, theories and models of auditory speech understanding are presented, the second and third part examine research on auditory speech understanding with cochlear implants and speechreading, respectively.

Auditory speech processing models

A number of theories and models of spoken word recognition have been developed during the past decades (see Altmann, 1995; Marslen-Wilson, 1989a; Massaro, 1998 for reviews). A basic assumption in these models is that spoken word recognition requires the individual to relate an acoustical–auditory speech signal to stored lexical representations of words (Ellis & Young, 1996; Liberman & Mattingly, 1985; Luce & Pisoni, 1998; Marslen-Wilson, 1987; 1995). In this section, three models or theories (e.g., the TRACE model; the Cohort model; and the NAM) are selected and reviewed because they recently have been or still are influential on contemporary theory in speech processing. They have in common that they all emphasise the roles of activation and competition (i.e., differences in activation levels) in spoken word recognition.

McClelland and Elman (1986) have developed the interactive TRACE model based on connectionist principles. The model includes three interacting levels of processing: the feature level, the phoneme level and the word level. A central assumption in the TRACE model is that bottom-up and top-down processing interact during spoken language processing. The three levels of representation/processing (i.e., feature, phoneme and word level) are connected and facilitate each other in both directions. The different units or nodes that are at the same level are also connected to each other, but these connections are inhibitory (i.e., competing). These connections between and within levels serve to raise and lower activation levels of the nodes depending on the acoustic input and the activity of the overall system. Auditory information is first entered at the feature level and flows bottom-up to the phoneme and word levels. Thus, the TRACE model postulates that the mapping of the acoustic signal onto the lexicon is mediated by prelexical representations at the feature and phoneme

levels, which are used to access the word level. Information also flows top-down, so that higher mental processes influence lower mental processes during speech processing. The top-down processes include various sources of information, such as contextual, lexical, syntactical, and semantical information (McClelland, 1991; McQueen, 1993). At the word level, each word is represented by a separate unit or node and these units compete for recognition. That is, when the activation level for a word unit surpasses a criterion level, the word is recognised.

Another interactive model is the Cohort model developed by Marslen-Wilson and Tyler (1980). Similar to the TRACE model, this model assumes that various sources of information (e.g., contextual, lexical, syntactical, and semantical) interact during speech perception. According to the revised versions of the Cohort theory (Marslen-Wilson, 1987; 1989b), the acoustic signal activates all words that have some similarity in sound to the signal. This collection of words is called the "word-initial cohort". As long as new incoming speech information is registered, a word could be activated even if its initial phoneme did not match the first auditory segment. Thus, the selection of the words in the cohort is not considered an all-or-nothing phenomenon and is determined by the overall goodness-of-fit between the acoustical signal and the lexical representations. The better the stored representation matches the acoustic signal, the stronger is the activation level of that particular word. Word frequency is also important because this type of information affects the activation levels of the word candidates and thereby contributes to the competition between the words in the cohort (Bard, 1995; Marslen-Wilson, 1995). As more acoustic information becomes available from the presented word, members of the cohort are eliminated if they are no longer consistent with that information or other sources of information (semantic, lexical, syntactic). Recognition of a word occurs at the point when only one word is left in the cohort. This point of recognition can occur prior to the end of the word, because syntactic and semantic information can eliminate words in the cohort. In contrast to the TRACE model, the cohort theory does not include the existence of any prelexical representations that mediate between the acoustic signal and the lexicon. Instead, the lexical representations of the words, which are featurally organised, are directly accessed by featural information extracted from the speech signal (Marslen-Wilson, 1987; 1995; Marslen-Wilson & Warren, 1994; Warren & Marslen-Wilson, 1988).

A more recently developed activation-competition model is the **Neighbourhood Activation Model** (NAM; Luce, Goldinger, Auer & Vitevitch, 2000; Luce & Pisoni, 1998). The NAM is especially concerned with providing an account of how the structural relationships among lexical items affect the word identification process. The model is founded on two basic principles: First, spoken word recognition involves discriminating between similar-sounding lexical candidates that are activated in memory by the acoustic input. That is, the acoustic signal activates a neighbourhood of phonologically similar words, which then compete for recognition. Second, discriminating among this set of similar-sounding lexical candidates is a function of the number and nature of the words included in the set. Increased lexical competition results in slower and less accurate processing. A set of acoustic-phonetic patterns is activated by the acoustic input and the activation level of the patterns is a direct function of their similarity with the acoustic signal. These patterns then activate a neighbourhood of word decision units that are connected to the acoustic-phonetic patterns. However, as the listener can recognise new words, as well as nonsense words, it is assumed that all acoustic-phonetic patterns do not correspond to a real word. When the word decision units are activated they monitor the activation level of the acoustic-phonetic pattern to which they correspond but also higher level lexical information relevant to the word unit. Thus, the word decision unit system is a key function in the NAM, as it constitutes an interface between bottom-up and top-down information. The word decision units are also interconnected, which allows each single unit to monitor the overall level of activity in the complete system (i.e., word decision units and acoustic-phonetic patterns). The higher level lexical information, which includes word frequency information, is assumed to affect speech processing by biasing the word decision units, but does not affect the initial activation of the acoustic-phonetic patterns. Thus, the NAM gives an account of the effect of word frequency on spoken word recognition. As the presentation of the word continues, the match between the acoustic signal and the acoustic-phonetic pattern increases, as does the activation level of that particular pattern, whereas the activation levels of the other similar-sounding patterns decrease. Word recognition occurs when the word decision unit for a given acoustic-phonetic pattern exceeds the criterion level.

All in all, the NAM, Cohort and TRACE models provide rather complex accounts of spoken word recognition in the normal hearing population.

However, an important aspect of speech processing, which the researchers have failed to include in their models, is the contribution and function of prosodic information. The importance of word prosody (i.e., number of syllables and syllabic stress) and sentence prosody (i.e., rhythm and intonation) in auditory speech processing (Cutler, 1989; Kjelgaard & Speer, 1999; Lindfield, Wingfield & Goodglass, 1999a; 1999b; Norris, McQueen & Cutler, 1995) and visual-tactile speechreading for hearing impaired individuals is well established (Auer, Bernstein, & Coulter, 1998; Kishon-Rabin, Boothroyd, & Hanin, 1996; Rönnerberg, 1993; Waldstein & Boothroyd, 1995; Öhngren Rönnerberg & Lyxell, 1992). Spoken word-recognition is facilitated when word stress is taken into account and not just initial phonology. That is, the word-initial cohort is constrained when the only words included are those that share both stress pattern and initial phonology with the stimulus word (Lindfield et al., 1999a; 1999b). Furthermore, syllabic stress is assumed to serve a key function in the segmentation of the continuous speech stream (Cutler and Norris, 1988; Grosjean & Gee, 1987). That is, to understand a spoken utterance, the listener must decide where the different words in the utterance begin so that each separate word can be identified. A hypothesis (the **M**etrical **S**egmentation **S**trategy) proposed by Cutler and Norris (1988), states that syllabic stress is used to set word boundaries in the continuous speech stream. According to the hypothesis, a process of segmentation is triggered by the occurrence of a strong syllable in the speech signal. In other words, a lexical access attempt is initiated at the beginning of each strong syllable, whereas weak syllables do not initiate such an attempt. Although strong syllables are not the only cues for detecting word boundaries (e.g., lexical competition; Norris et al., 1995; Vroomen & de Gelder, 1995), the MSS hypothesis has received extensive empirical support from experimental studies (Cutler & Norris, 1988; Norris et al., 1995; Sven & Samuel, 1997; Vroomen & de Gelder, 1995; Vroomen, van Zon, & de Gelder, 1996).

Sentence prosody contributes to auditory speech processing by solving syntactic ambiguities, and by identifying syntactic boundaries (Kjelgaard & Speer, 1999; Pisoni & Luce, 1987; Schepman, & Rodway, 2000; Steinhauer, Alter & Friederici, 1999). Although a fair number of studies have provided evidence on the importance of prosodic processing, neither of the models includes this aspect of speech processing.

In summary, the reviewed models provide quite similar accounts of how spoken words are recognised. This is not surprising considering that they are all so-called activation-competition models sharing the assumption that spoken word recognition involves discrimination between lexical candidates that are activated by the acoustic input. The models also assume that items are activated and processed in parallel. Another fundamental principle is that bottom-up and top-down processes interact during spoken word recognition. In addition, the models state that items receive reduced levels of activity when disconfirming acoustic is presented. The Cohort theory and the NAM are similar as both models assume bottom-up priority in the activation of items in memory and that activation of the decisions units is direct (i.e., no intermediate prelexical representations). Word recognition according to the TRACE model (i.e., the word nodes level) is, on the other hand, accomplished through pre-processed input (i.e., the feature and phoneme levels) and not directly from the acoustic input. The TRACE and the NAM models are similar as their nodes and word decision units are interconnected, whereas such interconnections are not included in the Cohort model.

Although the presented models provide accounts of how normal hearing individuals process and recognise spoken language one might assume that the basic concepts and processes are also applicable for individuals who have acquired a severe hearing loss. That is, the NAM, Cohort and TRACE models provide base-line accounts of how speech is processed. The remainder of this section illustrates, on the other hand, how individuals with an acquired hearing loss perceive and process spoken language by means of cochlear implants and visual speechreading.

Auditory speech understanding with cochlear implants

A cochlear implant is a technical device that is used in audiological rehabilitation of severely and profoundly deaf individuals. Cochlear implants differ from hearing aids, as they bypass the damaged inner ear and directly stimulate the auditory nerve in the cochlea (O'Donoghue, Nikolopoulos & Archbold, 2000; von Ilberg, et al., 1999). The efficiency of cochlear implants is well documented (NIH consensus conference, 1995; Tyler, Parkinson, Woodworth, Lowder & Gantz, 1997). As new multi-channel cochlear implants are developed and the speech sound processing techniques are becoming more sophisticated, open-set speech

understanding (i.e., without speechreading) with cochlear implants is a common finding (e.g., Gstoettner, Adunka, Hamzavi, Lautischer & Baumgartner, 2000; O'Donoghue et al., 2000; Waltzman, Cohen & Roland, 1999). However, even though most treated patients gain from the implant they vary widely with respect to what they can hear with the implants (O'Donoghue, et al., 2000; Tyler et al., 1997). Some patients can only recognise environmental sounds without being able to interpret them, whereas others can communicate over the telephone or follow a conversation (without visual information) when both the topic and the speaker are unfamiliar (Lyxell et al., 1996). A number of studies have been performed to identify factors that can account for the large variation in auditory performance of cochlear implanted individuals (Blamey et al., 1996; Pisoni, 1999; van Dijk et al., 1999). This research shows that duration of deafness and age at implantation constitute two important predictors of outcomes in terms of speech understanding in both adults and children. The tendency is that individuals who have been deaf for short periods of time have a better speech recognition than those who have been deaf for long periods of time. Younger recipients of implants obtain, in general, better hearing ability than older recipients (Balmey et al., 1996; O'Donoghue, et al., 2000; Waltzman et al., 1999). Furthermore, for implanted children an oral communication mode environment is a key factor for developing an efficient speech understanding ability (O'Donoghue, et al., 2000; Pisoni, 1999).

Despite the fact that cochlear implants provide an opportunity for deaf individuals to recover their hearing ability, the implant recipients do not recover normal hearing. The signal delivered through the implant differs in many ways from that delivered through the normally functioning cochlea (e.g., reduced spectral resolution; Bahner, Carrell & Decker, 1999; Skinner et al., 1994). This means that hearing with a cochlear implant involves decoding and processing of a distorted and incomplete auditory signal (Naito et al., 2000). This question has also been addressed by researchers using the neuroimaging methodology (PET) to investigate if speech processing with a cochlear implant is more effortful and demanding and/or involves different speech processing strategies than speech processing with normal hearing. The results show that speech processing with cochlear implants involve both an increased activation in traditional speech processing cortical areas (i.e., bilateral superior temporal areas) and a more widespread activation in these areas

compared to normal hearing (Giraud et al., 2000; Naito, et al., 2000; Wong, Miyamoto, Pisoni, Sehgal & Hutchins, 1999). Wong et al. (1999) could demonstrate that cochlear implant users showed a more extensive right temporal activation (from anterior to such middle parts as the primary auditory cortex; BA 41) in the transverse temporal gyrus, secondary auditory area (BA 42). Similar findings were obtained by Naito et al. (2000) and Giraud et al. (2000). Naito et al. also found higher activation in the left superior and middle temporal gyri, Broca's area and its right hemisphere homologue, the supplementary motor area and the anterior cingulate gyrus, whereas Giraud et al. (2000), also found that listening to sentences with cochlear implants elicited higher activation in Heschl's gyrus, the posterior left superior temporal gyrus, and the right inferior parietal and premotor cortices. In addition, cochlear implant users showed less activation in inferior temporal regions (Giraud et al., 2000) and left inferior frontal gyrus (BA 47; Naito et al., 2000), regions that are known to reflect semantic processing. These neurophysiological studies suggest that hearing with a cochlear implant is different from normal hearing. Specifically, the processing of speech through a cochlear implant involves increased low-level phonological processing (bilateral activation of superior and middle temporal gyri) and a decreased semantic processing (i.e., inferior temporal regions; Giraud, et al., 2000). For example, the increased activation of the right superior temporal gyrus and the Broca's area suggests that individuals with a cochlear implant rely to a larger extent on prosodic information processing and phonological working memory (Giraud, et al., 2000; Naito et al., 2000; Wong et al., 1999). As a consequence of this increased phonological processing, less time and resources may be available for semantic processing (Giraud, et al., 2000; Wong et al., 1999). The activation of prefrontal and parietal modality-specific attentional areas suggests that hearing with a cochlear implant is more attention demanding than normal hearing (Giraud, et al., 2000; Naito et al., 2000).

In line with the conclusion that speech processing with cochlear implants is more demanding on phonological processing and attentional resources, Lyxell and colleagues (1996) reported data showing that specific cognitive abilities can serve as pre-operative predictors of post-operative speech understanding in postlingually deaf adults (i.e., deafened adults). Phonological processing skill, verbal working memory capacity and verbal information processing speed were all important predictors of 6-8

months postoperative performance. Especially, phonological processing was an important predictor. Patients who, pre-operatively, were in possession of good cognitive skills benefited more from the implants than those with poor cognitive skills. The former patients could follow and understand a speaker who was out of sight, whereas the latter only improved their speechreading performance or managed to recognise environmental sounds.

In summary, this empirical picture indicates that speech processing with a cochlear implant involves different speech processing strategies and is more effortful and demanding than is speech processing with normal hearing.

Speechreading

The term speechreading refers to the perception and comprehension of a spoken message on the basis of viewing rather than listening to a talker (see Campbell, Dodd & Burnham, 1998; Dodd & Campbell, 1987; Plant & Spens, 1995 for reviews). This form of communication is employed and useful for hearing impaired individuals, but also for normal hearing individuals when communicating in, for example noisy environments (Summerfield, 1992). During speechreading the individual extracts information not only from the lips, jaws and tongue, but also from facial expression and body language (see Arnold, 1997 for a review; Johansson, 1997; Lidestam, Lyxell & Andersson, 1999). Although information for word identification is primarily obtained from the lower part of the face (i.e., lips, jaws and tongue; Marassa & Lansing, 1995; Rosenblum, Johnson & Saldana, 1996) other aspects of spoken language are displayed in other parts of the face (Lansing & McConkie, 1999; Vatikiotis-Bateson, Eigsti, Yano & Munhall, 1998). Specifically, in two experiments Lansing and McConkie (1999) provided evidence that segmental and primary stress information is primarily obtained from the mouth region, whereas intonational information primarily is obtained from the upper parts of the face (i.e., forehead and eyes). A number of experiments have also established that contextual and linguistic cues are used to improve speechreading performance (Arnold, 1997; Lidestam, Lyxell & Lundeberg, in press; Samuelsson & Rönnerberg, 1991; 1993).

In contrast to the domain of auditory spoken word recognition, few attempts have been made to develop an explicit model of visual

speechreading. Instead, much of the research on speechreading has focused on three main questions: How visual cues contribute to and are integrated with acoustic information during speech processing (Bernstein, Demorest & Tucker, 1998; Summerfield, 1992; Walden, Busacco & Montgomery, 1993), what distinguishes skilled from less skilled speechreaders (Jeffers & Barley, 1971; Rönnerberg, 1995), and to what extent speechreading, as the main mode of communication, affects acquisition and development of different cognitive skills (see for example Alegria, 1998; Campbell, 1997; Dodd, McIntosh & Woodhouse, 1998).

Some researchers, however, have adopted an auditory or spoken word-recognition approach in the study of the speechreading process (Auer & Bernstein, 1997). This appears to be a reasonable approach as neurophysiological studies have shown that visual speech activates similar cortical areas as auditory speech (i.e., left superior temporal areas including Heschl's gyrus; Calvert et al., 1997; MacSweeney et al., 2000; Puce, Allison, Bentin, Gore & McCarthy, 1998). Auer et al. (1997) examined, by means of computational modelling, if the structure of the lexicon (e.g., perceptual similarity and frequency) affects the speed and ease of word recognition for the speechreader. Based on their results, Auer et al. hypothesised that during speechreading, frequency biasing processes are operating in a similar manner as in auditory speech processing. Consequently, by selecting the most frequent word in a lexical equivalence class the speechreader could optimise word recognition accuracy.

Although few attempts have been made to develop models of speechreading, the working memory model for poorly specified language input proposed by Rönnerberg, Andersson, Andersson, Johansson, Lyxell, and Samuelsson (1998) is an exception. The Rönnerberg et al. model provides a summary of their cognitive individual difference research on visual, visual-tactile, and audio-visual speech understanding. The model assumes that the processing of poorly specified language input is more demanding from a cognitive point of view than normal auditory speech processing, an assumption that is in line with the PET data previously reported in this section (e.g., Giraud et al., 2000). The model is composed by a multimodal input component, an amodal part, and a semi-abstract phonological processor. In the multimodal input component the different types of distorted language input are integrated, based on the natural complementarities between the visual, auditory and tactile modalities

(Rönnberg, 1993; Summerfield, 1987; Öhngren, et al., 1992). This early integration process is assumed to be completely automatized and performed at the perceptual level. Cognitive functions, such as early lexical access, general processing speed, and verbal inference-making are included in the amodal part. As the speech signal delivered through the input channels is incomplete and poorly specified as well as transient (Berger, 1972; Dodd, 1977; Rönnberg, 1990), early and rapid access to a lexical address for identification (i.e., lexical identification speed) are important cognitive operations (Lyxell, 1989; Lyxell & Rönnberg, 1992; Rönnberg, 1990). The fragmentary speech signal also forces the individual to rely on two types of inference-making processes, predictive inference-making and retrospective disambiguation. The former is forward directed and refers to the prediction of incoming information based on the contextual information available in a given situation, as well as previously presented and apprehended information. The latter is backward directed and concerns the use of new information to solve inconsistencies encountered earlier in the speech understanding process. The amodal part and the multimodal part are connected via the semi-abstract phonological processor. The main function of this component is to mediate lexical access by assembling and ordering smaller multimodal linguistic units or segments (i.e. phonemes, syllables or hand configuration/palm orientation) into larger higher-order meaning units that can be mapped on to lexical representations. One disadvantage with the Rönnberg et al. (1998) model is that it does not, in its present formulation, include a temporal dimension that gives a time course of all these processes involved in speechreading. Neither does it provide any statements concerning serial and parallel processing during language processing. Finally, although phonological processing is a central process component in the model, this term lacks a clear definition.

In summary, it is interesting to note that all three modalities (i.e., hearing, speechreading, hearing with cochlear implant) of speech understanding are very similar from an information processing point of view. For example, all three modalities, including speechreading, involve activation of the auditory cortices implying the importance of phonological processing. This is what should be expected for normal hearing and hearing with cochlear implants, but may seem less likely for visual speechreading. Another significant similarity is that bottom-up and top-down processing interact during all three forms of speech processing. The

contribution of top-down information is especially important during speechreading (e.g., contextual support). The major difference between these modalities is that visual speechreading and speech processing with cochlear implants are effortful and demanding forms of communication, whereas auditory speech processing with normal hearing is an easy and effortless task. Given the large similarities that exist between the three modalities it appears reasonable to use models of auditory speech understanding as a theoretical framework when studying speech processing in individuals with an acquired hearing loss (i.e., speechreading and hearing with cochlear implants).

4. COGNITIVE AND PHONOLOGICAL PROCESSING IN SPECIAL POPULATIONS

Cognitive processing is important in almost everything we do, and the knowledge we have about this fundamental aspect of life is largely based on research performed on the general (hearing) population. This section, however, addresses cognitive processing in three specific populations who all have some sort of disability or impairment. First an overview of cognition in the populations of congenitally deaf is presented, followed by research on deafened adults. Thirdly, relevant literature on adult dyslexics is reviewed.

Congenitally deaf and hearing impaired individuals

The interest in examining cognition in the population of congenitally deaf or hearing impaired has derived from the question whether an auditory deprivation, or having sign language as a first language, affects acquisition and development of various kinds of cognitive skills (Marschark & Clark, 1993; Marschark, Siple, Lillo-Martin, Campbell & Everhart, 1997). This line of research has for a long period of time demonstrated that deaf individuals differ on a wide variety of cognitive tasks compared to hearing individuals (Wolff, Kammerer, Gradner & Thatcher, 1989). Individuals who were born deaf usually show enhanced visuo-spatial cognitive skills, whereas their abilities to read and write as well as maintain verbal information in working memory are less developed compared to hearing populations (Conrad, 1979; Marschark & Clark, 1993; Myklebust, 1960). In the following section focus is on different aspects of verbal cognition.

Research that has investigated verbal cognition in the population of deaf individuals has addressed the question whether congenitally or prelingually deaf individuals develop a phonological function or representation despite their lack of experience of hearing speech (Conrad, 1979; Marschark & Clark, 1993). This question derives from the fact that in the hearing population, phonological processing is critical for a number of cognitive tasks, such as reading, spelling, arithmetics and verbal short-term/working memory (Baddeley, 1966; Baddeley, 1997; Conrad & Hull, 1964; Ellis & Young, 1996; Gathercole & Baddeley, 1993; Share & Stanovich, 1995; Wagner & Torgesen, 1987). Research examining phonological processing in the deaf have consequently focused on three main areas; the so called three "Rs", that is, remembering (i.e., working memory), rhyming and reading (Campbell, 1992; Leybaert & Charlier, 1996).

Working memory: It is well established that temporary storage of verbal information in working memory is performed by means of phonological coding and maintained by means of articulatory-phonological rehearsal (Baddeley, 1966; 1997; Conrad & Hull, 1964; Gathercole & Baddeley, 1993). Conrad (1970; 1979), using a short-term memory paradigm, was one of the first to examine phonological functions in the congenitally deaf. He reported in 1970 that some deaf British schoolboys, exposed only to spoken language, showed smaller short-term memory spans for word lists of similar-sounding words compared to dissimilar-sounding ones. This phonological similarity effect is normally found in the population of hearing individuals and indicates the use of speech-based phonological memory codes. In his famous work "The deaf schoolchild" (1979), he replicated his early findings (1970) by showing that the short-term memory spans of some deaf 15 to 16 year old schoolchildren were reduced when the to-be-remembered material consisted of lists of rhyming letter names compared to non-rhyming ones. A number of subsequent studies have confirmed and extended Conrad's results, showing that deaf individuals can use a phonological code to remember lists of linguistic material whether the material is presented in print, signs, or pictures (Campbell & Wright, 1989; Dodd, Hobson, Brasher & Campbell, 1983; Waters & Doehring, 1990). This is found in both deaf individuals, primarily using an oral communication strategy, and those who have sign language as their first language (Conrad, 1979; Hanson, 1982; MacSweeney, Campbell & Donlan, 1996). There is also an overwhelming

amount of evidence showing that deaf children and deaf adults have shorter verbal short-term memory spans and tend to remember less in other verbal short-term memory tasks (e.g., supra-span tasks) than hearing peers (Campbell & Wright, 1990; Conrad, 1979; Hanson, 1982; Logan, Maybery & Fletcher, 1996; MacSweeney et al., 1996; Mayberry, 1992; Marschark & Mayer, 1998; Parasnis, Samar, Bettger & Sathe, 1996; Spencer & Delk, 1989; Tomlinson-Keasey & Smith-Winberry, 1990).

Campbell and Wright (1990) provided evidence that deaf teenagers also conduct articulatory rehearsal processes while performing immediate serial recall of pictures. They presented deaf and hearing children with three different sets of pictures of objects with long or short names (i.e., 1, 2, or 3 syllables). Like the hearing participants, the deaf teenagers' recall was poorer for the long words compared to the control condition, that is, they showed the classical word length effect (cf. Baddeley, Thomson & Buchanan, 1975). Furthermore, MacSweeney et al. (1996) found that deaf teenagers' immediate memory for pictures was affected by articulatory suppression (cf. Marschark & Mayer, 1998) as well as phonological similarity, indicating that they use phonological codes when they maintain verbal information in working memory.

Rhyming: Phonological functions in deaf people have also been demonstrated in studies using rhyme paradigms (Campbell & Wright, 1988; Charlier & Leybaert, 2000; Dodd, 1987; Dodd & Hermelin, 1977; Hanson & Fowler, 1987; Miller, 1997). To judge whether two words rhyme requires access to the phonological representations of words and a comparison of the two phonological representations (cf. Besner, 1987; Campbell, 1992; Johnston & McDermott, 1986; Leybaert & Charlier, 1996). Hanson and Fowler (1987) included a rhyme-judgement task in a study on reading and deafness. Deaf and hearing college students were asked to decide whether two written words in a wordpair rhymed. The deaf students performed above chance level, indicating that they possess phonological processing skills, but their performance was considerably lower compared to the hearing students. Similar studies have also been performed on deaf children by Campbell and Wright (1988) and Charlier and Leybaert (2000) employing pairs of pictures, as well as written words as stimuli material. The results of these two studies were consistent with previous studies (Dodd, 1987; Dodd & Hermelin, 1977; Hanson & Fowler, 1987), showing that the deaf children were able to make judgements on words and pictures, but that they did not perform at the same level as

the hearing children. In a related study, Hanson and McGarr (1989) examined deaf college students' ability to generate rhymes. The participants' task was to generate as many words as possible that rhymed with a specific target word. Hanson and McGarr (1989) found that approximately 50% of the generated words were correct rhymes. Out of these 50%, 30% were orthographically dissimilar to their target, suggesting an ability to generate rhymes independent of orthographic structure. Together these studies demonstrate that it is possible for deaf individuals to develop phonological abilities required to perform rhyme-judgements on words and pictures without auditory input. However, they are less accurate and more influenced by spelling similarity when performing rhyme tasks than hearing individuals (Campbell & Wright, 1988; Charlier & Leybaert, 2000; Hanson & Fowler, 1987; Hanson & McGarr, 1989)

Reading: Studies examining congenital deafness and reading also indicate that some deaf individuals have access to phonological information and perform phonological coding during reading (Hanson & Fowler, 1987; Kelly, 1993; Leybaert & Alegria, 1993; Leybaert, Alegria & Fonck, 1983). Hanson and Fowler (1987) examined reading by means of lexical decision making tasks in which the participants' task was to decide whether pairs of letter strings were real words or not. When hearing individuals perform this task the response time is faster for rhyming words than for non-rhyming. Similar to the hearing students, the deaf students were faster in deciding when the words rhymed, and this rhyme effect was independent of orthographic similarity. Hanson and Fowler's (1987) finding has subsequently been confirmed by Kelly (1993) who used the same lexical decision tasks as Hanson and Fowler (1987). Signs of phonological processing in congenitally deaf individuals' reading have also been found in studies using a Stroop paradigm (Leybaert & Alegria, 1993; Leybaert, et al., 1983). In a Stroop task, the participant has to name, as quickly as possible, the colour of letter strings while ignoring the actual word. An interference effect is observed when colour words appear in incongruent colours (i.e., RED written in blue) compared to a control condition (e.g., meaningless letter strings). The interpretation of this data pattern is that two phonological output codes (derived from the mental lexicon), one corresponding to the word, and one to the colour are automatically activated. The former interferes with the latter, resulting in longer latencies and more errors. Leybaert and colleagues (1983; 1993)

presented this task to deaf and hearing children and found that both groups displayed the classical interference effect. That is, these studies indicate that deaf children have access to phonological information when presented with written isolated words (Hanson & Fowler, 1987; Kelly, 1993; Leybaert, et al., 1983; Leybaert & Alegria, 1993). Hanson, Goodell and Perfetti (1991) have expanded this conclusion to be valid also for sentence comprehension. In their study, deaf and hearing college students had to judge the semantic acceptability of printed sentences, half of which were tongue-twisters (e.g., The tired dentist dozed, but he drilled dutifully) and half were not. The hearing as well as the deaf students made more errors when the sentences were phonologically difficult (i.e., tongue-twisters). Furthermore, the phonological content of a concurrent memory load task affected the responses made by the participants. The error rate was higher when the tongue-twister sentences and the memory load material were phonologically similar. The authors concluded that deaf college students use a phonological code when silently reading sentences. There are also data showing that deaf individuals can perform phonological recoding and assembly (see Coltheart, Curtis, Atkins & Haller, 1993) during reading (Leybaert, 1993). Specifically, the deaf participants in Leybaert's study (aged 14 – 20 years) were able to correctly pronounce pseudowords which require that they recode letters into phonemes and assemble them into a string of phonemes.

Spelling: Another source of evidence concerning phonological processing in the deaf is spelling. A number of experiments investigating spelling of deaf people indicate that they can use phoneme-grapheme rules when performing this task (Burden & Campbell, 1994; Dodd, 1980; Hanson, Shankweiler & Fischer, 1983; Leybaert & Alegria, 1995). This conclusion derives mainly from the phonologically acceptable spelling error made by deaf children and adults when they spell words that are not spelled as they are pronounced (i.e., phonologically opaque words). A phonologically acceptable spelling error occurs when the individual applies phoneme-to-grapheme rules when spelling a phonologically opaque word, resulting in a spelling that is compatible with the word pronunciation. These phonologically acceptable spelling errors demonstrate that deaf people possess the phonological representations of familiar words and that they use these representations in order to write the words (Alegria, 1998; Burden & Campbell, 1994; Leybaert & Alegria, 1995; Leybaert, 2000). The ability to use phoneme-to-grapheme information is less pronounced and

develops more slowly in deaf individuals compared to hearing individuals, but it improves with age (Leybaert & Alegria, 1995; Sutcliffe, Dowker & Campbell, 1999).

An important implication of the development of phonological representations in the deaf is that it is not solely dependent on the ability to hear spoken language. Instead, it seems that deaf individuals are able to develop a phonological code through speechreading (Calvert et al., 1997; Dodd, 1980; Dodd & Campbell, 1987; Summerfield, 1987). However, as the main forms of communication for the congenitally deaf (i.e., sign-language and speechreading), do not provide well-specified and distinct phonological input, they do not develop phonological processing skills or representations comparable to those of hearing individuals (see Leybaert, Alegria, Hage, & Charlier, 1998 for a review). This fact is demonstrated by another fact; that deaf individuals rarely have a clear speech (Campbell & Wright, 1988; Hanson & Fowler, 1987; Leybaert & Alegria, 1993; Leybaert et al., 1983), and do not perform on a par with hearing individuals on tasks of verbal short-term memory and phonological awareness (Charlier & Leybaert, 2000; Logan et al., 1996; MacSweeney et al., 1996; Miller, 1997). Another consequence of inadequate phonological representations is that they do not obtain reading and spelling skill levels comparable to those of normal hearing individuals (Aaron, Keetay, Boyd, Palmatier & Wacks, 1998; Conrad, 1979; Harris & Beech, 1995; King & Quigley, 1985; Marschark, & Harris, 1996; Merrills, Underwood & Wood, 1994).

In summary, the studies reviewed above indicate that congenitally deaf people are in possession of phonological skills which can be used to solve cognitive tasks that require phonological processing. This is true not only for orally educated individuals, but also for the deaf that have sign language as their first language. Thus, lack of auditory speech stimulation does not completely prevent the development of phonological processing skills in congenitally deaf individuals. However, congenital deafness makes the phonological processing skills develop more slowly and less accurately compared to what is found in the hearing population.

Deafened adults

It is apparent from the review on congenitally deaf individuals that a relatively large body of knowledge about cognitive processing does exist

with regard to this population. The literature is, in contrast, less informative with respect to cognitive processing in the population of deafened adults, as it seems only two studies have examined this issue (Lyxell, et al., 1996; Lyxell et al., 1994). Since cognitive processing in general begins with a sensory input, the obvious question is "What happens to the cognitive system when the auditory sense is either lost or severely distorted and, particularly, what happens to the phonological system in the absence of auditory stimulation?". Lyxell et al. (1994) examined this domain of cognitive processing in a group of deafened adults by comparing their performance to a group of hearing adults on a physical matching task, a semantic decision-making task, and a rhyme-judgement task. They found that the deafened adults' performance was significantly poorer on the rhyme-judgement task with regard to level of accuracy, but not for speed of performance. Their performance was, on the other hand, on a par with the hearing individuals on the physical matching and semantic decision-making tasks. A negative relationship between duration of deafness and level of accuracy on the rhyme-judgement task was also obtained. Based on these findings, Lyxell et al. (1994) concluded that the representational aspects of phonological processing deteriorate in deafened adults over time as a function of auditory deprivation, but that this phonological deterioration is only detectable in tasks that explicitly require phonological processing (e.g., rhyme-judgement). Lyxell et al. (1996) replicated this finding in a group of deafened adults who were candidates for cochlear implantation and could also demonstrate that the quality of the phonological representations predicted the level of speech understanding that the individual reached six to eight months after the implantation had been made.

In summary, the available research on the population of deafened adults focusing on cognitive issues suggests that deafness acquired in adulthood affects the phonological aspects of cognitive processing.

Adults with developmental dyslexia

Individuals who have been diagnosed as having developmental dyslexia (most often during childhood), display specific and severe reading and spelling difficulties with neurological and genetic bases (Cardon et al., 1994; DeFries & Light, 1996; Galaburda, 1994; Pennington, 1991). A large body of evidence indicates that a phonological deficit constitutes the

underlying cause of dyslexia at a cognitive level of explanation (see Gustafson, 2000 for a review). Thus, similar to congenitally deaf and deafened adults, the population of adult dyslexics perform poorly on cognitive tasks that require access to and manipulation of the phonological structure of words (e.g., rhyme tasks; Byrne & Ledez, 1983; Hanley, 1997; Snowling, Nation, Moxham, Gallagher & Frith, 1997). Adult dyslexics also in general perform poorly on verbal working memory task performance (i.e., word and digit span; Paulesu et al., 1996; Pennington, Van Orden, Smith, Green, & Haith, 1990). In addition, studies examining adult dyslexics' ability to quickly name nongraphic stimuli (e.g., pictures, colours) have shown that adult dyslexics are slower and less accurate in performance than adults with normal reading skills (Felton, Naylor & Wood, 1990; Wolff, Michel & Ovrut, 1990). One view that has been proposed to explain the well-documented phonological difficulties shown by dyslexics is that the quality of phonological representations stored in the mental lexicon is inadequate (Elbro, 1996; Fowler, 1991). Two different types of hypotheses have been proposed within this account: the segmentation hypothesis (Fowler, 1991) and the distinctness hypothesis (e.g., Elbro, 1996; Elbro, Borstrøm, & Petersen, 1998).

According to the segmentation hypothesis, the phonological representations of dyslexics are not fully segmentally organised into sequences of discrete phonemes. Thus, the words may be represented as more or less unsegmented gestalts. If adult dyslexics have not developed sufficiently segmented phonological representations, it should then not be surprising that they have problems with performing tasks that require phonological analysis or segmentation of those representations (e.g., phoneme deletion, Fowler, 1991; Hulme & Snowling, 1992).

The distinctness hypothesis states that the structural problem with phonological representations is that they are insufficiently distinct and precise in nature (Elbro, 1996; Elbro et al., 1998). "Distinctness refers to the magnitude of the difference between a representation and its neighbours" (Elbro, 1996, p 467). If the phonological representation has many features that distinguishes it from other phonological representation, then it is a relatively distinct phonological representation (Elbro, 1998). A phonological representation is completely specified if each unit (e.g., phoneme), constituting it, is represented by a complete set of distinctive features. Indistinctness has, according to this hypothesis, a negative effect on the speed by which the phonological

representations can be accessed from long-term memory. Because, the right phonological representation is easily confused with other similar-sounding representations if it is less well separated from other representations (cf. Luce & Pisoni, 1998). In order to perform rhyme-judgement, phoneme segmentation and phoneme identification tasks a uniquely defined whole-word phonological representation is not sufficient. Instead, each segment that constitutes the representation must be clearly defined (i.e., distinct) and accessible to the individual. If not, the individual will suffer from difficulties when performing this type of tasks. Thus, an individual's whole-word phonological representation may be sufficiently distinct to allow for adequate lexical access (i.e., word identification, pronunciation), but the individual's representations may not be sufficiently specified at the segmental level, which in turn might impair performance on specific tasks that require phonological operations on that level (i.e., rhyme tasks, phoneme segmentation tasks). Either of these two hypotheses can account for most of the phonological difficulties displayed by dyslexics and it is also important to note that the two hypotheses are not mutually exclusive (see Elbro, 1996 for a review).

In summary, the present review shows that the populations of congenitally deaf, deafened adults, and adult dyslexics all have varying degrees of problems with phonological processing, and for different reasons. Congenitally deaf individuals and adult dyslexics have a profound and global phonological deficit, whereas individuals with an acquired deafness (i.e., deafened adults) seem to have a more specific phonological deficit. The phonological problems displayed by congenitally deaf individuals and adult dyslexics seem to be of a developmental nature (although for different reasons), whereas the problem of deafened adults is that their phonological processing skills may deteriorate as a function of lack of, or a severe distortion of auditory speech stimulation. The underlying cause for the populations of congenitally deaf people and deafened adults is lack of auditory speech stimulation whereas the cause for adult dyslexics probably is neurological.

5. PHONOLOGICAL PROCESSING

It is evident from the previous sections of this thesis that phonological processing is a key process component in all cognitive activities involving language, such as listening, reading and maintaining

verbal information in working memory. In this section an attempt is made to provide a definition of this important concept by examining more closely the role of phonological processing in auditory speech processing, speech production, reading, speechreading and working memory. A short review of the existing research directly focusing on phonological processing is also included in this section.

Phonological processing in auditory speech processing

Most contemporary models and theories of auditory speech processing for normal hearing individuals (Ellis & Young, 1996; Luce & Pisoni, 1998; Marslen-Wilson, 1987; McClelland & Elman, 1986) assume that the individuals' mental lexicon contains representations of what words sound like, that is, phonological representations which are activated during the process of word recognition. Spoken word recognition is assumed to involve finding a phonologically legal match between the speech signal and the phonological representations stored in the mental lexicon. Studies reported by Gaskell and Marslen-Wilson (1996; 1998) suggest that the mapping of speech onto phonological-lexical representations is a complex process which among other things, involves on-line phonological inference processes, in order to handle phonological variation due to co-articulation. In addition, a number of studies have demonstrated that prosodic information processing contributes to auditory speech processing by facilitating the process of word recognition and segmentation of the continuous auditory speech signal (Cutler & Norris, 1988; Lindfield et al., 1999a; 1999b; Norris et al., 1995; Sven & Samuel, 1997; Vroomen et al., 1996)

Phonological processing in speechreading

A few correlational studies have demonstrated that performance on phonological processing tasks is related to visual speechreading performance, suggesting that phonological processing is involved in visual speechreading (Arnold & Köpsel, 1996; Lyxell et al., 1994; Öhngren 1992). Some authors have hypothesised that the contribution of phonological processing in speechreading might be similar to that in reading, that is, decoded visual information is recoded and transformed into a phonological code that can be mapped on to existing and appropriate phonological-

lexical representations (cf. Lyxell et al., 1994; Rönnerberg, 1995; Öhngren, 1992). Thus, both reading and speechreading involve phonological recoding, in the former case letters are transformed into sounds, whereas in the latter case visual lip movements are recoded into phonological codes. A similar view is suggested in the Rönnerberg et al. model (1998), as the main function of the semi-abstract phonological processor is to mediate lexical access by assembling and ordering smaller multimodal linguistic units or segments (i.e. phonemes, syllables, or hand configuration/palm orientation) into larger higher-order meaning units that can be mapped on to lexical representations. However, considering the cortical activation similarities with auditory speech processing (Calvert et al., 1997; MacSweeney et al., 2000; Puce, et al., 1998), it seems plausible that similar phonological processes are involved in speechreading as in auditory speech processing. Specifically, one might speculate that the extracted initial speech segments of a word are converted into abstract phoneme or syllable representations (cf. McClelland & Elman, 1986; Pisoni & Luce, 1987). These phonemic or syllabic representations activate the phonological-lexical items in the lexicon that share this word-initial information, which eventually results in lexical identification of the speechread word (cf. Luce & Pisoni, 1998; Marslen-Wilson, 1987). Furthermore, the fact that the individual extracts prosodic information (i.e., syllabic stress, rhythm and intonation) from the face of the talker suggests that prosodic information processing is another important aspect of phonological processing during speechreading, as in auditory speech processing (Lansing & McConkie, 1999).

In summary, despite the fact that speechreading is a visual mode of communication, like reading, the available research suggests that the contribution of phonological processing during speechreading is more likely to be the same as in auditory speech processing than as in reading.

Phonological processing in reading

Several studies have demonstrated that phonological processing has an important role in reading. This is especially evident during the process of reading acquisition (Bradley & Bryant, 1983; Lundberg, Frost & Petersen, 1988; Share & Stanovich, 1995; Wagner & Torgesen, 1987). According to the dual route models, the major contribution of phonological processing in reading is phonological recoding (Coltheart, 1978; Coltheart

et al., 1993; Ellis & Young, 1996). This process involves recoding or transforming letters (graphemes) into sounds (phonemes), resulting in a pre-lexical phonological code of words, prior to the identification of meaning. This phonological code gives the reader access to the phonological representations in the mental lexicon, and hence, to the meaning of a word. In order to become a skilled reader, children have to develop an efficient phonological recoding skill, but skilled readers also use this strategy when they encounter unfamiliar words (Bradley & Bryant, 1983; Wagner & Torgesen, 1987). Efficient phonological recoding requires in turn that the individual is explicitly aware of the phonology (i.e., phonemes) in the native language, so he/she can identify the sounds that the letters represent and put the sounds together to form a pre-lexical phonological code (McBride-Chang, 1996; Wagner & Torgesen, 1987).

Phonological processing in speech production

If auditory speech processing involves transforming sound into meaning, speech production involves transforming a mental concept into a sequence of spoken sounds (Levelt, 1989). According to current models, speech production involves three major cognitive processes: conceptualisation, formulation and articulation (Dell, 1986; Levelt, 1989; Roelofs, 1997). The conceptualisation process generates a conceptual structure, a message, that is to be verbally expressed. During the formulation processing stage the pre-verbal conceptual structure is translated into a linguistic form. This translation consists of two distinct stages of processing, grammatical encoding and phonological encoding. In the first stage, the grammatical encoding stage, the lexical items that constitute semantically and grammatically appropriate matches with the conceptual structure are selected and retrieved from the mental lexicon. The output of this lexical access process is a linguistic structure that is semantically and syntactically specified, but phonologically unspecified. During the phonological encoding stage of speech production, the lexical items in the linguistic structure is given a phonological form which results in a phonetic program that serves as input for articulation. During the articulation stage, the phonetic program is translated into an articulatory motor program that is executed, thus, resulting in overt speech. The two encoding stages of lexical access during formulation are uncontroversial. There are, however, disagreements among models concerning how they

are computed and there are also different views how lexical items are selected and whether they assume discrete or interactive stages of processing (e.g., Bock & Levelt, 1994; Dell & O'Seaghdha, 1991). In spite of this, phonological processing is critically involved in the production of speech in all theoretical perspectives.

In summary, models and theories of auditory speech processing, reading, speechreading as well as speech production, all converge on the assumption that the individual's mental lexicon includes representations of what words sound like, that is, their phonological representations. Phonological processing, in hearing, speechreading and reading, is also assumed to be the medium by which linguistic information is linked to higher levels of language processing (e.g., semantic processing), whereas the reverse process is assumed for speech production. However, the precise nature of these mediating processes differs between models and modalities with respect to whether they assume pre-lexical representations or not.

Phonological processing in verbal short-term memory

It is widely recognised that phonological processing is an important aspect of verbal short-term memory functioning (see Gathercole, 1997 for a review). One of the most influential models of short-term memory was originally proposed by Baddeley and Hitch (1974, see Baddeley, 1986; 1990; 1997 for revisions). Their working memory model consists of three different components: A central executive and two slave components, the phonological loop and the visuo-spatial sketchpad. The central executive, is the main component and assumed to be an attentional-controlling system. As such, it fulfils many different functions, of which some are regulatory in nature, such as transmitting information within the working memory system, as well as retrieving and transferring information from long-term memory. The central executive is also responsible for specific cognitive functions, such as logical reasoning and semantic verification (Baddeley, 1992; Baddeley & Hitch, 1974). The central executive is supplemented by two slave components, the phonological loop and the visuo-spatial sketchpad. These two components are specialised in processing and storing verbal information and visuo-spatial information, respectively. Thus, the phonological loop is of particular interest in relation to phonological processing. This component is comprised of two parts, a

phonological store where verbal material is stored by means of a phonological code which decays after approximately one-and-a-half to two seconds and an articulatory control process which serves to refresh the decaying codes by means of rehearsal. Verbal memory span, the longest sequence of items a person can encounter once and immediately recall in the correct serial order, depends on the number of items that can be refreshed before they decay. This depends, in turn, on both how quickly the traces decay and the rate of rehearsal. This model, further, postulates that auditory information gains direct access to the phonological store, whereas written material must first be recoded, by the articulatory control process, into a phonological code in order to be retained in the store (Baddeley, 1997). Baddeley (2000) recently proposed a revised version of the original three-component model in which he added a fourth episodic buffer component to the model. This component comprises a system that can integrate information from the other two slave components and from long-term memory and temporarily store this information in the form of a unitary episodic representation. According to the new model, the slave systems are more active, for example they have direct connections with the long-term memory, which means that transfer of information between working and long-term memory is not only performed by the central executive. However, the involvement of phonological processing in either of these working memory models (three- or four-component) consists of phonological coding and articulatory-phonological rehearsal.

Research on different components of phonological processing

The concept of phonological processing has received extensive attention from researchers within different domains, such as speech understanding (Kjelgaard & Speer; 1999; Smith & Pitt, 1999), speech production (Schriefers, Meyer & Levelt 1991; van Turenout, Hagoort & Brown, 1997), reading (Elbro et al., 1998; Gathercole, Willis, & Baddeley, 1991; Høien, Lundberg, Stanovich, & Bjaalid, 1995), and working memory (Baddeley, 1966; Conrad & Hull, 1964; Hulme, Maughan, & Brown, 1991; Service, 1998).

In spite of this, few studies have examined if and how there is any connection between phonological processing in these different domains. However, there are a few notable exceptions, within the domain of reading

research (Høien et al., 1995; McBride-Chang, 1995; 1996; McBride-Chang, Wagner & Chang, 1997; Wagner, Torgesen, Laughon, Simmons, & Rashotte, 1993; Watson & Miller, 1993). According to Wagner and Torgesen (1987) one can distinguish between three bodies of research on phonological processing skills: phonological awareness (i.e., the ability to access and manipulate the phonology of one's language), phonological coding in verbal short-term/working memory, and retrieval of phonological codes from long-term memory (i.e., speeded naming of objects, colours, letters, digits, and words). Wagner et al. (1993) performed a study on kindergarten and 2nd grade students examining the relationship among these three aspects of phonological processing. They explicitly addressed the question whether different phonological processing skills constitute different manifestations of a single underlying construct or whether each ability constitutes a separate underlying construct. Phonological processing was defined as the use of phonological information in processing written and oral information. Multiple measures of phonological awareness, verbal short-term/working memory, and speeded naming of letters, and digits were collected and analysed with confirmatory factor analysis. They found evidence for 4 distinct but correlated phonological processing abilities for the kindergarten students and 5 distinct phonological processing abilities for the 2nd grade students. The five latent abilities were phonological analysis, phonological synthesis, working memory, isolated naming and serial naming. Thus, phonological awareness (i.e., phonological analysis, phonological synthesis) and naming (i.e., isolated naming; serial naming) consisted of two latent variables each. In contrast to the 2nd grade students, a single latent ability accounted for individual differences on phonological analysis and working memory tasks for the kindergarten students. The results suggest that the structure of young children's phonological processing abilities includes four to five distinct abilities and that these abilities are relatively stable and coherent individual differences attributes. Furthermore, the facts that the phonological structure of kindergarten children and 2nd grade students differed and that the correlations among the phonological skills were overall lower for the older children than the younger children indicate that children's phonological processing skills became more differentiated with development. This latter conclusion is consistent with results from other studies on 4- and 5-year-old children (Gathercole et al., 1991) and 9- and 10-year-old children (McBride-Chang, 1996), showing that the nature of

younger children's phonological processing abilities can be described with fewer latent abilities than can older children's phonological processing abilities. Wagner et al's (1993) findings have been confirmed and extended by subsequent research (McBride-Chang, 1995; 1996; Watson & Miller, 1993) examining the relationship among phonological awareness, verbal short-term/working memory, and speeded naming, but also speech perception. In the study by McBride-Chang (1996), the output of a factor analysis revealed that speech perception constituted a separate factor, as did phonological awareness, verbal working memory, and speeded naming. Interesting for the present thesis is that a substantial correlation was found among the speech perception, phonological awareness and naming speed factors, providing further support to the notion that speech perception serves an important role in the development of phonological processing skills (cf. Gathercole & Martin, 1996; Leybaert et al., 1998; McBride-Chang, 1995; McBride-Chang et al., 1997; Watson & Miller, 1993).

To summarise, the concept of phonological processing covers a number of different processes involved in verbal cognition. Accordingly, the literature usually gives a rather general definition of the term, such as "the use of phonological information (i.e., the sounds of one's language) in the processing of oral and written language" or "to construct, maintain, and manipulate a segmented phonological representation of speech" (cf. Campbell, 1992; Catts, 1989; Wagner & Torgesen 1987).

A definition of phonological processing

In the present thesis, and in line with the reviewed research literature, the term phonological processing is used as an umbrella term referring to a number of cognitive operations where phonological aspects of language are processed, represented and used in different contexts. The main operations included in this term and used in the studies are: Activation of phonological-lexical representations of words (i.e., what words sound like; Campbell, 1992; Luce & Pisoni, 1998; Marslen-Wilson, 1987) or representations of single speech segments at phoneme and syllable levels (McClelland & Elman, 1986), the construction (e.g., from phonetic features and speech segments or letters; Nickels, Howard & Best, 1997; Snowling et al., 1997) of phonological codes and, to consciously maintain and/or manipulate a segmented phonological representation of speech (Elbro, 1996; Wagner & Torgesen, 1987)

6. GENERAL PURPOSE

The general purpose of this thesis was twofold: First, to examine cognitive consequences of an acquired severe or complete hearing loss. Second, to examine the possible impact of the hearing-loss related cognitive changes on speech understanding with or without hearing devices. Specifically, the effect of auditory speech deprivation on the individual's phonological processing skills was examined, and how this relates to speech understanding with cochlear implant (i.e., hearing) and visual speech understanding (i.e., speechreading).

A central point of this thesis, is the assumption that a long period of auditory deprivation or a severe distortion of the auditory signal may inhibit the possibility to maintain adequate auditory-based phonological processing capabilities (Lyxell et al., 1994). The rationale is based on the assumption that the full spectrum of phonological information is only available through the auditory modality (cf. Leybaert et al., 1998). Thus, following a severe or complete loss of hearing, the individual has no longer access to, nor the possibility to process, all aspects of the phonological information conveyed by the speech signal. Absence of a complete phonological input may consequently result in that the individual loses aspects of his/her phonological processing capabilities. This basic assumption is consistent with the notion expressed by some researchers (cf. Baddeley, 2000; Gathercole & Martin, 1996; Leybaert et al., 1998; McBride-Chang et al., 1997; McBride-Chang, 1995; Watson & Miller, 1993) that speech perception is important for the development of phonological processing skills (e.g., phonological working memory, rhyme-judgement). Empirical support for this speech perception-phonological processing connection has been provided by studies on congenitally deaf children who use cued-speech, a manual system that provides visually well-specified speech information about the phonological contrasts of spoken language, as a complement to speechreading (Charlier & Leybaert, 2000; Leybaert & Charlier, 1996).

Thus, the opportunity to perceive and process spoken language may not only be important for the development of phonological processing skills but also for the maintenance of such skills.

7. METHODOLOGICAL ASPECTS

Conducting comparative research on populations with disabilities involves a comparison of groups that are differentiated on the basis of the pre-existing disability variable (e.g., hearing impairment). Random allocation of participants to experimental or treatment groups and control groups is not possible, which may create non-equivalent groups. Thus, a quasi-experimental approach is the rule rather than an exception within the domain of disability research. This imposes restrictions with respect to the conclusions that can be drawn from the results (Cook & Campbell, 1979; Graziano & Raulin, 1997). Specifically, the experimenter is always running a risk that the groups differ on some other variable than the independent variable and that this other variable is responsible for the difference on the dependent variable (Breakwell Hammond & Fife-Schaw, 1995; Cook & Campbell, 1979; Graziano & Raulin, 1997). The threat to internal validity is a problem that must be taken seriously, and every possible step should be taken in order to reduce the potential effect of confounding variables. The most important step to reduce threats to internal validity in quasi-experimental studies is to use an appropriate control group (Cook & Campbell, 1979; Graziano & Raulin, 1997). This is done by first identifying, from a theoretical and/or empirical basis, variables that will affect the dependent variable and then use these variables as selection criteria when selecting participants to the control group. Thus, in disability research it is extremely important to employ a control group that is matched with the disability group on potential confounding variables, because this will reduce threats to internal validity and thereby strengthen the causal conclusions drawn from the study (Cook & Campbell, 1979; Graziano & Raulin, 1997). In the present research, the disability and control groups were matched with respect to age, gender, years of formal schooling, and verbal ability.

Another methodological difficulty connected to disability research, which is related to the problem with quasi-experimental design, is that individuals in these populations might also have additional impairments that exclude them as potential research participants, which consequently makes it difficult to obtain large samples.

A longitudinal design would, obviously, be the optimal way to examine phonological deterioration, because it allows for an examination of cognitive changes within individuals over time (Breakwell et al., 1995).

That is, the hearing-impaired individual's performance on cognitive tasks should be studied when he/she first becomes hearing impaired and then on several subsequent occasions. However, this design has two major disadvantages in the present context which makes it less suitable as a means for studying phonological deterioration in individuals with an acquired hearing loss. Firstly, when performing longitudinal design studies, it is important that the time between the test occasions are long enough so that changes in the variable of interest could occur, which in this case probably means five to ten years (Ito, Iwasaki, Sakakibara & Yonekura, 1993). Thus, one major disadvantage with longitudinal designs, in general and particularly in the present case, is that they take a long time to complete (Breakwell et al., 1995). Secondly, it is often difficult to get in contact with individuals who are willing to participate in such time demanding studies and the number of drop outs is often large (Graziano & Raulin, 1997).

As many research issues are not possible to address by means of experimental studies, or even quasi-experimental studies, the researcher has to rely on correlation research. However, this type of design is a less constrained research method than a quasi-experimental design, because in correlational studies the researcher cannot control for confounding variables by selecting a matched control group (Graziano & Raulin, 1997). A fundamental procedure to minimise effects of confounding variables in correlation research is to statistically control for the influence of other variables by using partial correlation analysis (Graziano & Raulin, 1997). This type of statistical procedure was employed in this thesis in order to remove effects of chronological age.

An additional way, which was used in the present thesis, to strengthen the conclusions of the results is to combine group comparisons and correlational analyses in the same study. The use of such a hybrid study design provides an opportunity to corroborate the conclusions drawn from group comparisons with results from an individual difference approach.

The literature on methodological issues related to research on specific populations (e.g., the geriatric population; see Kausler, 1991 for a review) presents a number of research designs that can be used to control for confounding variables. However, all these designs require repeated observations over time (i.e., longitudinal designs) or relatively

large numbers of participants, which, as previously noted, is not possible to obtain with the present population.

In summary, when performing disability research one is confronted with many methodological issues that complicate the pursuit of empirically based knowledge. The researcher's task is to handle these problems as well as possible by employing every available method and technique separately or in combination.

8. PURPOSES OF STUDIES I-IV

The overall purpose of this thesis was to investigate the existence of cognitive consequences of an acquired hearing loss, and the possible impact of these cognitive changes on the ability to speechread and to understand speech with a cochlear implant. The specific purposes of and questions addressed in the four studies that constitute the empirical part of the present thesis are as follows:

In study I focus was on phonological processing skills in individuals with an acquired severe hearing impairment. The specific purpose was to examine whether severely hearing impaired individuals display impaired phonological processing capabilities as previously has been found in deafened adults. In contrast to deafened adults, this population still has enough of functional residual hearing capacity to enable them to communicate with other individuals by using their hearing aids.

Study II further examined the impaired phonological processing skills of individuals with an acquired severe hearing impairment observed in study I. The specific question addressed was: Which aspects of the phonological processing system are impaired, and which are preserved? This question derives from a conceptual framework of the place and role of different aspects of phonological processing.

Study III examined possible pre-operative cognitive predictors of post-operative speech perception performance after 12 months of experience with cochlear implants in a group of deafened adults. It was assumed that the quality of the phonological representations of speech sound, verbal information-processing speed, and working memory capacity, could account for some of the variation in the outcome with cochlear implants (cf. Lyxell et al., 1996).

The main purpose of study IV was to identify cognitive predictors of visual speech understanding. The specific purpose was to examine whether

performance in different visual speech understanding tasks, varying in linguistic complexity and level of contextual constraint, is related to a single set of cognitive abilities; or whether some tasks are more strongly associated with some specific cognitive skill or skills. A special focus was on phonological processing.

9. SUMMARY OF EMPIRICAL STUDIES

Study I

The study was conducted in order to examine the phonological processing skills in a group of 18 adults who have acquired a severe hearing loss in adult life. The specific research interest was whether this population, similar to deafened adults, displays difficulties when performing cognitive tasks that impose high demands on phonological processing skills. The phonological dysfunction of deafened adults correlates with duration of deafness, such that a longer duration of impairment is associated with lower levels of phonological skills. Thus, following a long period of auditory deprivation it seems hard to maintain adequate auditorily based phonological processing capabilities.

Five classes of cognitive tasks, varying in demands on phonological processing, were selected to examine whether a severe hearing impairment has consequences for the individuals' phonological processing skills. The following tasks were used: a phonological lexical access task, rhyme-judgement tasks, working/short-term memory tasks (i.e., reading span and letter span), a task of verbal information processing speed (i.e., semantic decision making), and a task of verbal inference-making (i.e., time-pressured sentence completion). An antonym test was also employed to obtain one index of verbal ability which was used to match the control group on verbal ability. Performance on these tasks for the hearing impaired group was compared to a group of normal hearing participants. These two groups were matched with respect to age (mean age 53 years), gender, years of formal schooling (mean = 11 years) and one index of verbal ability (i.e., the antonym tasks).

The severely hearing impaired individuals performed at a significantly lower level on the four rhyme-judgement tasks and the letter span task, but performed on a par with the control group on the reading span task,

the sentence completion task, the semantic decision making task and the phonological lexical access task.

In the rhyme-judgement tasks, lower accuracy levels were obtained in the wordpair test in two conditions: when the words in the wordpairs rhymed and were orthographically dissimilar and when the wordpairs were not rhyming but orthographically similar, that is, in those conditions where there is a mismatch between the graphemic and the phonological information. A difference between the groups also emerged in the rhyme tests that included pairs of words and non words, pairs of monosyllabic, and bisyllabic non words, when "Yes" responses were considered, whereas no significance was obtained for "No" responses. The combined results of the four rhyme-judgement tasks indicate that when the severely hearing impaired individuals have to rely on phonological information only, they will encounter difficulties in performing the task.

In the letter span task the severely hearing impaired individuals recalled significantly fewer items, compared to the control group, when the letters were phonologically dissimilar, but performed on a par when the letters were phonologically similar. Thus, the normal hearing group showed a significant phonological similarity effect whereas the severely hearing impaired did not.

A correlation analysis suggests that longer duration of hearing loss is associated with a lower level of performance on those tasks that impose high demands on the individual's phonological processing skills (i.e., the rhyme-judgement and letter span tasks). These relationships suggest that the deterioration of phonological processing skills is progressive in nature.

A re-analysis of data from study I: The present re-analysis was motivated for two reasons: First, the finding that the hearing impaired participants in study I did not show any phonological similarity effect on the letter span task was confusing, especially in the light of the results obtained in study II included in this thesis. Thus, in order to investigate if this lack of phonological similarity effect was due to spurious effects, performance on the letter span task was scored according to two additional scoring strategies. Second, a more close inspection of the individual performances on the cognitive tasks used in study I revealed that one participant in the hearing control group obtained extremely low accuracy scores compared to the other participants on the phonological lexical access task (pseudohomophones: .72, non-words: .22). These accuracy scores were 3.20 and 14.60 standard deviations below the group

mean of the other members of the control group and may imply that this particular individual has misunderstood the phonological lexical access task. This individual's scores were, therefore, replaced by another matched control person's scores on this task. The selected control person was matched on gender, age, educational level and verbal ability with the person she was replacing.

As the letter span task was administered according to a span procedure (see the method section study I), a letter span size scoring procedure was employed in the re-analysis (cf. Hulme, Roodenrys, Brown & Mercer, 1995). Letter span size was determined as the longest list perfectly recalled, plus .33 points for each subsequent list of the same length recalled correctly. Thus, a participant who managed to perfectly recall two lists of list-length 5 was given a span size of 5.33. An additional immediate serial recall scoring procedure was also employed in the re-analysis. In contrast to the original scoring procedure used in study I, this scoring procedure only included completely and perfectly recalled lists (cf. Baddeley et al., 1975). Thus, if an individual only managed to recall four out of five items in a list she/he did not obtain any points for this list, whereas the individual obtained four points for this list according to the original scoring procedure employed in study I. The participants' responses were scored as proportion correct.

The means and standard deviations according to the new scoring procedures along with the scoring procedure used in study I on the letter span task and the phonological lexical access task for both groups are presented in Table 2.

Table 2.

Mean performance on the letter span task, expressed as span size and proportions, and the phonological lexical access task expressed as accuracy and latency

| | Hearing impaired | Normal hearing |
|--|---------------------|------------------------|
| Letter span size | | |
| phonologically dissimilar: | 5.46 (1.08) | 6.06 (.96) |
| phonologically similar: | 4.69 (1.16) | 5.29 (.93) |
| Immediate serial recall (complete lists) | | |
| phonologically dissimilar: | .34 (.20) | .48 (.21) ^a |
| phonologically similar: | .21 (.20) | .26 (.14) |
| Immediate serial recall (not complete lists, study I) | | |
| phonologically dissimilar: | .52 (.20) | .65 (.18) ^a |
| phonologically similar: | .49 (.17) | .49 (.14) |
| Phonological Lexical access | | |
| Pseudo-homophones | .84 (.13) | .88 (.05) |
| Non-words | .87 (.14) | .95 (.05) [*] |
| Pseudo-homophones (sec) | 1.55 (.50) | 1.53 (.50) |
| Non-words (sec) | 2.43 (.82) | 2.24 (.66) |

a = $p < .05$, one-tailed t-test

* $p < .05$, two-tailed t-test

Contrary to the results reported in study I, the hearing impaired group showed a significant phonological similarity effect when performance was scored according to the two new procedures (i.e., letter span size, $t(15) = 2.31$, $p < .05$; serial recall of complete lists, $t(15) = 2.44$, $p < .05$.) and so did the hearing controls (letter span size, $t(15) = 2.99$, $p < .05$; serial recall of complete lists, $t(15) = 4.81$, $p < .05$). Thus, the absence of a phonological similarity effect observed for the scoring procedure used in Study I may be spurious. The population of hearing impaired individuals seems to use phonological codes when they maintain verbal information in working memory (cf. Baddeley, 1966; Conrad & Hull, 1964).

For immediate serial recall of complete lists, the hearing impaired group recalled significantly fewer items, compared to the control group when the letters were phonologically dissimilar and a one-tail t-test was

employed ($t(30)=1.86$ $p<.05$), as was reported in study I. However, a similar finding was not obtained when letter span size was considered.

The hearing-impaired individuals also obtained significantly lower accuracy scores on the phonological lexical access task (i.e., non-word condition; $t(30)=2.23$, $p<.05$), a task that, similar to the rhyme-judgement tasks impose high demands on phonological processing (Ellis & Young, 1996).

The difference between the rhyme-judgement, phonological lexical access and letter span tasks, and the other tasks (i.e., reading span, semantic decision making, sentence completion tasks) used in this study is that phonological processing is a predominant cognitive process in the former tasks. In the other tasks, on the other hand, phonological processing is included, but not as a central task demand. In a rhyme-judgement task, the individual is required to analyse and compare the phonological structures of wordpairs (Campbell, 1992; Johnston & McDermott, 1986; Nickels et al., 1997). In a phonological lexical access task it is necessary to recode letters (graphemes) into sounds (phonemes), resulting in a phonological code that can be matched with existing lexical representation in the mental lexicon (Ellis & Young, 1996), whereas the letter span task involves phonological coding and articulatory-phonological rehearsal (Baddeley, 1966; 1997; Conrad & Hull, 1964; Gathercole & Baddeley, 1993). The role of phonological processing in the reading span, semantic decision making, and sentence completion tasks, is important but less central compared to the other three tasks, as phonological processing is only one of several cognitive sub-processes (e.g., lexical activation, semantic and syntactic analysis) necessary for solving the task.

Thus, the poorer performance of the severely hearing impaired individuals on the rhyme-judgement, phonological lexical access, and letter span tasks collectively indicates that their phonological processing skills may have deteriorated.

The present results show that the hearing-impaired group has verbal memory spans comparable to the hearing control group. The hearing-impaired participants' performance in the phonologically similar conditions and their displayed phonological similarity effect suggest also that their ability to store and process verbal information by means of phonological codes (i.e., the phonological loop) is in fact functioning adequately. That is, their capacity to store and retain verbal information in serial order seems

to be intact, although they show a slightly lower performance (according to a one-tailed t-test) for phonological dissimilar letters when the two immediate serial recall scoring procedures were used. The reason for this might not be related to verbal working memory (i.e., the phonological loop) *per se*, but to aspects of accessing and retrieving information from long-term memory. In order to temporarily maintain a visually presented sequence of letters in verbal working memory, the letters must be phonologically recoded into phonological codes (Baddeley, 1997). This transformation requires long-term memory involvement, because in order to transform a letter into a phoneme code the individual must access his/her letter-name knowledge stored in long-term memory (Nickels et al., 1997; Wagner, Torgesen, & Rashotte, 1994). This phonological information may be impaired or otherwise difficult to retrieve for hearing impaired individuals and will consequently affect their performance on the letter span task. The reason why this does not affect their performance when the items are phonologically similar is that these difficulties may be masked by the higher demands on phonological coding that this condition imposes. An alternative account is that the potential problems with retrieving letter name information from long-term memory might be reduced when all the letters used as stimulus material sound alike (Baddeley, 1976).

The results from this study may be summarised in four main conclusions: Firstly, the results obtained on some of the tasks used in the study (i.e., the rhyme-judgement and phonological lexical access tasks) indicate that the phonological processing capabilities of individuals with an acquired severe hearing loss deteriorate as a consequence of their hearing impairment and that this deterioration is progressive in nature. Secondly, as this decrement is present in individuals with a severe hearing impairment, but with a functional hearing with their hearing aid the cause of the deterioration is apparently not the absence of hearing sensations as such. Rather, it seems that an impoverished auditory experience is enough to initiate a process of phonological deterioration. Thirdly, this phonological deterioration is, however, only observed in some specific cognitive tasks that explicitly require phonological processing. The deterioration is, thus, not an affair of all or none, rather it is restricted to specific aspects of phonological processing. Fourthly, the common feature of those tasks in which the phonological impairment is detectable is that they impose high demands on various kinds of phonological

processing. These tasks are phonologically complex as they involve phonological analysis and comparison processes (i.e., rhyme-judgement) or phonological transformation and matching processes (i.e., phonological lexical access tasks).

Study II

Study II was conducted to further examine the nature of the phonological deterioration observed in the population of individuals who have acquired a severe bilateral hearing-impairment (hearing loss greater than 70 dB) in adult life. The specific aim was to identify those aspects of the phonological processing system that are impaired and those aspects that are preserved in this population of individuals.

To accomplish this, a theoretical framework of the place and role of different aspects of phonological processing was developed, based on the following three assumptions. One assumption is that the mental lexicon includes, besides semantic representations, representations of what words sound and look like, that is, phonological representations and orthographic representations. Another assumption is that these phonological-lexical representations are activated during spoken word recognition, reading and speech production (i.e., phonological lexical access or encoding). The final assumption is that phonological processing is critically involved in verbal working memory (i.e., the phonological loop; see Baddeley, 1997 for a review). That is, temporary storage of verbal information is performed by means of phonological coding. The codes are retained in the phonological store and prevented from decaying by means of an articulatory-phonological rehearsal, which is performed by the articulatory control process component. The articulatory control process is also responsible for phonological recoding of non-phonological language input such as print and pictures.

According to the framework, two different aspects of the phonological system can be affected by the hearing impairment: 1) The phonological representations in the lexicon may be of less good quality. Poor phonological representations will, according to some authors (e.g. Elbro et al., 1998; Leybaert & Charlier, 1996), affect the speed with which these representations can be accessed and also impair the ability to perform phonological operations (e.g., rhyme-judgements). 2) The phonological deficit may be related to the phonological loop system (i.e.,

the phonological store and the articulatory control process) in verbal working memory. 3) A third possibility is that both these structures are affected.

These different phonological structures were examined by using a number of cognitive tasks where the different structures are, to a varying degree, critically involved in the performance of the task.

A visual rhyme-judgement task and a rhyme generation task were employed to allow for a specific examination of the quality of the phonological representations and the ability to perform phonological operations (i.e., analyse and compare) on the phonological representations.

An antonym generation task was employed as a control to the rhyme generation task. The task was introduced to tap the ability to match words from meaning, which requires access to the semantic representations stored in long-term memory.

A word span and a pseudo-word span task were selected to assess verbal working memory (i.e., phonological coding and articulatory-phonological rehearsal). A specific examination of possible deficits in the ability to store and process verbal information by means of phonological codes (i.e., the phonological loop) was accomplished by manipulating the phonological similarity of the stimulus material used in a short-term memory task.

A spelling-judgement task was also administered to assess the participants' general literacy ability.

Phonological processing was examined in a group of 16 severely hearing-impaired (seven males) individuals and compared to a group of 22 normal hearing individuals, matched for gender, age and educational level.

The hearing-impaired group performed significantly poorer on the two tasks (detecting that orthographically dissimilar wordpairs rhyme and the rhyme generation task) that explicitly tap the quality of the phonological representations in the lexicon, compared to the normal hearing group.

They were also significantly slower in the rhyme-judgement task when confronted with orthographically and phonologically similar non-rhyming wordpairs, these wordpairs were assumed to explicitly tap the individuals ability to phonologically compare and analyse the phonological structure of words. The finding suggests that the hearing-impaired individuals are slower in performing phonological manipulations. However, the negative correlation between the latency and accuracy measures in this specific

rhyme-judgement condition suggests that this deficit may be attributed to poor phonological representations (cf. Elbro, 1998; Leybaert & Charlier, 1996). This interpretation is consistent with the assumption that poor phonological representations will impair the ability to perform phonological operations.

In contrast to the problems with poor phonological representations and performing phonological manipulations, the hearing-impaired participants' ability to store and process semantic information (i.e., the antonym generation task) was normal. They also displayed a normal level of literacy as indicated by the spelling-judgement task.

The hearing-impaired participants performed on a par with the normal hearing individuals on the three working memory tasks. The implication is that their verbal working memory, which involves phonological coding and articulatory-phonological rehearsal of verbal information, appears to be intact.

In sum, the hearing impaired individuals suffer from difficulties when performing rhyme tasks but not when performing working memory tasks. The dissociation between the rhyme tasks and the working memory tasks was accounted for in terms of rhyme tasks imposing higher or different demands on the quality of the phonological codes than verbal memory tasks. Rhyme tasks require an analysis and a comparison of the two phonological representations, while the function of the phonological code during verbal memory tasks is "only" to maintain and store verbal material. The critical aspect of the quality of phonological codes in performing verbal memory span tasks is how quickly the codes decay. Thus, the important thing is that the phonological codes are durable, and do not decay too quickly, because memory span performance depends on the number of items that can be refreshed, by means of rehearsal. Although the same phonological code is used when performing these two types of tasks, rhyme tasks may require more well segmented and distinct phonological representations than verbal memory tasks. Verbal memory tasks require, on the other hand, phonological codes that are durable. This would mean that a severe hearing-loss makes the phonological representations less distinct or less segmented, but not necessarily less durable.

The following conclusions were made: 1) The empirical pattern from this study corroborated previously reported findings (cf. Lyxell et al., 1994; 1996; study I) that the auditorily based phonological processing

capabilities in adults with an acquired severe hearing impairment deteriorate following a severe or complete auditory deprivation. 2) The phonological deterioration in this population is not complete, rather it is restricted to certain aspects of the phonological system. 3) Specifically, the phonological representations of words in the mental lexicon are of less good quality (i.e., less distinct or segmented). The impaired phonological representations also affect the ability to rapidly perform phonological operations (i.e., analyse and compare). 4) This population has, on the other hand, a normally functioning verbal working memory. Specifically, the functioning of the phonological loop to temporarily store verbal material by means of phonological codes and articulatory-rehearsal is preserved.

Study III

The purpose of study III was to identify pre-operative, cognitive abilities that might contribute to the large variation in speech understanding after 12 months of experience with cochlear implants. Cognitive tasks assessing verbal working memory capacity (i.e., reading span; word span), verbal information processing speed (i.e., name matching; lexical decision-making; semantic decision-making) and phonological processing/representations (i.e., rhyme-judgement) were administered to 15 deafened adult cochlear implant candidates and 19 normal hearing control participants matched for age, gender and verbal ability. Estimates of the cochlear implant candidates' functional communicative abilities were obtained by classifying each cochlear implant candidate into one of four categories on an ordinal scale. The four categories in a falling scale were; 1) the ability to understand speech transmitted by telephone, 2) the ability to follow and understand speech when the speaker is out of sight, 3) improvement in speechreading with the implant, and 4) awareness of environmental acoustical stimuli.

The results revealed that the implant group performed on a par with hearing controls in all cognitive tasks used in the study, with two exceptions. Accuracy performance was significantly lower in one condition of the lexical decision task (i.e., the pseudo-homophone condition). The cochlear implant candidates also performed at a lower level of accuracy on the rhyme judgement task, when confronted with orthographically dissimilar rhyming wordpairs and orthographically similar non-rhyming

wordpairs. Thus, the results suggest that the implant group have difficulties in performing cognitive tasks that require access to and operation of the phonological representations of words. Furthermore, a correlational analysis revealed that duration of deafness was negatively related to the pseudo-homophone condition and the two critical rhyme-judgement conditions.

Pre-operative performance on the rhyme-judgement and lexical decision-making tasks was related to post-operative level of speech understanding with cochlear implants. Specifically, lower levels of accuracy on these tasks were associated with the two lower categories of the communicative ability scale (i.e., improvement in speechreading with the implant, awareness of environmental acoustical stimuli), whereas high levels of accuracy were associated with the two highest levels of speech understanding (i.e., the ability to understand speech transmitted by telephone, the ability to understand speech when the speaker is out of sight).

Working memory capacity (i.e., the reading span and word span tasks) also turned out to be related to speech understanding with cochlear implants. However, this association is less clear, because two individuals, who fell into the two highest levels of speech understanding, displayed relatively low working memory capacity. Thus, as long as the phonological representations are relatively intact, a capacious working memory is not a prerequisite for the ability to follow a conversation with a speaker who is out of sight.

The following conclusions were made. a) The quality of the deafened adults' phonological representation deteriorates as a function of absence of external auditory stimulation. b) This phonological deterioration is progressive in nature, such that longer duration of deafness is associated with poorer phonological representations. c) The quality of the phonological representations is related to the level of speech understanding with 12 months experience with the implant. The importance of having intact phonological representations when hearing with a cochlear implant is related to the process during which the acoustic-auditory speech signal is mapped on to the existing phonological representations in the mental lexicon. Poor phonological representations will interfere with this matching process and the individual will have difficulties to interpret the spoken sounds. d) A capacious working memory is not a prerequisite for auditory speech understanding given that

the individuals' phonological representations are intact, but might be useful in order to compensate for poor phonological representations.

Study IV

This study examined whether performance in different visual speech understanding tasks, varying in linguistic complexity and contextual constraints, is related to a single set of cognitive abilities or whether some tasks are more strongly associated with some specific cognitive skill or skills. These questions emerge from the fact that research showing that variations in visual speech understanding can be accounted for by individual differences in specific cognitive skills, has commonly used sentence-based speechreading as a measure of visual speech understanding. Because the various tasks differ in contextual constraints (e.g., speech tracking vs. sentence-based speechreading), and linguistic complexity (e.g., visual word-decoding vs. sentence-based speechreading), it seems plausible to assume that different measures of visual speech understanding may engage different sets of cognitive skills.

To address the research questions of this study, three measures of speech tracking and two speechreading tasks were employed. These five tasks were assumed to tax different aspects of visual speech understanding. The speech tracking measures were: conventional words-per-minute rate, optimum words-per-minute rate, and blockages. The speechreading tasks included: sentence-based speechreading and visual word-decoding. The optimum words-per-minute rate measure and the blockage index assess opposite aspects of speech tracking. The former measure provides an estimate of a speech process that runs efficiently and smoothly (i.e., no blockages), whereas the blockage index provides an estimate of a speech process that breaks down.

Speech tracking and sentence-based speechreading differ in contextual constraints. Speech tracking is more contextually constrained, such that a coherent story is presented, sentence by sentence, to the individual. In contrast, during sentence-based speechreading, as presented in this study, the only contextual information given concerns the scenario to which the sentence belongs. Finally, in order to include tests that involve less complex linguistic information, (i.e., speechreading of single words) a visual word-decoding test was employed.

The cognitive skills examined and related to visual speech understanding were lexical identification speed (i.e., lexical decision-making task), working memory capacity (i.e., reading span task, letter span), verbal ability (i.e., analogy test; antonym test), and verbal inference-making (i.e., sentence completion task). As the relationship between phonological processing and visual speech understanding was of special interest, three rhyme-judgement tasks and a phonological lexical decision task were included. In addition, the material to-be-remembered in the letter span task was phonologically manipulated to explicitly examine phonological coding of verbal information in working memory.

The results showed that lexical identification speed, phonological processing and working memory are the major cognitive correlates of visual speech understanding. In addition, chronological age was significantly correlated with visual speech understanding (i.e., younger participants were better speechreaders than older participants). Linguistically complex tests (i.e., sentence-based speech reading, speech tracking) were more strongly associated with the lexical decision speed task and the rhyme judgement speed tasks than were linguistically less complex tests (i.e., word-decoding). The pattern of correlation did not differ between the contextually constrained speech test (speech tracking) and the contextually less constrained speech test (sentence-based speech reading). In contrast to the other speech tests, none of the present cognitive tasks were associated with individual differences in number of blockages encountered during speech tracking. It was suggested that prediction of this type of measure may require tasks tapping the early stages of visual speech processing (i. e., perceptual functions). The obtained findings, regarding working memory, suggest that skilled speechreading requires the ability to use both phonological and visual working memory coding strategies.

Based on an auditory spoken word-recognition approach the correlation between rhyme-judgement speed and speechreading performance was hypothesised to reflect a stage in the speechreading process when the extracted initial speech segments of a word are converted into abstract phoneme or syllable representations (cf. Pisoni & Luce, 1987), and/or the subsequent process when these phonemic or syllabic representations activate the phonological-lexical items in the lexicon that share this word-initial information, which eventually results in lexical identification of the speechread word (cf. Marslen-Wilson, 1987).

As rhyme-judgement tasks involve manipulation and comparison of supra-segmental information (i.e., syllables), including syllabic stress, it was also argued that the associations with speechreading performance might display the processing of prosodic information during speechreading. It was assumed that word stress patterns (syllabic stress) and the rhythm of an utterance can be extracted from lips and face movements, as these speech cues have a direct correspondence to the energy of the acoustic signal, and this energy, as such, should also be displayed in the face of the talking person. Thus, the speechreader might be able to obtain these speech cues and use them to facilitate lexical identification and to disambiguate the speechread utterance. Thus, phonemic processing and prosodic processing constitute two aspects of phonological processing hypothesised to mediate lexical identification during visual speechreading.

In conclusion, specific cognitive skills were related to individual differences in visual speech understanding, and the pattern of cognitive associations varied with the different tests of visual speech. The major cognitive correlates were lexical identification speed and phonological processing speed.

10. SUMMARY OF THE EMPIRICAL FINDINGS

The overall purpose of the present thesis was to address two general questions: To examine cognitive consequences of an acquired hearing loss, and to examine the possible impact of these cognitive consequences on the ability to process spoken language presented through visual speechreading or through a cochlear implant.

The main empirical findings from the present research are as follows: The results obtained in study I, II and III provided sufficient evidence to suggest that individuals with an acquired severe hearing loss or deafness have difficulties in performing cognitive tasks involving phonological processing. An additional contribution of the present research is that these difficulties are not present across all cognitive tasks that require phonological processing, but only in those tasks that impose high and specific demands on phonological processing. The negative relationship found in study I and III between duration of deafness or hearing loss and performance on the phonological processing tasks employed in this thesis suggests that difficulties in these functions aggravate as the number of years with the impairment increases. The fact that individuals who have

been deaf or severely hearing impaired for a long period of time display poorer phonological processing capabilities than individuals who have been impaired for a short period of time provides some sort of independent evidence that the phonological deterioration is due to lack of auditory speech stimulation (cf. Gathercole & Martin, 1996; Leybaert et al., 1998; McBride-Chang, 1995; McBride-Chang et al., 1997; Watson & Miller, 1993). As such, the present results describe an acquired cognitive disability not previously documented in the literature.

It is important to note that some of the severely hearing impaired or deafened adults performed on a par with the controls on the phonological processing tasks (e.g., rhyme-judgement) used in the present research. This finding might be interpreted as some individuals managing to keep their phonological processing skills intact despite the fact that they have been severely hearing impaired or deaf for a substantial number of years. An alternative and more parsimonious interpretation is that the phonological processing skills deteriorate in all individuals with an acquired severe hearing loss, but the process of deterioration starts at different levels of phonological processing ability. In other words, it is not possible to detect, with the present methodology, the existence of a phonological deterioration in individuals with an originally high level of phonological processing skills level. Because even after a relatively substantial deterioration the status of their phonological processing skills is such that they do not display any difficulties in performing the phonological processing tasks that were employed in the present research.

The obvious question raised by the findings obtained in study I and II was whether the observed phonological deterioration affects the individual's ability to process speech, presented visually (i.e., speechreading) or through an electronic stimulation of the 8th cranial nerve by a cochlear implant. The empirical data reported in study III and IV suggest that the deteriorating phonological skills may have a negative effect on the individuals' speech processing ability. The results of study III show that the hearing capacity of deafened adults receiving a cochlear implant is related to the quality of the deafened adults' phonological representation. That is, open-ended speech understanding with cochlear implants (i.e., no visual cues of the spoken signal) requires intact phonological representations (i.e., comparable to that of normal hearing individuals). Intact phonological representations are important as they ensure that the mapping of the acoustic speech signal onto the

appropriate phonological representation is performed fast and reliably. In study IV it was shown that phonological processing speed was related to speechreading performance. Specifically, fast processing of phonemic/syllabic and prosodic information is important in order to facilitate lexical identification and to disambiguate speechread utterances.

11. DISCUSSION AND CONCLUSIONS

A general conceptual framework

In order to provide an integrated account of the present research, a descriptive conceptual framework is proposed (see Figure 1) where the findings of the empirical studies of this thesis will be discussed.

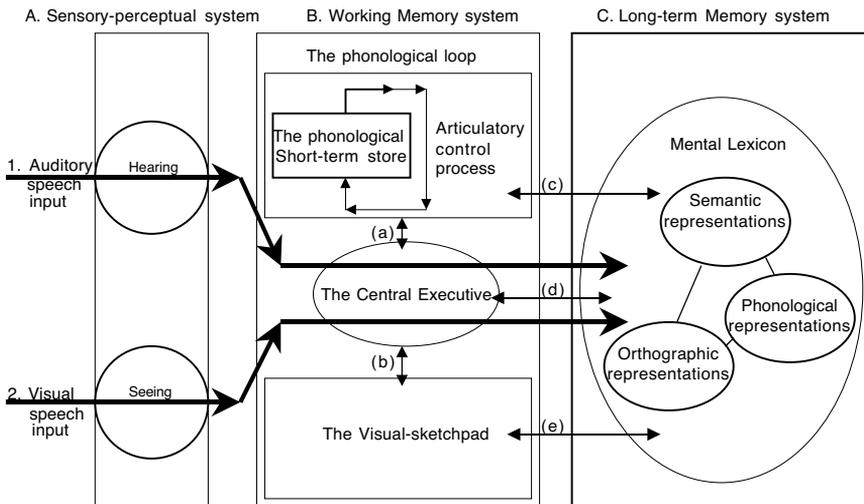


Figure 1. A framework of the place and role of different aspects of phonological processing.

The framework derives from theories of working memory (Baddeley, 1997; 2000; Gathercole, 1997) and theories of spoken word recognition (Luce & Pisoni, 1998; Marslen-Wilson, 1987; McClelland & Elman, 1986 see sections 3 and 5) and includes the following assumption: the framework includes three major components, a sensory-perceptual processing system (A), a working memory system (B), and a long-term memory (C). Information is processed within and transmitted between these three systems. The small two-way arrows display how information is transmitted within (arrows a–b) and between (arrows c–e) the different parts of the framework. Located in long-term memory is the mental lexicon, which includes not only semantic representations of the words but also the phonological and orthographic representations of these words, and the different representations are interrelated (Bock & Levelt, 1994; Caramazza & Hillis, 1990; 1991; Coltheart, 1987; Hulme et al., 1995; Taft & van Graan, 1998). It is assumed that the phonological-lexical representations are activated during spoken word recognition (Luce & Pisoni, 1998; Marslen-Wilson, 1987) and during speechreading (Calvert et al. 1997; Lyxell et al., 1994; MacSweeney et al., 2000; Puce et al., 1998). As individuals can not only recognize real familiar words but also hear single speech sounds (i.e., phonemes and syllables), new words as well as non-words, the long-term memory must also contain representations of each single speech sound at phoneme and syllable levels of the individuals' language (cf. TRACE model McClelland & Elman, 1986). In addition, the information stored in the phonological representations should not only include segmental information but also supra-segmental information, such as syllabic stress and number of syllables (i.e., word prosody; Lindfield et al., 1999a, 1999b).

The working memory system in the framework is basically a somewhat modified version of the Baddeley and Hitch three-component working memory model discussed in previous sections of the thesis (see sections 4 and 5 for more details). An additional assumption regarding this part of the framework is required. It is therefore, assumed that most cognitive tasks are executed by this component of the framework and in particular the phonological processing tasks employed in the present research.

The functions of the sensory-perceptual processing system are not specifically addressed in the present thesis. However, an assumption is that this component is responsible for an initial analysis of the acoustic or

visual speech signal. The sensory information is then transmitted to the other components in the framework. The auditory part of the sensory-perceptual processing system is impaired in the population of present interest. It can not, as such, efficiently analyse and extract information from the acoustic signal, which results in an incomplete and poorly specified auditory sensory signal. The sensory-perceptual processing system also provides the individual with a fragmentary visual sensory signal, because it is extremely difficult to extract linguistic information by viewing the face and body of the talker (Campbell et al., 1998; Dodd & Campbell, 1987; Plant & Spens, 1995). Thus, this framework is concerned with the processing of distorted or poorly specified language input (cf. Rönnerberg et al., 1998).

The purpose of the framework is not to provide a complete and detailed account of the human phonological processing system or how speech is decoded and processed. Thus, the framework does not make any causal claims about how individuals with an acquired hearing loss process speech presented visually (i.e., speechreading) or through a cochlear implant. This task is well beyond the scope of the present thesis. For example, the framework does not provide any statement regarding the issue whether the different stages and processes involved in speech processing are performed in a serial versus parallel fashion. Instead, the purpose of the framework is to describe cognitive structures which are relevant in order to illustrate which parts of the phonological system that are impaired and which are preserved, and how the phonological deficit observed in individuals with an acquired hearing loss might affect their ability to process speech.

In this framework, the empirical pattern from the present research suggests that the phonological representations in the mental lexicon (see study II) are of poor quality in the group of hearing impaired individuals. There are at least two possible complementary accounts of the nature of this impairment (cf. dyslexics; Elbro, 1996; 1998; Fowler, 1991). The phonological representations may turn into more or less unsegmented *gestalts*. That is, the phonological representations may not be fully segmentally organised into sequences of discrete phonemes (cf. Fowler, 1991; Hulme & Snowling, 1992). The second account is that the phonological representations do not have features sufficiently distinct to allow them to be separated from each other in a fast and reliable manner (cf. Elbro, 1996; 1998). That is, the individual's phonological

representation is indistinct relative to its phonological neighbours (cf. Luce & Pisoni, 1998). Either of these two types of deficits in isolation or combined, should reduce the individuals' ability to perform cognitive tasks that require phonological processing, but also, as suggested in study III and IV, impair the individuals' speech processing capability.

The present studies have not specifically examined the quality of the sub-lexical representations of the individuals' language (i.e., representations of phonemes and syllables) in long-term memory. All the same, the sub-lexical representations are assumed to be impaired as well as the phonological representations of whole words. The rationale for this assumption is that it seems reasonable that the sub-lexical units composing the word representation (i.e., phonemes and syllables; Fowler, 1991; Hulme & Snowling, 1992) are impaired if the gestalt is impaired (cf. Elbro, 1996; 1998). Furthermore, as the speech stream consists of a continuous sequence of phonemes and syllables this information need to be processed (Cutler & Norris, 1988; Grosjean & Gee, 1987) and possibly matched against sub-lexical representations (cf. the TRACE model; McClelland & Elman, 1986). Lack of auditory speech stimulation should consequently affect the sub-lexical representations in similar manner as the phonological representations of words are affected.

Furthermore, the results obtained in study II indicate that the impaired phonological representations under specific conditions affect the speed with which the individual can process phonological information (cf. Elbro et al., 1998; Leybaert & Charlier, 1996).

A basic assumption in the present research is that lack of auditory speech stimulation may result in a phonological deterioration. The negative relationship found in study I and III between duration of deafness or hearing loss and performance on the phonological processing tasks supports this assumption and suggests that the phonological deterioration is progressive in nature. This finding is consistent with the hypothesis that speech perception is important for the development of phonological processing skills (e.g., phonological working memory, rhyme-judgement; cf. Baddeley, 2000; Gathercole & Martin, 1996; Leybaert et al., 1998; McBride-Chang, 1995; McBride-Chang et al., 1997; Watson & Miller, 1993). The present results suggest that auditory speech stimulation is also important for the maintenance of the phonological processing capabilities. A further specification of this finding, provided by the present research, is that a complete absence of hearing sensations (i.e., deafness) is not

necessary for this deterioration to occur. Rather, the results of study I shows that an impoverished auditory experience (i.e., a severe hearing loss) is enough to initiate a process of phonological deterioration.

As a contrast to the problems with the phonological representations in the lexicon, the combined results from study I, II and III suggest that the verbal working memory system (see component B in Figure 1) is intact in the population of hearing impaired individuals. That is, the function of working memory to store and retain verbal information in a serial or non-serial fashion by means of phonological codes (i.e., the phonological short-term store) and articulatory-phonological rehearsal (i.e., the articulatory control process) seems to be at the same level as for normal hearing individuals. Neither are there any indications of (see study I and III) the central executive component of the working memory system being impaired. In other words, the general capacity and function of the working memory structure seem to be unaffected, whereas the phonological codes used to perform the phonological-cognitive operations in the working memory system are impaired. These conclusions are based on the assumption, presented in study III, that there is only one phonological code/representation within the whole phonological system. Specifically, when performing phonological-cognitive operations on real words or sub-lexical language units the phonological representations stored in long-term memory are activated, retrieved (see section 9) and temporarily held in working memory during further processing. When the verbal material consists of non-words, as in some of the tasks used in the present research (see study I and II), individual sub-lexical language units are activated and assembled to construct a phonological code (cf. Nickels et al., 1997; Snowling et al., 1997). The structure and function of working memory per se seem to be unaffected, but due to the fact that the linguistic information (i.e., phonemes, syllables, words) processed in working memory to solve different tasks in the same way must be retrieved from long-term memory, and as this information is of less good quality the performance level in specific operations is reduced. Specifically, individuals with an acquired hearing loss suffer from difficulties when they are confronted with cognitive tasks that require phonological operations of well segmented and/or distinct phonological representations. In contrast, the present research suggests that long-term lack of auditory speech stimulation (complete or partial) does not affect the durability of the phonological codes/representations. This

conclusion is based on the finding that the present population's ability to store and retain verbal information in working memory is comparable to the normal hearing population (see study I, II and III).

The present thesis contributes to the context of other populations with phonological disabilities, such as adult dyslexics and congenitally deaf (Byrne & Ledez, 1983; Hanley, 1997; Marschark & Clark, 1993; Pennington et al., 1990; Snowling et al., 1997), by showing that individuals with an acquired severe hearing loss also display phonological problems. It is well recognised that a congenital deafness prevents the development of adequate phonological processing skills and that neurological and genetic factors are the presumed basis of the phonological problems displayed by adult dyslexics. In addition, the present research show that a complete or partial deprivation of auditory speech stimulation in adulthood is a factor that can give rise to a phonological disability. There is, however, a number of empirical findings indicating that congenitally deaf and adult dyslexics have a more severe and global phonological deficit compared to adults with an acquired hearing loss. First of all, individuals with an acquired severe hearing impairment have, in contrast to adult dyslexics and congenitally deaf individuals, normal reading and spelling skills (see study I, II, III; Lyxell et al., 1994; 1996). Second, poor verbal working memory performance is usually found in congenitally deaf individuals (Conrad, 1979; MacSweeney et al., 1996) and adult dyslexics (i.e., word span, digit span; Paulesu et al., 1996; Pennington et al., 1990), whereas there is no indication of verbal working memory malfunctioning in the population of hearing impaired adults. Third, adult dyslexics also display an impaired ability to quickly name nongraphical stimuli (e.g., pictures, colours; Felton et al., 1990; Wolff et al., 1990). Thus, individuals with an acquired severe hearing impairment show signs of a specific and less global phonological disability than congenitally deaf individuals and adult dyslexics.

Speechreading and hearing with cochlear implants are, in contrast to listening with normal hearing, difficult and effort demanding tasks from a cognitive point of view. This statement is based on clinical observations, the relatively low levels of performance in speechreading and the large variability in performance for speech understanding with cochlear implants (Lyxell et al., 1996; O'Donoghue, et al., 2000; Rönnerberg, Samuelsson, Lyxell & Arlinger, 1996; Samuelsson & Rönnerberg, 1993). Although quite many cochlear implanted individuals are able to follow a conversation without visual support, the neuroimaging and cognitive studies reviewed in

section 3 suggest that hearing with a cochlear implant is more effortful than normal hearing in general and particularly demanding on the individuals attention and phonological processing resources. Thus, a basic assumption in the model is that the attention and executive functions of the working memory system are vital for efficient speechreading and hearing with cochlear implants.

Similar to most models of spoken word recognition, the framework postulates that speech processing involves matching the speech signal (visual or auditory) to stored phonological-lexical representations of words (cf. Luce & Pisoni, 1998; Marslen-Wilson, 1987; 1989b; McClelland & Elman, 1986). This matching process includes activation of and competition among word candidates stored in the mental lexicon (see Figure 1). As indicated by arrows 1 and 2, the speech signal is first entered into the sensory-perceptual processing system where the initial processing of the speech signal is performed. The information then flows through the working memory system and reaches the lexicon where it activates all phonological representations that phonologically match the incoming speech signal (cf. Luce & Pisoni, 1998; Marslen-Wilson, 1987). The fact that the arrows pass through the central executive component in working memory is only an illustration of the enhanced attentional requirements during speechreading and hearing with cochlear implants and do not necessarily indicate that the information is processed by this component. The phonological representation that best fits the extracted information is recognised, which, in turn, activates the semantic representation of that word also stored in the lexicon. In this framework, it is also assumed that speech recognition is strongly influenced by top-down processes, which includes various sources of information such as contextual, lexical, syntactical, and semantic information.

In the present framework the results from study III, that the quality of the cochlear implantees' phonological representations is important for what the individuals can hear with their implants, are quite clear. Low-quality phonological representations will impair the activation of the phonological representations sharing some similarities with the speech signal and will also impair the necessary process of discriminating between these activated representations so that a recognition can occur. Specifically, the probability that "incorrect" phonological representations in the lexicon, that is, representations that only share minor similarities with the presented word, will be activated by the poorly specified speech

signal delivered by the cochlear implant is higher when the phonological representations are of poor quality as opposed to when they are of good quality. Poor phonological representations should also make it more difficult to discriminate between the activated phonologically similar representations competing for recognition because the features that distinguish the representations from each other are turning less distinct during the process of phonological deterioration (cf. Luce & Pisoni, 1998; Marlen-Wilson, 1987). Given that these two critical aspects of speech processing are impaired by the poor quality of the phonological representations the cochlear implanted individual will inevitably suffer from difficulties to interpret the speech signal presented through the implant.

The results of study III also suggest that low-quality phonological representations may result in increased demand on working memory processing. The rationale for this is that a larger proportion of the spoken message will be missing or ambiguous, and, consequently, a larger amount of fragmentary speech information must be temporarily held in working memory (i.e., the phonological loop, see Figure 1) while waiting for further speech information which allows the individual to perform some form of verbal inference-making (cf. Rönnberg et al., 1998). Thus, along with the increased attentional demands imposed by the impoverished speech signal delivered through the implant (Giraud, et al., 2000; Naito et al., 2000; Wong et al., 1999) poor phonological representations might uniquely contribute to different speech processing strategies being used during hearing with a cochlear implant, compared to that used during normal hearing.

In study IV it was found that phonological processing speed is important in visual speech understanding. Consistent with the assumptions included in the present framework, it was hypothesised that phonological processing speed may be involved in the speechreading process in a number of ways that are related to lexical identification processes. As visual speechreading engages similar cortical regions as listening to auditory speech (i.e., left superior temporal areas including Heschl's gyrus; Calvert et al., 1997; MacSweeney et al., 2000; Puce, et al., 1998) it seems plausible that similar phonological processes are involved in speechreading as in auditory speech processing. Assuming this, it was proposed in study IV that one such process might be the conversion of the initial visual speech segments of a word into abstract phoneme or syllable

representations (cf. Pisoni & Luce, 1987), which, subsequently activates the phonological-lexical items in the lexicon that match this word-initial information, eventually resulting in lexical identification of the speechread word (cf. Luce & Pisoni, 1998; Marslen-Wilson, 1987; 1989b). An exact account of how the transformation of visual information into phonological codes is performed during speechreading has not yet been proposed, and neither is the present framework able to prove a satisfactory explanation of this process.

As prosodic information constitutes an important aspect of auditory speech processing (Cutler, 1989; Kjølgaard & Speer, 1999; Lindfield et al., 1999a; 1999b; Norris et al., 1995) it was proposed in study IV that prosodic information processing might be another way in which phonological processing is involved in the speechreading process. This notion was based on the assumption that word stress patterns (syllabic stress) and the rhythm of an utterance can be extracted from lips and face movements. Support for this assumption has been provided by experimental evidence showing that segmental and primary stress information is primarily obtained from the mouth region, whereas intonational information primarily is obtained from the upper parts of the face (i.e., forehead and eyes; Lansing & McConkie, 1999). Thus, similar to spoken word recognition, the number of phonological representations that are activated by the incoming speech signal is not only determined by the initial phonemic information but also by word prosody (i.e., number of syllables and syllabic stress). That is, by also taking advantage of information about the syllabic stress pattern, the number of items in the word-initial cohort can be reduced and thus, promote word recognition in speechreading (cf. Lindfield et al., 1999a; 1999b). It is reasonable to assume that the segmentation of the speech signal during visual speechreading of continuous speech follows the same principles as for auditory speech processing (Cutler & Norris, 1988; Grosjean & Gee, 1987). The extraction and processing of word stress patterns during speechreading in order to detect word boundaries in the continuous speech stream which serves as a starting point for word recognition seems like an important phonological process involved in speechreading. Thus, the necessity of segmenting the speech signal during continuous speech is a plausible explanation of why phonological processing speed showed such a strong association with visual speechreading of continuous speech. Sentence prosody may, on the other hand, contribute to visual speech

reading by identifying syntactic boundaries and solving syntactic ambiguities (Kjelgaard & Speer, 1999; Pisoni & Luce, 1987; Schepman, & Rodway, 2000; Steinhauer et al., 1999).

The results of study II indicate, and other researchers generally assume, that poor phonological representations affect the speed with which the phonological representations in the lexicon can be accessed and also impair the ability to perform phonological operations (Elbro et al., 1998; Leybaert & Charlier, 1996). As such, it is conceivable that the deteriorating phonological representations also have a negative effect on speechreading performance, which is critically dependent on fast phonological processing. Thus, according to the framework, lexical identification of the speechread words should suffer if the activation of phonological items is slowed down, because activation of all phonological representations that match the incoming speech signal constitute an important stage in lexical identification. Given that the deterioration of the phonological representations also affects word prosody information (i.e., syllabic stress and number of syllables; Lindfield et al., 1999a, 1999b) included in the phonological representations of words, it would mean that this information could not be used to reduce the number of items activated by the speech signal. Lack of adequate lexical prosodic information may also impair processes of segmentation of the speech signal during visual speechreading. These two types of deficits in phonological processing will obviously have negative consequences for the understanding of visually presented speech.

Final conclusions

The main conclusions of the present thesis can be summarised in the following five points:

- 1.) The phonological processing capabilities of individuals, who have acquired a severe hearing loss or deafness in adulthood, deteriorate progressively as a function of a period of complete auditory deprivation or with a severe hearing impairment. However, the phonological deterioration is not complete but restricted to certain aspects of the phonological system. Specifically, the phonological representations of words in the mental lexicon are of less good quality, whereas the phonological system in verbal working memory is preserved. The quality of the phonological

representations deteriorate as the representations may become less distinct and/or less well segmented.

2.) In the context of other populations with phonological disabilities, the present thesis shows that a complete or partial deprivation of auditory speech stimulation in adulthood is a factor that can give rise to a phonological disability. This disability is not previously described in the literature.

3.) The deteriorating phonological representations may have a negative effect on the ability to process and understand speech delivered through a cochlear implant, as it may both complicate the activation of the phonological representations in the lexicon and the necessary process of discriminating between these activated representations.

4.) Phonological deterioration might also impair the individual's visual speechreading performance which relies heavily on fast phonological processing. Poor phonological representations may slow down the activation of phonological items during the process of lexical identification. Another possible impact is that lack of adequate word prosody can reduce the contribution of prosodic information during visual speechreading.

5.) A clinical implication of the present findings is that audiological rehabilitation by means of cochlear implants should be implemented as soon as possible after the onset of an acquired severe hearing loss, that is, before the phonological representations have started to deteriorate. A direct test of the hearing impaired individual's phonological processing skills should also be performed as it may provide an opportunity to develop individualised rehabilitation programs adopted to the cognitive-phonological capabilities of that particular individual.

Further research

The present research and the assumptions included in the framework provide a number of research questions that need to be addressed by further studies on adults with acquired severe hearing loss.

For example, further studies should include a direct test of the ability of this population to activate and access the phonological representations stored in the mental lexicon. This specific aspect of phonological processing constitutes an important stage in speech processing. According to the present framework, low-quality phonological

representations should have a negative effect on such phonological operations and, consequently, on the individuals' speech processing capacity.

The precise nature of how the phonological representations are impaired should be examined in more detail (distinctness, segmentation, durability). This line of research should also address issues regarding supra-segmental information and the quality of the sub-lexical representations (i.e., representations of phonemes and syllables) in long-term memory.

The increasing use of cochlear implants as a means of auditory rehabilitation provide an opportunity to investigate whether the phonological deterioration is reversible, that is, if presenting speech through a cochlear implant could prevent further deterioration and possibly regain some of the lost specifications of the phonological representations.

The present research does not provide any results showing that the phonological deterioration affects the functioning of verbal working memory to temporarily store verbal material. However, this negative finding does not preclude the existence of such an effect. It is therefore necessary to examine the function of verbal working memory in more detail using experimental manipulations such as word length effect, articulatory suppression and word-frequency effect.

Finally, future research should, in general, try to validate and extend the findings of the present thesis by employing non-text based cognitive tasks (e.g., pictures; fluency task; speechreading task) and more large-scale experimental studies. It is also important to develop more sophisticated methods and tasks in order to detect signs of phonological deterioration in individuals who do not display any difficulties in performing conventional phonological processing tasks.

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