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READING STRATEGIES AND COGNITIVE SKILLS IN CHILDREN WITH COCHLEAR IMPLANTS

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SUMMARY

Background: The present study investigated working memory capacity, lexical access, phonological skills and reading ability in 6 children with cochlear implants (CI), attending grades 1-3. For each test measure, the individual performance of the children was compared to a grade-matched comparison group of children with normal hearing. Performance was also studied in relation to demographic factors.

Material/ Methods: Cognitive skills were assessed in a computer-based test battery. Different aspects of each of the component skills were tapped in various subtests. Reading comprehension was measured by the Woodcock Reading Mastery Test and decoding was assessed in the Test of Word Reading (TOWRE). The children were also tested on orthographic learning.

Results: These children with CI have specific difficulties in tasks of phonological skills and phonological working memory (WM) where nonwords are used as test stimuli. They do not seem to have problems with phonological processing of words for which they have a well defined phonological representation. They also experienced relatively more difficulties in tasks on lexical access without any contextual information.

Conclusions: We suggest that children with CI are particularly efficient in using compensatory strategies in situations where their auditory perception does not provide sufficient information to correctly match the incoming speech signal to a corresponding representation in long-term phonological storage. The children with CI in this study were skilled readers, both for decoding of words and nonwords and for reading comprehension. They may use both orthographic and phonological reading strategies, although most of them seem to be dependent on phonological decoding to some extent.

Key words: working memory, phonological skills, lexical access, reading ability

INTRODUCTION

In industrialized countries, most children who have severe to profound hearing impairment, congenital, early acquired or progressive, are fitted with cochlear implants (CI). Hearing with CI is qualitatively different from normal hearing and there continues to be considerable individual variability in outcome after cochlear implantation in terms of speech and language development, as well as academic achievement (Marschark, Roten & Fabic, 2007; Pisoni et al., 2008). A number of studies have found large variation in academic performance in children with CI. For example, 94 out of 181 children in a study by Geers (2003) achieved above the average range for normal hearing children on a composite measure of reading recognition and reading comprehension. A slightly larger proportion of children, 10 out of the 13 children in the study by Asker-Árnason, Wass, Ibertsson, Lyxell & Sahlén (2007), had reading comprehension performance in the normal range for their age. Similarly, 9 out of 16 children in the study by Mukari, Ling & Ghani (2007) were rated by their teachers as having language skills within the average range for hearing children in language subjects, and 14 out of 16 were rated as performing within this range in mathematics. The underlying causes of this variation are not yet fully understood (Pisoni et al., 2008). Most of the previous studies on children with CI have been focused on the effects of demographic variables on implant benefit. Outcome of implantation has been associated with time factors, such as earlier age at implantation in prelingually deaf children (e.g. Geers, Tobey, Moog & Brenner, 2008; Holt, Svirsky, Neuburger & Miyamoto, 2004; McDonald Connor & Zwolan, 2004), shorter period of auditory deprivation (e.g. Dorman, Sharma, Gilley, Martin & Roland, 2007; Tait, Nikolopoulos & Lutman, 2007), and length of implant use (Fallon, Irvine & Shepherd, 2007). The use of oral communication at home and attendance in mainstream education programs have also proved to have positive effects on linguistic and academic development (Geers et al., 2008), as well as variables associated with the implant, e.g. processing strategy and number of active electrodes (Geers, Brenner & Davidson, 2003).

A substantial part of the individual variability in outcome after cochlear implantation remains to be explained after demographic variables have been taken into consideration. Recent neurobiological studies suggest atypical development of neural systems and cognitive processes that are not related directly to the auditory system alone, e.g. attention, control, and self regulation (Fallon et al., 2007; Pisoni et al., 2008).

Research addressing the cognitive development in children with CI has been rather sparse. However, recent studies have found atypical development of phonological working memory (WM) in children with CI (e.g. Cleary, Pisoni & Geers, 2001; Cleary, Pisoni & Iler Kirk, 2000; Lyxell et al., 2008; Wass et al., 2008; Willstedt-Svensson, Löfqvist, Almqvist & Sahlén, 2004). Difficulties with lexical tasks (e.g. Spencer, 2004; Young & Killen, 2002) as well as phonological problems have also been reported (Dillon & Pisoni, 2006; Ibertsson, Willstedt-Svensson, Radeborg & Sahlén, 2008). In a previous study by Wass et al. (2008), children with CI between 6-13 years of age were found to have significantly poorer performance than a comparison group of children with normal hearing in tasks of working memory, lexical access and phonological skills. They experienced relatively more problems in tasks of verbal working memory (assessed by serial recall and repetition of nonwords) and phonological processing (phoneme discrimination).

The present research is a multiple case study of six children with CI. The aim of the study is two fold. First, we will investigate phonological skills in children with CI in further detail than in the studies mentioned above, where phonological skills were measured with nonword repetition (Dillon & Pisoni, 2006; Ibertsson et al., 2008; Wass et al., 2008) and nonword discrimination (Ibertsson et al., 2008; Wass et al., 2008). Specifically, we will study different levels of phonological processing, by including tasks of segmentation, identification, discrimination and representation of phonemes. However, since phonological skills play an essential part in, for example, working memory and lexical access, these cognitive abilities are studied as well. Secondly, we will relate cognitive performance to three aspects of reading: decoding of words, decoding of nonwords, and reading comprehension. Potential differences in performance between the decoding tasks may give an indication of reading strategy.

We will focus on children in grades 1- 3 (i.e. 7-9 years of age), since a majority of children have not acquired automated reading skills in this age range, and phonological skills have been suggested to be particularly important in the acquisition of decoding skills for children with typical development (e.g. Durand, Hulme, Larkin & Snowling, 2005). Therefore, it is very important to study the relation between phonological skills and reading skills in children with CI in this age range. Recent research reports that prelingually deaf children with CI, 8-9 years of age, have reading skills at the same level as children with normal hearing (Geers et al., 2008; Asker-Árnason et al., 2007), but that by the time they are 15-16 years of age they read behind grade level by 2 years (Geers et al., 2008).Thus, it is important to study cognitive and linguistic subskills that may be of importance in later reading development, at an early age. It is also important to investigate the reading strategies that children with CI may use, since orthographic reading strategies have been suggested to cause children with normal hearing to make slower progress in reading skill than children who rely on phonological strategies to a greater extent (Share, 1995).

Reading ability

A few studies indicate that children with CI have relatively high reading comprehension skills, despite poor phonological skills (Asker-Árnason et al., 2007; Dillon & Pisoni, 2006). Extensive research on children with normal hearing indicates a strong relationship between phonological skills and reading ability (e.g. Castles & Coltheart, 2004; Dally, 2006; Durand et al., 2005). There is also a relationship between working memory and reading skills (Cain, Oakhill & Bryant, 2004; Bayliss, Jarrold, Baddeley & Leigh, 2005; Gathercole, Packiam Alloway, Willis & Adams, 2005). These associations have been found in Swedish children with CI as well (Sahlén, Willstedt-Svensson, Ibertsson & Lyxell, 2008; Asker-Árnason et al., 2007). For example, in a study of 18 children with CI, 7-12 years of age, decoding of words and nonwords was associated with discrimination and repetition of nonwords and with phonological output (Sahlén et al., 2008). Accuracy and speed of reading were significantly correlated in the word decoding task (i.e. the faster, the more accurate) but not in nonword reading, where decoding was faster and more inaccurate for children with CI than for controls. The authors interpret their findings as an indication of orthographic/visual reading strategies when reading relatively common words. Decoding of new and uncommon pseudowords, on the other hand, taps phonological processing skills, since the reader must decode the unfamiliar word/ nonword phoneme by phoneme. The authors' explanation for the fast and inaccurate nonword decoding in the children with CI was that they compensate for phonological decoding problems by guessing. Associations between phonological WM and reading skills were also found by Dillon & Pisoni (2006) in a study of children with CI, 7-9 years of age, where nonword repetition was correlated with decoding of words and nonwords, and with reading comprehension. The interpretation was that the children with CI may not rely on visual word recognition in reading, but rather use phonological coding skills. When lexical diversity (produced in an oral interview) was partialled out, the correlation between nonword repetition and reading was substantially reduced. The authors therefore claim that output phonology/vocabulary may be a mediating factor in the relation between nonword repetition and reading skills by providing the child with more robust phonological representations.

Phonological skills

Previous research reveals varying results on the expressive phonology of children with CI. For example, Chin & Lento Kaiser (2000) reported inferior expressive phonology compared to children with normal hearing in the same age range. Young & Killen (2002) studied 6 prelingually deaf children with CI with a range in age at implantation between 3;0 and 6;10 years of age. Four of these children had expressive vocabularies within the average range. Measures of output phonology may provide some information about the distinctness of phonological representations for output. It is important, however, to remember that in children with output constraints, a poor production of phonemes does not rule out that the phonological representations are distinct, nor do problems discriminating phonemes always indicate that a child cannot produce them (Swingley & Aslin, 2000; Jacquemot & Scott, 2006). Furthermore, the inclusion of measures of output phonology, in this study a picture naming task (Hellqvist, 1995), provides information about whether deviant or inaccurate responses in other tasks, for example nonword repetition, are simply a product of poor output phonology.

Previous studies (Boada & Pennington, 2006; Elbro & Nygaard Jensen, 2005) suggest that phonological representations, i.e. the mental representations of words and speech sounds, play an important role for the development of phonological and linguistic skills in children with normal hearing. Some studies indicate that phonological representations of words may be phonetically well specified in children at a very young age (Swingley, 2003). For example, 18-23 month-old children were able to discriminate between correctly and incorrectly pronounced words in visual fixation tasks (Swingley & Aslin, 2000). Neither spoken vocabulary size nor ability to produce the words correctly was related to their word recognition. These results indicate that children at this young age may encode words in phonetic detail. Furthermore the perception of phonetic contrasts, below the word level, is altered by the native language for children as young as 6 months of age (Kuhl, Williams, Lacerda, Stevens & Lindblom, 1992).

Today congenitally deaf children receive cochlear implants at an earlier age than before. In Sweden, implant surgery is performed on children as young as 6 months of age. The results from some studies (e.g. Sharma, Dorman & Kral, 2005; Sharma, Dorman & Spahr, 2002; Sharma, Nash & Dorman, 2009) indicate that the sensitive period, during which the plasticity of the central auditory system is maximal, lasts until the child is 3.5 years of age. Nevertheless, even children implanted at 6 months of age experience a period of auditory deprivation before implantation, which may initially cause atypical development of phonological representations. The sound stimulation provided by CIs is different compared to normal hearing (Fallon et al., 2007; Houston, Carter, Pisoni, Iler Kirk & Ying, 2005). As a consequence, the phonological representations of words and speech sounds may become less well specified. In the present study, phonological representations of words were assessed by means of a phonological matching task.

Phonological processing is denoted here as the ability to manipulate and make decisions about phonological information. Phonological processing has been claimed to reflect a common underlying factor, which is strongly related to children's language development, and particularly reading and writing skills (e.g. Anthony et al., 2002). Significant correlations between low-level auditory processing, speech perception and phonological processing have been found in subgroups of preschool children at risk for dyslexia (Boets, Ghesquière, van Wieringen & Wouters, 2007). Relations between these basic skills may be plausible in children with CI and should thus be considered in the study of phonological processing in this population.

The relative level of difficulty in tasks commonly used to assess phonological processing differs enormously. For example, children with normal hearing seem to acquire rhyming, phoneme identification and phoneme blending before phoneme segmentation and phoneme deletion (Vloedgraven & Verhoeven, 2008). Phonological processing has been assessed in children with CI by means of a nonword discrimination task (Reuterskiöld-Wagner, Sahlén & Nyman, 2005) where their overall result was lower than that of the comparison group. Poor results for the same type of test were also demonstrated by Willstedt-Svensson et al. (2004). In order to further elaborate on development of phonological processing in children with CI, the present study includes three tasks with different demands on phonological skill:

- *phonological discrimination*, where the sound structures of two nonwords, differing only by one phoneme, are to be compared in working memory;
- *phoneme identification*, where a nonword is to be held in working memory while searched for a specific phoneme;
- *phoneme segmentation*, where the task is to mark each phoneme in a number of words.

Working memory

General working memory (WM) refers to the ability to simultaneously process and store information for a short period of time (Just & Carpenter, 1992). This ability plays a key role in various cognitive activities, including reading ability (Gathercole et al., 2005; Dally, 2006) and arithmetic skills (Durand et al., 2005). In children with CI, general WM is related to lexical and grammatical development (Willstedt-Svensson et al., 2004), and reading comprehension (Asker-Árnason et al., 2007). Results from some studies indicate atypical development of general WM in children with CI (e.g. Burkholder & Pisoni, 2003). Poorer performance of children with CI in tests of general WM may depend, however, on the modality of the task, since they, like children with SLI (Gathercole, 2006), may experience specific problems in auditory perception and/or phonological WM. Other studies have reported no significant differences between children with CI and children with normal hearing (NH) (Sahlén et al., 2008).

Phonological WM refers to the ability to store phonological information, such as a foreign word, for a brief period of time (Repovš & Baddeley, 2006). In children with normal hearing, phonological WM predicts, for example, vocabulary learning (Gathercole, 2006) and reading skill (Gathercole et al., 2005). For children with CI, phonological WM has also proved to be important for novel word learning (Willstedt-Svensson et al., 2004), word recognition, vocabulary (Cleary, Pisoni & Iler Kirk, 2000), and reading skills (Dillon & Pisoni, 2006; Asker-Árnason et al., 2007). Wass et al. (2008) found that children with CI had poorer performance levels relative to children with normal hearing both in a Serial Recall of Nonwords task (i.e. repetition of series of one-syllable nonwords), and in a Nonword Repetition task where longer and more phonotactically complex nonwords were to be repeated.

The visuospatial component of working memory is a predictor of reading comprehension in children with normal hearing (e.g. Swanson & Berninger, 1996). Poor visuospatial WM is one of the characteristics of children with reading disabilities (Gathercole et al., 2005; Del Giudice et al., 2000) but not of children with SLI (Gathercole, 2006). Atypical cognitive development associated with the hearing loss in children with CI has been claimed to impair visuospatial WM in this population (Burkholder & Pisoni, 2003). However, results from some studies indicate that children with CI can perform on par with their normal hearing peers on visuospatial working memory tasks (Wass et al., 2008; Mayberry, 1992).

Lexical access

Lexical access refers to the process of finding and retrieving verbal labels from long-term memory. The process of matching an incoming speech signal to a lexical representation in long-term memory is linked to phonological WM. In this process, i.e. reintegration (Gathercole, 2006), the incoming, possibly incomplete speech signal is held in the phonological loop until a matching long-term representation is activated. The relationship between lexical access and phonological WM may also go in the opposite direction through vocabulary, since there is a strong relation between novel word learning and phonological WM (Gathercole, 2006). Lexical access may, in turn, be dependent on vocabulary, i.e. “bigger is better.” Furthermore, lexical access has been found to predict reading and spelling performance in children with normal hearing (e.g. Plaza & Cohen, 2003; Swan & Goswami, 1997). This association may to some extent be independent of phonological working memory, since the association between phonological WM and word learning declines with age as lexical, phonological neighbours in the internal lexicon can be used as cues (Gathercole, 2006). A few studies have found children with CI to have relatively higher performance in tasks of semantic skills (Young & Killen, 2002; Wass et al., 2008), even though the overall performance was not commensurate with hearing comparison groups.

To sum up, the present research aims to investigate the phonological skills of children with CI by studying different levels of phonological processing. We will study three aspects of reading, i.e. decoding of words, decoding of non-words, and reading comprehension, as well as how cognitive skills relate to these reading measures.

METHOD

Participants

Six children with CI and 43 children with normal hearing (NH) participated in the study. The demographics of the children with CI are displayed in Table 1. Written parental informed consent was obtained for all of the participants.

The children with CI were all prelingually deaf and selected from two of the five Pediatric Cochlear Implant Programs in the southern part of Sweden.

Selection was by grade (grade 1 through 3), and children with additional known disabilities were not included. They were seen in two sessions at their schools or at a regular follow-up at their clinic. Information about hearing measures, etiology, age at implantation, and type of implant was received from medical case notes. Since the children attended pediatric cochlear implant programs in different parts of Sweden, we had to deal with the fact that speech recognition and hearing thresholds were measured by different tests. For three of the children, speech recognition was measured by phonetically balanced lists of 25 words for children. They were tested binaurally in a sound field. Based on this test, the following ranking could be made: Child 1 had the highest speech recognition level (76 %), Child 3 had the second best level (64%) and Child 5 had the third best level (60%) although it should be noted that when tested on one ear at a time, this child had 78% on one ear and 0% on the other. Child 6 was only test-

Table 1. Demographics on children with CI (PTA = Pure Tone Average)

Participant Number	Grade	Age at diagnosis (yrs; mts)	Number of implants	Age at 1st implantation (yrs; mts) Processor (type)	Age at 2nd implantation (yrs; mts) Processor (type)	Speech perception (phonetically balanced lists of 25 words)	PTA best ear (500-4000 Hz)	School setting	Main communication	Block Design Test WISC-III
1	2	2;5	2	3;6 Nucleus 24 R	6;7 Nucleus 24 Contour Advance	76% binaural	31	Special (oral+ sign)	Home: oral, school: oral + sign	70
2	3	1;0	1	3;7 Nucleus 24k	-	-	-	Special (oral+ sign)	Home: sign School: oral + sign	130
3	2	2;0	2	2;4 Nucleus 24	7;9 Nucleus Freedom with Contour Advance Electrode	64% binaural	33	Special (oral+ sign)	Home:oral School:sign	92
4	2	0;10	2	1;11 3G	6;9 3G	60% vs 36%	25	Special (oral+ sign)	oral+sign	100
5	3	0;10	2	2;0 3G	7;10 Freedom	78% vs 0% , binaural 60%	27.5	Main-stream	oral	138
6	1	0;8	2	1;7 3G	5;4 3G	88% vs 80%	25	Main-stream	Oral	138

ed on one ear at a time. This child reached 88% on one ear and 80% on the other. Since Child 6 was not tested binaurally in a sound field we cannot rank this child's speech recognition, although we may assume that the speech recognition levels would have been high even if tested binaurally in an open field. Child 4 was also only tested on each ear separately and had speech recognition levels of 36% and 60%, respectively. Child 2 was not tested with phonologically balanced lists of words.

Hearing threshold levels for the best ear measured with CI in a sound field averaged over the frequencies of 0.5, 1, 2 and 4 kHz (PTA) are presented in Table 1. Instead of using sound field hearing thresholds as an indicator of hearing, they should rather be used as a simple measure showing that the implant is functioning. Child 2 was not measured on PTA shortly before the time of testing, and the hearing levels of this child are therefore not presented.

We had 3 grade-matched comparison groups with normal hearing children, i.e. 16 children in grade 1, 15 children in grade 2 and 12 children in grade 3. The children with normal hearing were recruited from schools in Linköping, Sweden. The comparison groups were constituted by equal proportions of boys and girls. For each child with CI, an extensive case study of cognitive skills was performed, and the results were compared to the group of children with normal hearing in the same grade.

Procedure

The children with CI were seen at their school or at a regular follow-up at their respective pediatric cochlear implant program. The children with normal hearing were tested at school. The tests were administered in 2 separate 50-minute sessions. Test order was randomized within each session. The reading tests were presented on paper. All of the cognitive tests, except for the WISC-III Block Design test and the test of phonological output, were presented on the computer. Most of these computer-based tests, except the test of phonological representations and word discrimination, were taken from a computer-based test battery, the SIPS, i.e. the Sound Information Processing System with auditory-, and picture-based presentation of information. All of the SIPS tests, except the matrix pattern test and the passive naming test, had auditory-only presentation using the same female speaker's voice.

The SIPS tests were presented on a portable laptop computer with 38 cm screen (1024×768 pixels). The audio files were presented through 2 external loudspeakers. Before testing, the volume of presentation was adjusted to a comfortable level for each individual child. Before each test session began, the examiner made sure by asking the child whether the CI was working properly. The instructions were oral, but the children were offered the opportunity to have them signed as well. During the test session, the children's responses were oral. In those tests where response latencies were recorded, they responded by pressing the space key on the computer.

Tests

The description of the tests included in the SIPS battery is presented in a brief version. For more detailed descriptions the reader should consult Wass et al. (2008). Test abbreviations for all of the tests are presented in Table 2.

Working memory

Phonological WM was assessed in the *Serial Recall of Nonwords test* and the *Nonword Repetition test*. In the former test, the task is to repeat series of nonwords of increasing length, while in the latter task, individual 3-4 syllable nonwords are to be repeated. In both tests, performance was scored in two ways, as percent consonants correctly reproduced in the correct position in the nonword (pcc) and as percent suprasegmental accuracy (psa), i.e. correct stress and length of the nonword. Due to time limitations, this test was not administered to 2 of the children, Child 1 in grade 2 and Child 2 in grade 3.

General Working Memory, i.e. the capacity to simultaneously store and process information, was assessed in the *Sentence Completion and Recall task.* The task is to listen to series of sentences with the last word missing and to fill in and memorize the missing words, e.g. "Crocodiles are green. Tomatoes are ….", and thereafter to repeat the words that were previously filled in. The series of sentences included two, three and four sentences. The results were scored as the total number of correctly stored and reproduced words, with a maximum score of 18.

The *Visual Matrix Patterns test* was used to assess visuospatial working memory. A pattern of filled cells in a five by five matrix is displayed on the computer screen for two seconds. Thereafter, the task is to replicate the pattern of filled cells in an empty matrix. The level of difficulty increases from 1 to 8 filled cells. The children received span scores for the highest level of difficulty at which they correctly reproduced two out of three test patterns (maximum score = 8).

Phonological skills

Phonological Output was assessed in a picture naming test, the Swedish Test of Phonemes (Hellqvist, 1995). The repetition attempts were scored both binary, as either correct or incorrect, and as pcc. In the test of *Phonological Representations*, the task was to decide whether each of 5 oral versions of a word, auditorily presented on the computer, was correct or not. Only one version of the word was correct, e.g. dooth – *tooth* – nooth – rooth. The child answered by responding "yes" or "no" after each stimulus. Before the task, the child was asked to name a corresponding picture of the object, to make sure that he/she had the semantic/lexical representation of the target word. If the child could not name the pictured object, the experimenter provided the correct name and asked the child whether he/she knew the word. All of the words in the test were familiar to all of the participants. The representations of 3 different phonemes (s, n, t) were tested in three different positions of

Table 2. Tests used

Area	Test	Quantification
Phonological working memory	Serial Recall of Nonwords percent consonants correct (SR pcc)	% consonants correct out of 84
	Nonword Repetition percent consonants correct (NWR pcc)	% consonants correct out of 120
General working memory	Sentence Completion and Recall (SCR)	Total number of words correctly filled in and recalled (max=18)
Visuospatial working memory	Matrix Patterns (MP)	Highest complexity level, with 2 out of 3 test items correct (max=8)
Phonological skills	Output phonology	Percent consonants correct (pcc)
	Phonological Representations and Word Discrimination	Number of words with correct answers in both tests (max=9)
	Nonword Discrimination latency for correct responses (ND latency)	Mean Response latency (ms)
	Nonword Discrimination accuracy (ND accuracy)	Number of correctly discriminated pairs of nonwords (max=8)
	Phoneme Identification latency for correct responses (PI latency)	Mean Response latency (ms)
	Phoneme Identification accuracy	Score calculated according to formula (Foo et al., 2006)
	Phoneme segmentation accuracy	Number of correct responses (max=9)
Lexical access	Passive Naming latency	Mean Response latency (ms)
	Passive Naming accuracy	Number of correct responses (max=9)
	Wordspotting response latency for correct responses (WS latency)	Mean Response latency (ms)
	Wordspotting accuracy (WS accuracy)	Number of correct responses (max=9)
	Semantic Decision Making response latency for responses (SD latency)	Mean Response latency (ms)
	Semantic Decision Making accuracy (SD accuracy)	Number of correct responses (max=29)
Reading (decoding)	TOWRE Decoding of words	Number of correctly read words (max=208)
	TOWRE Decoding of nonwords	Number of correctly read nonwords (max=126)
Reading comprehension	Woodcock Reading Mastery Test- Revised	Number of correct answers (max=68)

words: initial position, middle position, and final position. The distracters were constructed by replacing the correct phoneme by another phoneme with approximately the same place of articulation. The test was scored binary, with a maximum score of 9, where 1 credit was given for correct identification of a word plus correct rejection of each of the incorrect alternatives.

The *Word Discrimination* test was designed as a complimentary test to the test of phonological representations, to make sure that the child could discriminate between the phonemes which were to be identified as correct or incorrect in the phonological representations task. In the Word Discrimination test, each target word from the Phonological Representations test was presented in live voice by the experimenter, once together with one of its corresponding distracters from the phonological representations test, and once together with an identical target word e.g. “dooth – tooth”, “tooth – tooth”. The task was to decide whether each pair of words/nonwords was identical or not. In order to receive full credit for a test item, the child had to both identify the identical word pair and the not identical word pair. A composite score for the Phonological Representations test and the Word Discrimination test was computed, where the child would need to have correctly discriminated a word in the word discrimination task in order to receive credits for the corresponding items in the phonological representations task.

In the *Phoneme Segmentation test,* the child was required to count the number of phonemes in separate words, by repeating an auditory presented word to herself / himself and to press a button on the computer for each sound, i.e. phoneme, present in the word. The maximum accuracy score in this test was 9.

A *Nonword Discrimination* task was used to assess the discrimination of phonemes. In this test, the task was to decide, by pressing a key on the computer, whether two auditorily presented nonwords were identical. The nonwords were presented in 16 pairs, and each target nonword was presented in two conditions, once together with an identical nonword and once together with a similar nonword, differing by a single phoneme (e.g. ranivadrup – ranivadrup, ranivadrup – ranivagrup). In order to receive credit for a nonword, the child had to make correct decisions in both conditions. Accuracy and speed of performance were recorded. The maximum score was 8.

In the *Phoneme Identification* test, the task was to decide whether a certain phoneme was present in an auditorily presented nonword, and to confirm by pressing a computer key only when the phoneme was present, e.g. Is there an /s/ in nessolà? Both accuracy and speed of performance were recorded.

Lexical access skills

Response latencies were recorded in all three tests on lexical access. In the *Passive Naming test*, the child was asked to identify nouns, as quickly as possible, by clicking on the corresponding picture out of 4 alternatives displayed on the computer screen. The maximum accuracy score was 9. The *Wordspotting* *test* required the child to identify real words in a context of non-words, by pressing a key on the computer whenever hearing a real word. The maximum accuracy score was 9. In the *Semantic Decision Making test*, the task was to indicate, by pressing a computer key, whether auditorily presented nouns belonged to certain, predefined semantic categories. The maximum score was 29.

Reading ability

Decoding of words was tested by the Test of Word Reading Efficiency (TOWRE; Torgesen, Wagner & Rashotte, 1999, Swedish version by Byrne et al., 2009). The children were required to read as many words as possible in 45 seconds. They were also asked to read as correctly as possible. This procedure was repeated twice with two separate lists of words. The children received credits for every word read correctly. The maximum score was 208. Decoding of nonwords was also assessed by the TOWRE. The relevant subtest is performed in exactly the same way as the TOWRE test of word decoding, except that nonwords are used instead of real words. The children received credits for every nonword read correctly. The maximum score was 126. Reading comprehension was further measured by a Swedish translation of the Woodcock Reading Mastery test – Revised (Woodcock, 1987, Swedish version by Byrne et al., 2009). The children's answers were scored according to the manual. A more lenient scoring was also used, in which the children received credits for answers which were semantically and syntactically correct. The maximum score for each of these measures was 68.

Nonverbal intelligence

Nonverbal intelligence was tested by means of the Block Design test from the WISC-III battery (Wechsler, 1991). This test was chosen because it does not require oral/auditory skills, and because the scores estimated from this test are known to be strongly correlated with performance on the entire WISC-III battery.

RESULTS

For each of the cognitive tests and reading tests, the performance of individual children is presented and related to their corresponding comparison group. Second, the cognitive characteristics of the two children with poorer reading comprehension scores are reported. Third, the cognitive performance of individual children is related to demographic aspects (e.g. age at diagnosis, school setting).

For those cognitive tests in which the children with normal hearing were considered to have a normal distribution of results, the modified t-test advocated by Crawford & Howell (1998) was used, comparing the individual performance of each child with CI to his/her grade-matched comparison group. Since the t-test could only be used for normally distributed data, it could not be used for several of our tests, in which the performance of the children with normal hearing was (and should be) very close to the maximum score. The accuracy measures of these tests were scored as number of correct answers, and the children received 1 credit for every correct test item. Thereafter, for each of these tests and for each child with CI, we calculated the probability (P) that he/she would give the correct answer. This score was compared to the probability that the children in the grade-matched comparison group would give the correct answer. Exact calculations in SPSS for binomial distribution were used, since normal approximation is not appropriate. Probability-scores of $P<.05$ are reported as significant with 99% confidence. This computation may be considered a straight-forward measure of the probability that the result of the child with CI was drawn from the same population of results as the children in the comparison group. For grade 2, in which we had 3 participating children with CI, we also used the Mann-Whitney U-test to compare the performance of the small group of children with CI to the children with normal hearing in the same grade.

Since only one significant difference in performance between the boys and girls was found in the normal hearing group (i.e. boys had shorter response latencies in the Passive Naming test), we considered it appropriate to have equal proportions of boys and girls in the comparison groups.

Correlation analyses between nonverbal intelligence and all other cognitive measures were performed for the normal hearing children. Nonverbal intelligence was only correlated with one of the other cognitive measures (Nonword Repetition, $r=.553$ - $.622$, depending on the scoring-method of the test, $p<.05$) in the children with normal hearing. These correlations were only significant in grade 1.

Working memory

The individual WM results of the children with CI together with the results of their respective grade-matched comparison group and statistical tests are displayed in Table 3.

Phonological working memory

All 6 children with CI performed significantly below the level of their corresponding comparison group on both measures (pcc and psa) of the Nonword Repetition test. Child 6 in grade 1 had a relatively higher performance compared to the other children with CI, but it was still significantly below the level of the children with normal hearing.

One of the children with CI, Child 6 in grade 1, did not perform significantly below the comparison group in grade 1 on either the pcc or the psa measures of the Serial Recall of Nonwords test. Child 4 in grade 2 performed on a level with the comparison group on the pcc measure, but not on the psa measure of the test, and Child 5 in grade 3 did not perform significantly below the comparison group on the psa measure.

Table 3. Results from working memory measures for each individual child with CI compared to the control group

test	Control mean (standard deviation)	Participant number	t-test,1-tailed	Estimated percentage of NH children falling below individual's score (95% lower confidence limit – 95% upper confidence limit)	Mann- Whitney U exact test (comparing the group of 3 children in grade 3 with their grade matched control group)
SCR	Grade 1: 11.2 (2.23) N=16	Child 6:11	-0.09 n.s.	46.6 (28.1 - 65.7)	
	Grade 2: 12.8 (1.61) N=15	Child 4:13	0.12 n.s.	54.7 (35.0 - 73.6)	8.5 n.s.
		Child 1: 7	-3.49**	0.18 (0,00 - 1.5)	
		Child 3:5	-4.69**	0.02 (0.0 - 0.1)	
	Grade 3: 12.6 (2.11) N= 12	Child 2:9	-1.64 n.s	6.5 (0.5 -21.5)	
		Child 5:14	0.64 n.s.	73.2 (50.9 - 90.0)	
MPp	Grade 1: 4.3 (1.18) N=16	Child 6:4	-0.25 n.s.	40.4 (22,7 - 59.8)	
	Grade 2: 4.8 (1.01) N=15	Child 4:5	0.19 n.s.	57.5 (37.6 - 76.0)	17.0 n.s.
		Child 1:3	-1.73 n.s.	5.3 (0.5 - 17.3)	
		Child 3:5	0.19 n.s.	57.5 (37.6 - 76.0)	
	Grade 3: 5.1 (0.9) N=12	Child 2:5	-0.11n.s.	45.9 (24.9 - 67.7)	
		Child 5:5	-0.11n.s.	45.9 (24.9 - 67.7)	
MP calculation	Grade 1: 0.493 (0.17) N=16	Child 6: .70	1.2 n.s.	87.2 (71.0 – 96.9)	
	Grade 2: 0.506 (0.16) N=15	Child 4: .66	0.93 n.s.	81.6 (63.1- 94.2)	18.0 n.s.
		Child 1: .24	-1.61 n.s.	6.5 (0.7 - 19.5)	
		Child 3: .67	0.99 n.s.	83.1 (64.9 - 95.0)	
	Grade 3: 0.663 (.09) N=12	Child 2:.52	-1.5 n.s.	7.8 (0.7 - 23.9)	
		Child 5:.58	-0.9 n.s.	19.7 (5.6 - 41.1)	

Table 3. Results from working memory measures for each individual child with CI compared to the control group (cont.)

NWRpcc	Grade 1: 81.7 (8.63) N=16	Child 6: 63.3	-2.2*	2.8 (0.1 - 11.1)	
	Grade 2:88.6 (5.70) N=15	Child 4: 37.5	-8.7**	0.0 (0.0)	0.000***
		Child 1: 20	-11.7**	0.0(0.0)	
		Child 3: 30.8	-9.8**	0.0 (0.0)	
	Grade 3: 87.6 (4.7) N=12	Child 2: 48.3	-8.0**	0.0 (0.0)	
		Child 5:60	-5.6**	0.01(0.0 - 0.04)	
NWRpsa	Grade 1: 76.3 (11.6) N=16	Child 6: 54.2	-1,8*	4.2 (0.3 - 14.5)	
	Grade 2: 86.4 (11.1) N=15	Child4: 8.3	-6.8**	0.0 (0.00)	0.000***
		Child 1: 4.2	-7.2**	0.0 (0.00)	
		Child3: 20.8	-5.7*	0.0 (0.01)	
	Grade 3: 81.3 (7.0) N=12	Child 2: 29.2	-7.2**	0.0 (0.0)	
		Child 5:12.5	-9.4**	0.0 (0.0)	
SRpcc	Grade 1: 55.3 (11.7) N=16	Child 6: 46	-0.8 n.s.	22.6 (8.9 - 41.3)	
	Grade 2:59.3 (12.1) N= 15	Child 4:45	-1.1 n.s.	13.6 (3.3 - 30.7)	
		Child 1: -	-	-	
		Child 3:29	-2.4*	1.5 (0.02 - 7.4)	
	Grade 3: 61.2 (7.2) N= 12	Child 2: -	-	-	
		Child 5: 39	-3.0**	0.7 (0.0 - 4.6)	

General working memory

Four of the children with CI (Child 6 in grade 1, Child 4 in grade 2, and Child 5 and Child 2 in grade 3) did not perform significantly below their respective grade-matched comparison group on the test of general WM. Two of the children with CI, Child 4 in grade 2 and Child 5 in grade 3, even had

Table 3. Results from working memory measures for each individual child with CI compared to the control group (cont.)

SRpsa	Grade 1: 76.3 (11.6) N=16	Child 6: 62	-1.2 n.s.	12.5 (3.0 - 28.6)	
	Grade 2: 86.4 (11.1) N=15	Child 4: 62	-2.1*	2.6 (0.08 - 10.8)	
		Child 1: -	-	-	
		Child 3: 24	-5.4**	0.0 (0.0 - 0.02)	
	Grade 3: 77.1 (10.33) N= 12	Child 2:	-	-	
		Child 5: 62	-1.4 n.s.	9.4 (1.2 - 26.8)	

higher scores than their comparison groups. According to the Mann-Whitney test, there were no significant group differences between the NH children and the 3 children with CI in grade 2.

Visuospatial working memory

None of the 6 children with CI performed significantly different from their comparison group on the measure of Visuospatial WM.

Phonological skills

Results on the measures of phonological skills are reported in Table 4 for individual children with CI and their hearing comparison groups.

The children with CI performed between 95 and 100 on the percent consonants correct (pcc) measure of the phoneme test. Child 5 and Child 6 both had a pcc score of 100. Child 1 and Child 4 had the lowest scores of 95 and 97 respectively. When a binary scoring of the test was applied, performance varied between 90 and 100 percent words correctly produced. Child 5 and Child 2 had the best performance on this measure with scores of 100 and 99 percent correctly reproduced words. Child 4 and Child 1 had the lowest scores on this measure of the test. The children with normal hearing were not tested, since children with typical development at age 5 reach 98% consonants correct, and have previously have been found to have maximum performance at the age of seven (Hansson & Nettelbladt, 2002).

A difference score between the pcc-measures of phonological output for words (the phoneme test) and nonwords (nonword repetition) revealed that the children with CI had difference scores ranging from 37 to 75 percent. Child 1 and Child 3 had the highest scores of 75 and 67.5 respectively. Child 6 and Child 5 had the lowest scores (37 and 40).

Table 4. Results from measures of phonological skills for each individual child with CI compared to the control group

test	Control mean (standard deviation)	Particip ant number	P (exact calculations for binomial distribution) , 99% confidence-level	t-test, 1-tailed	Estimated percentage of NH children falling below individual's score, (95% lower confidence limit – 95% upper confidence limit)	Mann-Whitney U exact test (comparing the group of 3 children in grade 3 with their grade matched control group)
Nonword Discrimi-nation (ND) accuracy	Grade 1: 7.7 (0.60) N=16	Child 6: 6	.187 n.s.	-	-	-
	Grade 2:7.9 (0.35) N=15	Child 4:4	.0013**	-	-	0.000**
		Child 1:3	7.86e^{-005}**	-	-	
		Child 3:4	.0013**	-	-	
	Grade 3:7.8 (0.4) N=12	Child 2: 5	.0289*	-	-	-
		Child 5: 7	.0529 n.s.	-	-	-
Nonword Discrimi-nation (ND) latency	Grade 1: 3545.5 (147.5) N=16	Child 6: 3469	-	-0.503 n.s.	31.1(15.0 - 50.5)	-
	Grade 2:3516.5 (267.8) N=15	Child 4: 3585	-	0.248 n.s.	59.6 (39.6 - 77.8)	11.0 n.s.
		Child 1: 3898	-	1.379 n.s.	90.5 (75.3 –98.4)	
		Child 3: 3592	-	0.273 n.s.	60,6 (40,5 - 78,6)	
	Grade 3: 3510.8 (185.6) N=12	Child 2: 3810	-	1.549 n.s.	92.5 (76.6 – 99.3)	-
		Child 5: 3545	-	0.177 n.s.	56.9 (34.8 - 77.4)	-

Table 4. Results from measures of phonological skills for each individual child with CI compared to the control group (cont)

Phoneme segmentation (PS) accuracy	Grade 1: 7.38 (1.67) N=16	Child 6: 6	.455 n.s.	-	-	-
	Grade 2:7.7 (1.54) N=15	Child 4:6	.371 n.s.	-	-	10.0 n.s.
		Child 1:8	.915 n.s.	-	-	
		Child 3:5	.148 n.s.	-	-	
	Grade 3:7.7 (1.7) N=12	Child 2:7	.700 n.s.	-	-	-
		Child 5:9	1.0 n.s.	-	-	-
Phoneme Identification Accuracy (PI)	Grade 1: 0.912 (.097) N=16	Child 6: .86	-	-0.520 n.s.	30.5(14.6 - 49.9)	-
						-
	Grade 2: .872 (.221) N=15	Child 4: .46	-	-1.805*	4.6 (0.3 - 15,8)	1.0**
		Child 1: -.06	-	-4.083**	0.06 (0.0 – 0.5)	
		Child 3:.14	-	-3.207**	0.3 (0.0 – 2.3)	
	Grade 3: .964 (.06) N=12	Child 2:1.0	-	0.576 n.s.	71.2 (48.9 – 88.6)	-
		Child 5: .86	-	-1.665 n.s.	6.2 (0.4 – 21.0)	-
Phoneme Identification (PI) latency	Grade 1: 4024 (313) N=16	Child 6: 4632	-	1.884*	96.1 (86.1-99.7)	-
	Grade 2: 4028 (170) N=15	Child 4: 4620	-	3.372**	99.8 (98.2-100.0)	0.000**
		Child 1: 5965	-	11.032**	100 (100)	
		Child 3: 4380	-	2.005*	96.8 (87.4-99.9)	
	Grade 3: 3737 (336) N= 12	Child 2: 4139	-	1.149 n.s.	86.3 (66.7-97.3)	-
		Child 5: 4041	-	0.869 n.s.	79.8 (58.4-94.2)	-

Table 4. Results from measures of phonological skills for each individual child with CI compared to the control group (cont)

Phonologial Representations partial credits (PRpc)	Grade 1: 17.94 (0.11) N=16	Child 6: 17.75	-	-	-	-
	Grade 2: 17.93 (0.11) N=15	Child 4: 16.75	-	-	-	0.0**
		Child 1: 15.50	-	-	-	
		Child 3: 16.75	-	-	-	
	Grade 3:17.98 (0.07) N=12	Child 2: 16.75	-	-	-	-
		Child 5: 17.5	-	-	-	-
Phonologial Representations binary scoring (PRbin)	Grade 1: 8.75 (0.48) N=16	Child 6:8	0.528 n.s.	-	-	-
	Grade 2: 8.73 (0.46) N=15	Child 4:5	.0057**	-	-	2.0**
		Child 1: 3	$3.51e^{-005}$***	-	-	
		Child 3:8	.572 n.s.	-	-	
	Grade 3:8.92 (0.29) N=12	Child 2:8	.427 n.s.	-	-	-
		Child 5: 8	.427 n.s.	-	-	-
Phonological representations partial credits adjusted for word discrimination (PRpc adjusted)	Grade 1: 17.94 (0.11) N=16	Child 6: 16.0	-	-	-	-
	Grade 2: 17.93 (0.11) N=15	Child 4: 15.25	-	-	-	-
		Child1: 10.25	-	-	-	-
		Child 3: 16.0	-	-	-	-
	Grade 3:17.98 (0.07) N=12	Child 2: 16.0	-	-	-	-
		Child 5: 14.0	-	-	-	-

Table 4. Results from measures of phonological skills for each individual child with CI compared to the control group (cont)

Representations binary scoring (PRbin) adjusted for word discrimination	Grade 1: 8.75 (0.48) N=16	Child 6:8	0.528 n.s.	-	-	-
	Grade 2: 8.73 (0.46) N=15	Child 4:5	0.0057**	-	-	-
		Child 1:2	0.000**	-	-	-
		Child 3:8	0.572 n.s.	-	-	-
	Grade 3:8.92 (0.29) N=12	Child 2:8	0.427 n.s.	-	-	-
		Child 5:7	0.098 n.s.	-	-	-
Phonological output(pcc)	Grade 1:	Child 6:100	-	-	-	-
	Grade 2:	Child 4:97	-	-	-	-
		Child 1:95	-	-	-	-
		Child 3:98	-	-	-	-
	Grade 3:	Child 2:99	-	-	-	-
		Child 5:100	-	-	-	-
Phonological output binary scores (bin)	Grade 1:	Child 6:97	-	-	-	-
	Grade 2:	Child 4:90	-	-	-	-
		Child 1: 91	-	-	-	-
		Child 3:92	-	-	-	-
	Grade 3:	Child 2:99	-	-	-	-
		Child 5:100	-	-	-	-

On the composite score of phonological representations and word discrimination, the NH children performed near ceiling in this test with small standard deviations. Four out of 6 children with CI did not perform significantly below the level of their respective comparison group.

None of the children with CI performed significantly below their age-matched comparison group on the phoneme segmentations test.

Two of the children with CI, Child 6 in grade 1 and Child 5 in grade 3, did not perform significantly below the level of the NH children on the accuracy measure of the Nonword Discrimination test. The other four children performed significantly below the level of their comparison groups, and the difference between the groups in grade 2 was significant for the accuracy measure.

Three of the children with CI, Child 6 in grade 1, and Child 2 and Child 5 in grade 3, did not perform significantly different from their grade-matched comparison groups on the accuracy measure of the Phoneme Identification test. The accuracy scores for each participant were calculated using the formula advocated by Foo, Rudner, Rönnberg & Lunner (2006) for the analysis of the results in tasks where only one type of response ("yes") can be made. Accordingly, accuracy scores are calculated based on rate of valid button presses minus the rate of invalid button presses according to the following formula:

$(w/y)-(x/(z-y))$

where
w=valid button presses
x=invalid button presses
y= number of targets in list
z= number of test items

On the response latency measure, Child 2 and Child 5 in grade 3 did not have significantly slower response latencies than their comparison group.

Lexical skills

The results from the lexical access tests for the children with CI and their corresponding comparison groups are presented in Table 5.

Two of the children with CI, Child 6 in grade 1 and Child 5 in grade 3, did not perform significantly below the level of their comparison groups on the accuracy measure of the Passive Naming test. Significant differences between the groups were found in grade 2. None of the children with CI had response latencies that differed significantly from that of the grade-matched children with normal hearing.

Two of the children with CI, Child 6 in grade 1 and Child 5 in grade 3, did not have accuracy scores significantly below their respective comparison group in the Wordspotting test. The other children with CI had accuracy scores ranging between 11 and 50% correct, and the difference between the groups in grade 2 was significant.

Child 6, Child 4 and Child 3 did not have significantly longer response latencies than the comparison group. Child 1 and Child 5 even had shorter response latencies than their comparison groups.

Table 5. Results on measures of lexical access for each individual child with CI compared to the control group

test	Control mean (standard deviation)	Participant number	P (exact calculations for binomial distribution) 99% confidence level	t-test, 1-tailed	Estimated percentage of NH children falling below individual's score (95% lower confidence limit – 95% upper confidence limit)	Mann-Whitney U exact test (comparing the group of 3 children in grade 3 with their grade matched control group)
Passive Naming (PN) accuracy	Grade 1: 8.8 (0.58) N=16	Child 6:9	1.0 n.s.	-	-	-
	Grade 2: 8.7 (0.59) N=15	Child 4:5	.0057**	-	-	0.000**
		Child 1:5	.0057**	-	-	
		Child 3:6	.0405*	-	-	
	Grade 3: 8.8 (0.45) N=12	Child 2:3	$6.42e^{-005}$ **	-	-	-
		Child 5:9	1.0 n.s.	-	-	-
Passive Naming (PN) latency	Grade 1: 2047.9 (380.6) N=16	Child 6: 2207	-	0.406 n.s.	65.46 (46.0 - 82.2)	-
	Grade 2: 2223.4 (308.5) N=15	Child 4: 2072	-	-0.475 n.s.	32.1 (15.4 - 52.2)	20.5 n.s.
		Child 1: 2776	-	1.734, n.s.	94.8 (82.9 - 99.6)	
		Child 3: 1772	-	-1.417 n.s.	8.9 (1.4 - 23.8)	
	Grade 3:1875.4 (266.4) N=12	Child 2: 2301	-	1.535 n.s.	92.4 (76.2 - 99.3)	-
		Child 5: 2001	-	0.45 n.s.	67.0 (44.6 - 85.6)	-
Wordspotting (WS) accuracy	Grade 1: 7.7 (1.3) N=16	Child 6:8	.905n.s.	-	-	-
	Grade 2: 8.4 (0.83) N=15	Child 4:3	.0004**	-	-	0.000***
		Child 1:2	$2.92e^{-005}$**	-	-	
		Child 3:1	$1.16e^{-006}$**	-	-	
	Grade 3:8.1 (1.2) N=12	Child 2:4	.016*	-	-	-
		Child 5:6	.236 n.s.	-	-	-

Table 5. Results on measures of lexical access for each individual child with CI compared to the control group (cont.)

Wordspotting (WS) latency	Grade 1: 1263 (104) N=16	Child 6: 1282	-	0.18 n.s.	56.9 (37.7 – 75.0)	-
	Grade 2:1242 (84) N=15	Child 4: 1369	-	1.46 n.s.	91.7 (77.3 – 98.8)	19.0 n.s.
		Child 1: 983	-	-2.995**	0.49 (0,00 - 3.3)	
		Child3: 1307	-	0.75 n.s.	76.7 (57.3- 91.0)	
	Grade 3:1180 (119) N=12	Child2: 1416	-	1.90*	95.8 (83.5 - 99.9)	-
		Child5: 958	-	-1.79*	5.0 (0.25 - 18.50)	-
Semantic Decision Making (SD) accuracy	Grade 1: 28.6 (0.73) N=16	Child 6:28	.694 n.s.	-	-	-
	Grade 2: 28.3 (0.82) N=15	Child 4:27	.429 n.s.	-	-	1.5**
		Child 1:25	.055 n.s.	-	-	
		Child 3:26	.175 n.s.	-	-	
	Grade 3:28.4 (0.9) N=12	Child 2: 21	$6.49e^{-005}$***	-	-	-
		Child 5:29	1.0 n.s.	-	-	-
Semantic Decision Making (calculation)	Grade 1: 0.973 (0.045) N=16	Child 6: .93	-	-	-	-
	Grade 2: 0.958 (0,05) N=15	Child 4: .87	-	-	-	0.000**
		Child 1: .74	-	-	-	
		Child3: .81	-	-	-	
	Grade 3: .96 (.06) N=12	Child 2: .44	-	-	-	-
		Child 5: 1.0	-	-	-	-

Table 5. Results on measures of lexical access for each individual child with CI compared to the control group (cont.)

Semantic Decision Making (SD) latency	Grade 1: 1262.8 (161.5) N=16	Child 6: 1200	-	-0.38 n.s.	35.6 (18.6 - 55.0)	-
	Grade 2:1240.7 (161) N=15	Child 4: 1339	-	0.59 n.s.	71.8 (51.9-87.6)	17.0 n.s.
		Child 1: 1343	-	0.62 n.s.	72.6 (52.8-88.2)	
		Child 3: 1259	-	0.11 n.s.	54.3 (34.6 - 73.22)	
	Grade 3:1147.8 (159) N=12	Child 2: 1945	-	4.82**	100.0 (99.8-100.00)	-
		Child 5: 1316	-	1.02 n.s.	83.4 (62.9 - 96.0)	-

Five out of six children with CI had accuracy scores that did not differ significantly from that of their comparison groups in the Semantic Decision Making test. The difference between the groups in grade 2 was significant according to the Mann-Whitney U test. This pattern of results was identical for the latency measure of the test, where Child 2 was the only child with CI who had significantly longer response latencies than the comparison group.

Reading ability

The results from the reading tests are presented in Table 6.

None of the children with CI performed significantly differently from their comparison group in either test of word decoding. Four children had higher raw scores than the mean of the normal hearing children for both decoding tests. When a difference score was calculated to estimate the discrepancy in decoding performance for words and nonwords, 5 out of 6 children with CI had a larger difference between these measures than their comparison groups. This difference was only significant, however, for one of the children, Child 3. Child 2 and Child 5, on the other hand, had smaller differences between the two decoding measures than their hearing comparison group. Four of the children with CI had reading comprehension scores not significantly different from the NH children, whereas 2 children, Child 1 and Child 3, performed significantly below their comparison group.

A closer inspection of the results from the cognitive tests for the two children who had poorer reading comprehension indicated significantly poorer performance than the comparison group and the other four children with CI on the measures of general WM, phonological WM (nonword repetition) and

Table 6. Results on reading measures for each individual child with CI compared to control group

test	Control mean (standard deviation)	Participant number	t-test, 1-tailed	Estimated percentage of NH children falling below individual's score (95% lower confidence limit – 95% upper confidence limit)	Mann-Whitney U exact test (comparing the group of 3 children in grade 3 with their grade matched control group)
TOWRE words	Grade 1: 67.1 (26.2) N=16	Child 6 :89	0.81n.s.	78,5 (60.1- 91.9)	
	Grade 2: 93.4 (27.7) N=15	Child 4: 112	0.65 n.s.	73.7 (53.9 – 89.0)	16.5 n.s.
		Child 1: 84	-0.33n.s.	37.4(19.6-57.4)	
		Child 3: 104	0.37n.s.	64.2 (44.1 – 81.6)	
	Grade 3:105.4 (21.6) N=12	Child 2: 114	0.38 n.s.	64.5 (42.1 – 83.6)	
		Child 5: 103	-0.11n.s.	45.9 (24.9 – 67.7)	
TOWRE nonwords	Grade 1: 40.6 (19.6) N=16	Child 6: 52	0.56 n.s.	71.0 (51.7-86.5)	
	Grade 2: 59.9 (20.0) N=15	Child 4: 68	0.39n.s.	65.0 (44.9- 82.3)	16.0 n.s.
		Child 1: 33	-1.30 n.s.	10.7 (2.1 – 26.6)	
		Child 3: 44	-0.77n.s.	22.7 (8.6 – 42.1)	
	Grade 3:69.3 (16.8) N=12	Child 2: 99	1.7n.s.	94.1(79.7- 99.6)	
		Child 5: 72	0.15n.s.	56.0 (34.0-76.6)	

phonological skills (nonword discrimination and phoneme identification). They also had the largest differences between phonological output for words and nonwords. These 2 children further performed significantly below the level of the comparison group, but similar to the other children with CI, on the Passive Naming and Wordspotting tests (accuracy measures), and they performed on par with the comparison group on the Semantic Decision Making test.

Table 6. Results on reading measures for each individual child with CI compared to control group (cont.)

TOWRE difference score	Grade1: 26.4375 (15.095) N=16	Child 6: 37	0.68n.s.	74.6(55.6-89.3)	
	Grade2: 33.53 (13.01) N=15	Child 4: 44	0,78 n.s.	77.6 (58.3 - 91.6)	
		Child 1: 51	1,30 n.s.	89.3 (73.4 - 97.9)	
		Child 3: 60	1,97*	96.6 (86.9 – 99.8)	
	Grade3: 36.17 (13.4) N=12	Child 2: 15	-1.518 n.s.	7.9 (0.8-24.1)	
		Child 5: 31	-0.37n.s.	35.9 (16.7- 58.3)	
Woodcock semantically correct	Grade 1: 26.8 (5.8) N=16	Child 6: 25	-0.30 n.s.	38.4(21.0- 57.8)	
	Grade 2: 30.0 (4.2) N=15	Child 4: 27	-0.69 n.s.	25.0 (10.1- 44.7)	4.5*
		Child 1: 12	-4.15**	0.05 (0.0-0.4)	
		Child 3: 20	-2.30*	1.9 (0.04-8.7)	
	Grade 3:33.8 (4.8) N=12	Child 2: 36	0.44 n.s.	66,6 (44.1- 85.2)	
		Child 5: 34	0.04 n.s.	51.6(30.0-72.8)	

SUMMARY

Generally, the children with CI had problems with phonological WM as measured by the Nonword Repetition test. These problems were less evident in the Serial Recall test of phonological WM, where 3 out of 4 children performed at the same level as their comparison group on at least one of the measures of the test. In the Sentence Completion and Recall test of general WM, four out of six children with CI performed comparable to their respective grade-matched comparison group. No significant group differences between NH children and children with CI were found in grade 2. All of the children with CI performed on par with their comparison group on the measure of visuospatial WM.

Performance on the tests of phonological skills varied considerably between the tests; in the Nonword Discrimination test, only 2 out of 6 children had accuracy scores comparable to the NH group, whereas none of them had longer response latencies than the controls. All of the children with CI had performance levels comparable to their controls on the Phoneme Segmentation test. Four out of six children with CI had Phonological Representation scores that did not differ significantly from those of their comparison group, and three children with CI had scores comparable to their comparison groups on the Phoneme Identification test.

Performance on the tests of lexical access also varied between tests. In the Wordspotting and Passive Naming tests, 2 and 3 children, respectively, performed at the level of their comparison groups, whereas 5 out of 6 children had an equivalent performance in the Semantic Decision Making task. Response latencies were generally not longer for the children with CI than for their controls in the tests of lexical access.

The children with CI had age-appropriate decoding skills, both for decoding of words and nonwords. Reading comprehension was comparable to that of the NH comparison group for 4 out of 6 children. The two children with poorer reading comprehension scores had a poorer performance than their comparison groups and the other children with CI on the measures of general and phonological WM, and most of the measures of phonological skills.

Demographic variables

Age at diagnosis and age at implantation

The children who had the highest performance in the tasks of phonological skills, phonological WM and lexical access (Child 6 and Child 5) also had the earliest age of diagnosis (at 8 and 10 months of age, respectively), whereas the children who had the lowest performance in those tests (Child 1 and Child 3) were diagnosed at a later age (2;5 and 2;0 years, respectively). Similarly, Child 6 and Child 5 were implanted with their first CI relatively early (at age 1;7 and 2;0 years), whereas Child 1 and Child 3 received their implants later (at age 3;6 and 2;4, respectively).

Hearing

When performance on the cognitive tests was compared to the ranking based on hearing levels (presented in the Participants section), Child 6, who performed on a level with the normal hearing children on most tasks of phonological skills, lexical access and phonological working memory, should be considered to have high hearing levels. Child 5, who also had a high performance level in most tests, had moderate hearing levels based on this ranking.

School setting and main communication mode

Child 6 and Child 5 were integrated in mainstream education and used oral communication only, at home and at school. The other four children attended special schools, where a combination of sign language and oral language was used in the educational programs. These children used oral communication and to some extent sign at home.

Nonverbal intelligence

The children with CI ranged between 70 and 138 in the WISC-III Block Design test. The two children who had the highest performance in many of the tests of cognitive skills and reading (5 and 6) both had scores of 138 on the Block Design test. Similarly, the two children who were identified as having the lowest levels of phonological skills and phonological WM and the relatively poorest phonological decoding skills and reading comprehension (Child 1 and 3) had scores of 70 and 92 respectively on the Block Design test.

DISCUSSION

The present study was designed to investigate different levels of phonological processing in children with CI and to relate these skills to the level of distinctness of phonological representations, output phonology, lexical access and different components of working memory. A second purpose was to study decoding of words, decoding of nonwords and reading comprehension in children with CI as compared to children with normal hearing and as related to cognitive skills.

The children with CI had specific problems in tasks of phonological working memory. Four out of six children performed on a par with their comparison group on the general working memory task, and all six children had visuospatial WM skills comparable to the hearing children. Performance on the measures of phonological skills varied between the tests, such that they performed on a par with the hearing children in the phoneme segmentation task, but had poorer results in the tasks which used nonwords as test materials.

The results on lexical access varied such that performance was relatively higher in the Semantic Decision Making task and poorer in the Passive Naming and Wordspotting task.

All of the children with CI had age appropriate decoding skills for words and nonwords. Two children had reading comprehension scores which were significantly lower than the mean scores of their comparison group. The two children with the highest performance in most of the cognitive tests and reading tests were diagnosed and implanted at a younger age. In contrast to the other four children with CI they also used oral communication only and attended mainstream education. Furthermore, they had relatively higher scores of nonverbal intelligence (cf. Geers et al., 2008).

Phonological skills and WM

The children with CI in this study had relatively high scores of phonological output for real words (pcc 95-100), for which they should be expected to have well established phonological representations. NH children with typical language development in this age range are expected to have maximum performance in this test (Hansson & Nettelbladt, 2002). Similar results were found in the study by Young & Killen (2002), where 4 out of 6 children with CI had an expressive vocabulary within the average range.

Phonological output for nonsense words (i.e. nonword repetition), of which the children should be assumed not to have any lexical representations, were substantially poorer compared to children with normal hearing of the same age. None of the 6 children performed within 1 SD of the mean of the NH children in the nonword repetition task. When a difference score was computed, comparing the phonological output for words (phoneme test, pcc) to phonological output for nonwords (nonword repetition, pcc), the children with CI had difference scores ranging from 37 percent to 75 percent. The comparison of output for words and nonwords allows us to consider the nonword repetition test to be a measure of phonological WM (Gathercole, 2006), where performance is not simply a consequence of phonological output skills. Three out of four children with CI did not perform significantly different from the NH children in at least one of the measures (pcc or psa) of the Serial Recall of Nonwords task. The test items in this test should be considered less phonologically complex than the test items in the nonword repetition test since the nonwords in the former test consist of consonant-vowel-consonant combinations, whereas the latter test uses up to 4 syllables and consonant clusters. These results support previous findings (e.g. Dillon, Burkholder, Cleary & Pisoni, 2004; Dillon, Cleary, Pisoni & Carter, 2004; Wass et al., 2008; Young & Killen, 2002) that children with CI have specific problems with phonological working memory, but that they experience relatively less difficulties when tasks with shorter and suprasegmentally less complex test items are used (Wass et al., 2008).

Four of the six children with CI performed on a par with their comparison group on the composite score of phonological representations and word discrimination. Thus they have fairly distinct phonological representations for phonological input of words, despite the fact that their auditory perception is not comparable to that of normal hearing children. These results are important since distinctiveness of phonological representations has been claimed to be the underlying factor of phonological skills and reading ability in children with normal hearing (e.g. Elbro & Nygaard Jensen, 2005). Hearing children generally have well specified phonological representations for familiar words (Swingley & Aslin, 2000; Swingley, 2003). On the other hand, newly learned words may not have as distinct representations, but undergo gradual refinement (e.g. Garlock, Walley & Metsala, 2001). This process of refinement may be slower and more dependent on redundant information in children with CI. However, children with CI may, just like children with poor phonological learning abilities, as proposed by Gathercole (2006:515), “with time and sufficient exposure…succeed in forming stable lexical representations of the sound of a new word.” It should be noted that the same four children with CI also performed between 98 and 100 percent correct on the phonological output test, and the other two children had scores of 95 and 98 percent correct, respectively. Thus, phonological representations of lexical items for both input and output should be considered fairly distinct for this group of children.

All six children with CI performed on par with the NH children on the phoneme segmentation task. Although this was the only test of phonological skills where real words were used as test items, this result may imply that children with CI are relatively skilled at manipulating familiar words for which they have fairly distinct phonological representations. On the other hand, since all children in this study have already acquired a certain level of reading skill, they may, to some extent, have used orthographic skills when solving the task. However, as argued by Castles & Coltheart (2004), the well-documented relationship between reading skills and phonological skills may be reciprocally causal, since children, once they acquire any reading and spelling skills, may use their orthographic skills either in addition to or instead of their phonological skills to solve phonological awareness tasks.

In tests of phonological skills which use nonwords as test items, children should not be able to benefit from already acquired orthographic skills when solving the tasks. Instead, they need to rely on purely phonological information (i.e. processing has to be performed on the sound information held in phonological WM) to a greater extent. In the present study, nonwords were used in two of the tests of phonological skills. Four out of six children in the nonword discrimination task and three out of six children in the phoneme identification task performed significantly below the level of their hearing comparison group. These results indicate substantially poorer phonological skills than would be expected from the results on the phoneme segmentation task alone. However, it is interesting that some children perform at the level of normal hearing children even in these relatively more demanding phonological tasks.

The fact that children with CI should have neither phonological nor orthographic representations for the nonwords which they have to process should make their performance particularly dependent on phonological working memory and auditory perception.

When comparing phonological skills to phonological working memory capacity, it turned out that Child 5 and Child 6 had the relatively highest levels of both phonological WM (as measured by nonword repetition) and phonological processing. Measures of phonological WM and phonological processing have previously been found to correlate in children with normal hearing, and it has been suggested that phonological skills contribute to the development of phonological WM, but that individual differences in WM span do not explain variances in phonological sensitivity (Kail, 1997; Ferguson & Bowey, 2005).

In many of the studies on phonological skills and phonological working memory, real words are used as stimuli (e.g. Castles & Coltheart, 2004; Durand et al., 2005; Muter, Hulme, Snowling & Stevenson, 2004). The present study used nonwords as stimuli in most of the tests of phonological skills to prevent the children from using lexical knowledge to improve performance. The use of nonwords is claimed to render more accurate tools for assessment of phonological WM, for example in nonword repetition tasks (Gathercole, 2006). In children with cochlear implants, performance on tasks of phonological WM and phonological skills is dependent on auditory perception to a greater extent than in children with normal hearing. Therefore, the ability to process (e.g. manipulate, discriminate and make decisions about) phonological information at the word level may be relatively high, since these children have fairly distinct phonological representations of familiar words. On the other hand, in tasks of phonological skills and phonological WM where nonwords are used as test stimuli, these children's performance may be underestimated in comparison with other populations of children. If this is the case, the children with CI in this study may have relatively higher levels of phonological skills than the tests used in the present study indicate. Higher levels of phonological skills may, in turn, explain their level of reading skills to some extent.

Lexical access

The result that five of the six children with CI performed on a par with their comparison group on the Semantic Decision Making test is in line with the findings from Young & Killen (2002). With the discussion from the previous section in mind, a part of the explanation may be that real, common words, which should be represented in the vocabularies of most young children, are used as test items in this test. Furthermore, the children were primed to perceive a certain semantic category. This feature allowed the children to use their phonological and semantic representations of words in long-term memory and thereby to a greater extent use top-down processing strategies to make more qualified guesses about which words they are being presented with. This strategy will be particularly useful when, for example, the auditory signal does not provide enough information to be correctly matched to an existent phonological representation. The other two tests of lexical access (the Passive Naming test and the Wordspotting test), where only 2 out of 6 children performed within 1 SD of the NH mean, do not allow for use of contextual info to the same extent. In the case of the Semantic Decision Making test, contextual information refers to the fact that the children knew in advance which semantic category they were supposed to identify, and all test items were real words. Thus, when making a decision about a word, they may use this information in case they have to make a guess. The identification of words in the tests of Passive Naming and Wordspotting is more dependent on auditory perception in order to match the incoming speech signal to its representations in long term memory.

Reading ability

According to dual-route models of reading (e.g. Coltheart, Rastle, Perry, Langdon & Ziegler, 2001) reading of unfamiliar words and nonwords is dependent on a phonological decoding strategy in which the graphemes of the word are converted and mapped to the corresponding phonemes in long-term memory. In contrast, reading of highly familiar words may reflect the operation of an orthographic strategy, in which words are identified in comparison with specific orthographic representations in long-term memory. In the present study, all six children had decoding skills comparable to their hearing comparison groups, both for decoding of words and nonwords. The difference between words and nonwords was even greater for most of the children with CI than the average difference in the hearing groups; however, this difference was only significantly larger than that of the comparison group for one of the children with CI. One child even had a smaller difference than the reference group. These results indicate that children with CI use various decoding strategies, but that, as suggested by Dillon & Pisoni (2006), they commonly use phonological decoding strategies when learning to read. Altogether, the pattern of results indicate that the automatic and fast phonological decoding skills which constitute a basic condition for high reading comprehension in various populations with normal hearing (Durand et al., 2005) is important for successful reading comprehension also for children with CI.

Two of the children with CI had significantly poorer reading comprehension scores than their comparison group. These children also had the lowest nonword decoding scores in relation to the other children with CI (irrespective of grade) and the largest differences between the measures of word- and nonword decoding. This may imply that that they rely on orthographic reading strategies to a greater extent. Since they also had the lowest performance on most measures of working memory and phonological skills, they may have used orthographic decoding as a compensatory strategy, since phonological and general working memory are established predictors of reading comprehension in children with normal hearing (e.g. Gathercole et al., 2005), and has also been reported in children with CI (Asker-Árnason et al., 2007). Orthographic reading strategies have been found to be insufficient when the child encounters unfamiliar words, and may therefore cause children to make slower progress than those who rely on phonological reading strategies (Share, 1995). There is some evidence that reading by means of orthographic strategies is not associated with any reading problems by grade 4 (Bowey, 2007). Findings by Geers et al. (2008) indicate that increasing proportions of children at age 18 compared to age 8 do not keep up with normal reading development. In this perspective, further studies of the reading strategies used by children with CI in a longitudinal perspective would provide information about how to best design reading instruction for these children.

The findings that the two children with the lowest levels of phonological working memory also had the poorest phonological skills and phonological decoding skills and vice versa was expected, since phonological working memory has previously been found to be related to phonological decoding in children with CI (e.g. Geers, 2003; Sahlén et al., 2008) and children with normal hearing (Durand et al., 2005). Some, however, argue that this relationship is mediated by other aspects of phonological skills, involving more explicit manipulation of phonemes (Durand et al., 2005; Dally, 2006). The two children with the highest reading skills attended grade 3 and therefore should be expected to be high performers, using highly automated decoding strategies for nonword decoding and orthographic strategies for decoding of words.

Demographic variables

The demographic variables included in this study seem to provide explanations for some of the variance in performance in the cognitive tests.

The two children who had the highest performance in most of the cognitive tests were diagnosed and implanted with their first CI at an early age, whereas the two children who had relatively poorer performance were diagnosed and implanted later. The advantages of early implantation on implant benefit (e.g. speech recognition, academic achievement) have been established by a number of previous studies (e.g Tomblin et al., 2005; Geers et al., 2008; Pisoni, 2008). Early cortical reorganization in children who have experienced longer periods of sensory deprivation is suggested to explain this advantage of early diagnosis and implantation (Anderson, et al., 2004; Pisoni et al., 2008; Sharma et al., 2005; Fallon et al., 2007).

The children with CI who participated in this study attended different cochlear implant programs and therefore their hearing and speech recognition levels were measured by different clinical tests. Thus a parametric analysis of their hearing and speech recognition was not possible. However, a visual inspection of the data reveals no obvious relationship between hearing levels and cognitive skills. When comparing the ranking of children based on the hearing results to their phonological skills, we were not able to detect a pattern of relations. Child 6, who performed on a level with the normal hearing children on both tasks of phonological skills, should be viewed as having relatively high hearing levels. Child 5, who also had a performance comparable to the hearing children on these cognitive tests, has only moderate hearing levels, based on this ranking. Child 2, who had the highest performance in the phoneme identification test, was not tested with the same auditory tests and therefore it was not possible to relate this child's results to the other children's performance.

The two children with the lowest levels of phonological working memory (Child 1 and Child 3) had the poorest phonological skills, but the highest hearing levels according to the ranking. Although we are not able to draw any conclusions about the directions of these relationships, it is interesting that we do not find clear relationships between hearing levels and performance in phonological tests. Furthermore, in line with Wass et al. (2008), there is an absence of valid tests on auditory perception for pediatric populations in Sweden. The tests that we have may be suitable for clinical evaluation of children's speech recognition in some situations, but they are not proper tests for use in research, since they provide a composite measure of auditory perception and cognitive skills.

The two children with the highest performance in the cognitive tests were the only participants in this study who were integrated in mainstream education and used oral communication only, both at home and at school. The other children attended special education programs and used a combination of oral speech and sign, both at home and at school. Children who are integrated in mainstream education have been reported to have better academic performance and greater implant benefit (Geers et al., 2003), but this relationship may be bidirectional.

Two of the children with the highest performance on many of the cognitive tests had nonverbal intelligence scores of 138, based on their performance in the WISC-III Block Design test. The children who had the lowest scores in many of the tests on the other hand had nonverbal intelligence scores of 70 and 92 respectively. Nonverbal intelligence has previously been found to be related to academic achievements and implant benefit for children with CI (Geers et al., 2008). In the present study, nonverbal intelligence may have been one of the factors influencing the performance of individual children. However, since phonological WM, which has proved influential language acquisition and reading skills, is claimed not to be related to general intelligence (Gathercole, 2006), we do not attach great importance to the possible relation between nonverbal intelligence and the other cognitive measures found in the present study. Furthermore, the Block Design subtest was chosen to be an approximate estimation of nonverbal intelligence, since we did not have time to administer the whole WISC –III battery. Thus it should be regarded merely as a screening test for nonverbal intelligence, which was used to assure that the participants did not have any intellectual disabilities. We cannot draw conclusions about the general IQ of the children based on their scores from this subtest only.

CONCLUSIONS

The children with CI in this study had specific difficulties in tasks of phonological skills and phonological WM where nonwords were used as test stimuli. They also experienced relatively more difficulties in tasks on lexical access without any contextual information. In tasks where real words were used to assess phonological skills and working memory (phoneme segmentation and sentence completion and recall), six and four children, respectively, performed at the level of the children with normal hearing. The explanation for the results may be that these children have relatively distinct phonological representations for well known words (as judged by the tasks on both input and output of lexical stimuli). Furthermore, they do not seem to have problems with phonological processing of words for which they have a well defined phonological representation. These distinct phonological representations, in turn, may be the product of exposure to redundant information at encoding (e.g. from both auditory and visual speech and text) and a substantial amount of practice over time. Regarding the tests of lexical access, most children did not perform significantly differently from their age-matched comparison group when a certain amount of contextual info was provided in the task. Therefore, we propose that these children are particularly efficient in using compensatory strategies in situations where their auditory perception does not provide sufficient information to correctly match the incoming speech signal to a corresponding representation in the long-term phonological storage.

The children with CI in this study have high reading skills both for decoding of words and nonwords and for reading comprehension. They may use both orthographic and phonological reading strategies, although most of them seem to be dependent on phonological decoding to some extent. We draw these conclusions since most of them did not have significantly larger differences in decoding of words as compared to nonwords than did the children with normal hearing. Children with normal hearing are, in turn, assumed to use phonological decoding to a substantial extent in the early grades. The children with relatively poorer reading comprehension had the poorest phonological decoding skills, the lowest scores for phonological skills, and the poorest phonological and general WM. These factors are known to be related in other populations, particularly in this stage of reading development.

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