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Cognitive and linguistic skills in Swedish children with cochlear implants – measures of accuracy and latency as indicators of development

Malin Wass, Tina Ibertsson, Björn Lyxell, Birgitta Sahlén,
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The purpose of the present study was to examine working memory (WM) capacity, lexical access and phonological skills in 19 children with cochlear implants (CI) (5;7 -13;4 years of age) attending grades 0 - 2, 4, 5 and 6 and to compare their performance with 56 children with normal hearing. Their performance was also studied in relation to demographic factors. The findings indicate that children with CI had visuospatial WM capacities equivalent to the comparison group. They had lower performance levels on most of the other cognitive tests. Significant differences between the groups were not found in all grades and a number of children with CI performed within 1 SD of the mean of their respective grade-matched comparison group on most of the cognitive measures. The differences between the groups were particularly prominent in tasks of phonological WM. The results are discussed with respect to the effects of cochlear implants on cognitive development.

A cochlear implant (CI) provides auditory sensations to individuals with severe or profound hearing impairment. Hearing is not restored to a normal level, but the auditory sensation opens up for the prospect of a different course of development in a wider variety of areas related to communication than would have been the case without the CI (Spencer, 2004; Geers, 2003; Houston, Pisoni, Iler Kirk, Ying & Miyamoto 2003; Richter, Eißele, Laszig, Löhle, 2002). This is particularly evident in areas where the development of cognitive and linguistic skills is central, e.g. working memory, phonological skills and reading (Geers, 2002; Dillon & Pisoni, 2004). Previous research has also demonstrated that demographic factors such as age at implant, duration of deafness, and time with the CI may correlate with the course of development of speech and language skills (Richter et al., 2002; Snik, Makhdoum, Vermeulen, Nrokkx, van den Broek, 1997). A general feature of the empirical picture is that cochlear implantation at an early age is more beneficial for development of language and academic skills than implantation at a later age (Geers, 2003; Tait, Nikolopoulos & Lutman, 2007). Increased knowledge about the cognitive development in children with CI is necessary in order to adjust these children's educational settings to best match their cognitive capacity.

For children with normal hearing, previous research has found a positive relation between academic skills, such as vocabulary learning, reading ability, spelling ability and the basic cognitive skills working memory (WM) (e.g. Swanson & Berninger, 1995; Hannon & Daneman, 2001), phonological skills (e.g. Kjeldsen, Niemi & Olofsson, 2003; Muter, Hulme,

Snowling & Stevenson, 2004) and lexical access skills (Plaza & Cohen, 2003; Plaza & Cohen, 2004; Swan & Goswami, 1997).

Children with CI have a different course of development of basic academic skills such as language and reading skills, compared both with children with normal hearing (Le Normand, Ouellet & Cohen, 2003), and children with severe deafness, who have not been implanted (Truy, Geneviève, Jonas, Martinon, Maison, Girard, Porot, Morgon, 1998). A few studies on cognitive skills in children with CI have also indicated a lower performance level for these children on measures of WM (Willstedt-Svensson, Löfqvist, Almqvist & Sahlén, 2004; Cleary, Pisoni & Geers, 2001), and phonological skills (Ibertsson, Willstedt-Svensson, Radeborg & Sahlén, 2007). Lexical access skills have not, to our knowledge, previously been studied in children with CI. The cognitive skills working memory, phonological skills and lexical access are composite skills which involve several subcomponents. It is therefore important to use several different tests to assess each subcomponent in order to reach a more detailed understanding of which specific aspects of these cognitive skills that may or may not be impaired in children with CI.

The purpose of the present study is to examine working memory capacity, lexical access and phonological skills in children with CI. We will examine these abilities as they are central and important building blocks in more complex and composite cognitive activities such as speech and language comprehension, reading ability, mental arithmetic and most aspects of communication. In the present study we will compare children with CI with age-matched children with normal hearing. Their performance on the cognitive tasks will also be discussed in relation to demographic factors such as age at implantation, communication mode and school setting. In this study, we apply a broad range of cognitive tests and scoring procedures, where each test assesses one particular aspect of a specific cognitive ability. This strategy will give us indications of whether the auditory stimulation from the CI promotes a general cognitive development or whether the development is restricted to some specific aspect such as the phonological loop in working memory. The inclusion of both accuracy and speed as dependent variables will give us a more detailed understanding of the efficiency of the underlying processing than we would obtain from measures of accuracy alone (Hällgren, 2005).

Working Memory

Previous research has indicated that phonological storage capacity may vary widely in children with CI. For example Dillon, Burkholder, Cleary & Pisoni (2004) studied phonological storage in prelingually deaf 8- and 9-year-old children with CI by means of a Non-word Repetition task. Their analysis was performed on the accuracy-scores of the test. The children's performance was found to vary between 8 and 76 percent and it was highly correlated with measures of word recognition, auditory language comprehension and speech intelligibility. Burkholder & Pisoni (2003) further found that children with CI had shorter forward and backward digit spans than age-matched children with normal hearing. Forward digit span is considered to tap the phonological subcomponent (storage only) of WM whereas backward digit span taxes more general aspects of WM, i.e. simultaneous processing and storage of information (Just & Carpenter, 1992; Conlin, Gathercole & Adams, 2005). These results may indicate that children with CI have less developed phonological and general working memory capacities. Burkholder & Pisoni (2003) also found that children who used total communication (i.e. sign language in combination with orally spoken words) had shorter forward digit spans than those children who relied on oral communication only, whereas there was no significant difference between the groups on a backward digit span task. These results suggest that the amount and quality of exposure to oral language may affect the development of the phonological component of working memory in deaf children with CI. The present study will examine the capacity of different components of WM in children with CI, the phonological loop, the visuospatial sketchpad, the central executive (Baddeley, 2000), and the capacity to simultaneously process and store information (e.g. Towse, Hitch & Hutton, 1998).

Phonological skills

Phonological skills, i.e. the abilities to process and make decisions about phonological information have been demonstrated to be important predictors of for example vocabulary learning and reading acquisition in young children with normal hearing (e.g. Kjeldsen, Niemi & Olofsson, 2003). In a longitudinal study on the predictors of early reading development, Muter et al. (2004) found that phonological skills, measured by phoneme sensitivity and letter knowledge, were strong predictors of word recognition skills in children with normal hearing between five and seven years of age. A few studies have investigated the relation between phonological skills and reading skills in children with CI. For example, correlations between phonological skills and measures of reading comprehension and word decoding have been

found in children with CI (Geers, 2003; Dillon & Pisoni, 2004). These results were interpreted as an indication that children with CI use phonological (coding-) skills in reading. This is an important finding since previous studies have indicated that phonological skills are strong predictors of reading ability in deaf children without cochlear implants, but that this population does not use phonological coding to the same extent as children with normal hearing (Harris & Moreno, 2004). In the present study, one aspect of phonological skills, i.e. the ability to discriminate between different phonemes, will be examined.

Jacquemot & Scott (2006) have presented a theoretical model of the relationship between phonological working memory and phonological speech processing, where phonological representations in speech perception and speech production are distinct from each other. According to this model, phonological working memory is composed of two separate buffers, an input buffer which is dedicated to the phonological processing and storage in speech perception and an output buffer dedicated to phonological processing and storage in speech production. The two buffers allow for the temporary maintenance of phonological representations in input and output, respectively. This model also has two conversion processes, one which converts input to output, and one which converts output to input.

According to this model, PhWM tasks which require repetition, such as the Non-word Repetition task used in the present study, may involve both phonological buffers and their respective conversion mechanisms. On the other hand, matching tasks such as our Non-word Discrimination task may involve only the phonological input buffer. The Non-word Discrimination test used in the present study may also be relatively more demanding for the phonological input buffer than the Non-word Repetition test. This is because two non-words at a time (the same words as in the non-word repetition test) have to be held in the input buffer simultaneously in order to compare their phoneme structures. Therefore, when interpreted in light of the theoretical model by Jacquemot & Scott (2006), a correlation between the tests of Non-word Repetition and Non-word Discrimination may indicate that these tests share a common factor, i.e. possibly impaired function in the phonological input buffer. The absence of a correlation between these tests may, on the other hand, indicate that performance in the Non-word Repetition task is not dependent on the function of the phonological input buffer, but may be found in either in the phonological output buffer or in the conversion mechanism converting phonological input into output. Speculatively, children

with CI may have impaired function in all or some components of this model due to limited auditory experience at an early age, before they received their implants.

Lexical Access

Lexical access refers to the process of finding and retrieving verbal labels from long-term memory. Lexical access predicts reading and spelling performance in children with normal hearing, independent of their phonological skills (Plaza & Cohen, 2003; Swan & Goswami, 1997). The source of this relationship is not clearly understood although different theories have been proposed to provide explanations (Powell, Stainthorp, Stuart, Garwood & Quinlan, 2007). Children with reading disabilities usually display difficulties in tasks on lexical access, compared to age-matched and reading age-matched children (Swan & Goswami, 1997). These difficulties have also been found to be associated with problems in identifying and discriminating phonologically similar syllables in oral language (Mody, Studdert-Kennedy & Brady, 1997). Less distinct phonological categories in long-term memory have been suggested to account for a substantial part of these difficulties (Elbro, Borstrom, Klint Petersen, 1998). Therefore, children with reading impairment may have difficulties in mapping written graphemes to phonemes in the long-term phonological storage. Children with CI may, similarly to children with reading impairment, have less defined phonological categories in long-term memory due to their different auditory experiences (Svirsky, Robbins, Iler Kirk, Pisoni, & Miyamoto, 2000). It is important to study lexical access skills in children with CI in order to investigate the quality of their phonological representations in long-term memory and the speed with which these representations are accessed. This is particularly important because lexical access skills might help predicting later reading and spelling performance in these children. In the present study, lexical access was assessed in three different tests where both correct answers and response latencies were recorded as dependent measures.

Demographic Variables

Demographic variables explain varying proportions of variance in performance in linguistic tasks (Willstedt-Svensson, Löfqvist, Almqvist & Sahlén, 2004; Dillon, Cleary, Pisoni & Carter, 2004). Many studies have demonstrated a relation between implant benefit and a number of variables associated with the child and the implant, for example age at onset of deafness, length of auditory deprivation, age at implantation (Tomblin et al., 2005) and duration of implant use (e.g. McDonald Connor & Zwolan, 2004), level of

non-verbal intelligence and the occurrence of additional disabilities (Fukuda et al., 2003). The educational setting has also been demonstrated to contribute to performance in language related tasks (e.g. Geers, Brenner, Nicholas, Tye-Murray & Tobey, 2003). It is important to study as many of these variables as possible in order to identify their relative contribution to implant benefit. The present research will study the following variables: age at diagnosis, age at implantation, time interval between first and second CI, main communication mode and school setting.

In sum, the present study is intended to investigate the development of different aspects of working memory, phonological skills and lexical access in children with CI, and to compare their performance level with that of age-matched children with normal hearing. We will also study the relationship between different aspects of these cognitive skills and a number of demographic variables.

METHOD

Participants

A total of 75 children from the southern parts of Sweden participated in this study. Parental informed consent was obtained for all of the participants. The group of children with cochlear implants consisted of 19 participants, 11 girls and 8 boys, aged 5;7 to 13;4, with a median age of 9;0 years. All of the children with CI were deafened before 3;0 years of age. As reported by the parents, they were diagnosed at the mean age of 1;5 years, with 17 out of 19 children having received their diagnosis before they were 2;1 years old.

The children were implanted within the Paediatric Cochlear Implant Programs in Lund, Gothenburg or Stockholm and were seen in a session at their school or at a regular summer camp for children with CI and their families. They had received their first implants between 1;9 and 10;0 years of age (median age at implantation: 2;5 years, mean age at implantation of the first CI: 3;4 years) and had used their first implants for more than 3 years (mean length of use 5;5 years, standard deviation 2.1 years). Fourteen children were implanted before 4;0 years of age. Twelve children were bilaterally implanted at the median age of 6;3 years, range 4;2 – 12;0 years, and the median time between the implantations of the first and the second CI was 4.3 years (range 2.3 – 7;0 years).

Etiology of hearing impairment was unknown in 9 children, of whom 2 were diagnosed with sudden deafness. Three children had non-syndromal and 1 had syndromal hereditary hearing impairment. Infectious disease was the cause in 4 children. Two children had a progressive deterioration of hearing.

Some of the demographic information, such as etiology and speech recognition, was received from the children's medical journals. Since the children attended paediatric cochlear implant programs in different parts of Sweden, we had to deal with the fact that their speech recognition levels were measured by different tests. For 14 of the children, speech recognition was measured by phonetically balanced lists of 25 words for children (Almqvist, 2004). These children had median speech recognition of 78%, range 0.0–88.0 %. One child did not achieve any credits on this test and when this child was removed from the analysis, the lower range limit changed to 34 %. Ten of the 14 children had maximum speech recognition scores of above 75% and were therefore grossly classified as having fairly good speech recognition ability. Three children who scored well below 75% were classified as having poorer speech recognition. For three children the speech recognition was measured by phonetically balanced lists of 50 words for adults (Almqvist, 2004). Two of those three children were under the age of twelve at the time of testing and are therefore considered to be too young for the adult version of the test. Thus, their speech recognition scores (below 75% correct in this version of the test) could not be classified. One child, who was older than 12 years of age, scored above 75% on the adult version of the test and was thereby classified as having relatively good speech recognition.

The child, who did not achieve any credits for the phonetically balanced lists of words test, was tested by a 3-digit span test. This child had a performance level of 50% in this test, a score which is considered to be poor speech recognition.

Furthermore, one child was tested with a version for children of the Hagerman sentences in noise test (Hagerman & Kinnefors, 1995), and had a signal-to-noise ratio of +3dB, which is also considered to be relatively poor speech recognition. Speech recognition data was missing for one child.

According to the Swedish education program for deaf children, all children were exposed to sign language before implantation. All of them used oral language as their main communication mode, but did sometimes use sign language or signed support at home or at school. All of the children had hearing parents. Ten of the children were integrated in mainstream schools, 6 children attended schools for children with hearing impairment, and 3 children attended schools for deaf children. The information regarding demographic factors was obtained from medical records and from a structured interview with the children's parents, where the answers to specific questions were recorded by the interviewer in a questionnaire.

The comparison group constituted a total of 56 age-matched children with normal hearing, 28 girls and 28 boys. They represented the grades 0, 1, 2, 4, 5 and 6 in the Swedish school system, and included 10 to 11 children from each grade. None of the children had a history of hearing impairment, according to their teachers.

Both children with CI and the age-matched controls performed within the normal range on nonverbal intelligence, as measured by the Block Design test from the WISC-III for children (Wechsler, 1991). There were no significant differences between the two groups on this measure.

Procedure

All children were tested individually by the same examiner. The tests were administered in a fixed order and were performed in one session lasting 35-50 minutes. All of the cognitive tests, except the WISC-III Block Design test and the reading tests, were taken from a computer-based test battery, the SIPS, i.e. the Sound Information Processing System with auditory-, text- and picture-based presentation of information. The SIPS was specifically designed for this purpose. The 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. 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. For each test, the number of participating children is shown in Table 1. There are missing data in most tests due to lack of cooperation of individual children.

Tests

All of the cognitive tests except the WISC-III block designs test were computer-based and presented in the SIPS test battery. All of the SIPS-tests, except the matrix pattern test and the passive naming test had auditory-only presentation in the same female speaker voice.

Table 1. Cognitive tests.

Area	Test	Quantification	N of children w. CI finishing task
Phonological Working Memory	Serial Recall of Non-words percent non-words correct (SR pnc)	% non-words correct out of 42	14
	Serial Recall of Non-words percent consonants correct (SR pcc)	% consonants correct out of 84	16
	Serial Recall of Non-words percent correct vowels and suprasegmental accuracy (SR psa)	% non-words with correct stress + length + vowel, out of 42	16
	Non-word Repetition percent consonants correct (NWR pcc)	% consonants correct out of 120	13
General Working Memory	Sentence Completion and Recall (SCR)	Total number of words correctly filled in and recalled (max=18)	14
Visuospatial Working Memory	Matrix Patterns (MP)	Highest complexity level, with 2 out of 3 test items correct (max=8)	19
Phonological skills	Non-word Discrimination latency for correct responses (ND latency)	Mean Response latency (ms)	12
	Non-word Discrimination accuracy (ND accuracy)	Number of correctly discriminated pairs of non-words (max=8)	12
Lexical access	Passive Naming response latency for correct responses (PN latency)	Mean Response latency (ms)	18
	Passive Naming accuracy (PN accuracy)	Number of correct responses (max=9)	18
	Wordspotting mean latency for correct responses (WS latency)	Mean Response latency (ms)	14
	Wordspotting accuracy (WS accuracy)	Number of correct responses (max=9)	15
	Semantic Decision Making mean latency for correct responses (SD latency)	Mean Response latency (ms)	18
	Semantic Decision Making accuracy (SD accuracy)	Number of correct responses (max=30)	18

Working Memory

Phonological WM was assessed in the *Serial Recall of Non-words test*, designed following procedures developed by Gathercole & Pickering (2000), and in the *Non-word Repetition test* (Sahlén et al., 1999). In both of these tasks, non-words were used as

stimuli as they do not involve support from long term memory, which might be the case in span tests with digits or real words. In both tests, non-words were presented from the computer and the children were asked to orally repeat each non-word. The children's answers were recorded on an external tape recorder and the recordings were subsequently used as the basis for scoring the accuracy of the answers.

In the *Non-word Repetition* test, the child was asked to repeat non-words of increasing syllable length. The repetition attempts were scored both binary as either correct or incorrect, and as percent consonants correctly reproduced (pcc).

In the *Serial Recall* test, the child was asked to repeat series of one-syllable non-words. The series were of increasing length, from 2 to 5 non-words. Since the serial recall test was considered to be a more difficult test, the answers were scored according to three different criteria: 1) binary, i.e. the percentage of correctly reproduced non-words out of the total number of non-words presented in the test 2) segmental accuracy, i.e. the percentage of correctly reproduced consonants out of the total number of consonants presented in the test, pcc 3) suprasegmental accuracy, i.e. the percentage of non-words pronounced with the correct vowel and number of syllables, psa. For example the child would receive a score of one for a non-word when correctly reproducing the vowel and syllable length of the non-word.

Sentence Completion and Recall, designed following procedures developed by Towse, Hitch & Hutton (1998) was used to assess complex working memory, i.e. the capacity to simultaneously store and process information. Sentences with the last word missing were presented and the task was to fill in and memorize the missing words, e.g. "Crocodiles are green. Tomatoes are". When a certain number of sentences had been presented, the child had to repeat back the words he or she had previously filled in. The answers were recorded on an external tape recorder for later transcription. The results were scored as the total number of correctly stored and reproduced words, where the words at all levels were added up, with a maximum score of 18.

The *Visual Matrix Patterns Test*, designed following procedures developed by Della Sala, Baddeley, Allamano & Wilson (1999), was used to assess visuospatial working memory. A pattern of filled cells in a 5 by 5 matrix was displayed on the computer screen. When the filled cells disappeared, the child was asked to click on the previously

filled cells in an empty matrix. The level of difficulty increased from 1 to 8 filled cells. The task was discontinued when children made a mistake on two consecutive levels. The results were automatically stored in the computer. The children received span scores for the highest level of difficulty at which they correctly reproduced two out of three test patterns. For example if a child would correctly reproduce two patterns consisting of four filled cells, he/she received a visual span score of four. The maximum span score was 8.

Phonological skills

A *Non-word Discrimination* task (Reuterskiöld-Wagner, Sahlén, Nyman, 2005) was used to assess phonological skills. In this test, the task was to indicate, by pressing a computer key, whether two non-words were identical. The non-words were presented in 16 pairs and each target non-word was presented in 2 conditions, once together with an identical non-word and once together with a similar non-word, differing by one single phoneme, eg. patinadrup – patinadrup, patinadrup - patinavrup. The non-words used were identical to the target non-words in the Non-word Repetition task. In order to receive the maximum score of 8, the child had to make the correct decisions about all of the non-words, in both conditions. Answers and response latencies were automatically recorded by the computer.

Lexical access skills

Lexical skills were assessed in three tests, in which answers and response latencies were automatically recorded by the computer. In the Passive naming test, designed following procedures developed by Johnson, Clark & Paivio (1996), the child had to identify a presented noun, 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* was designed following procedures developed by Cutler (1997). In this test, the child was required 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*, designed following procedures developed by Hällgren, Larsby, Lyxell & Arlinger (2001), the task was to press a key on the computer

if a presented noun belonged to a certain, predefined semantic category. The maximum accuracy score was 30.

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.

Statistical methods

For each test, the data were screened for extreme outliers. Children who had an accuracy score of zero on a particular test were considered as not having solved the task, and their results were therefore excluded before the analyses. Mann-Whitney exact tests were used to compare means. Since the children with CI varied in age from 5;7 to 13;4 years with only a few children in each age group, Pearson first order partial correlations, with age partialled out, were performed with all ages analyzed as one group. The reason for this choice of analysis is that the performance level on the different tests was expected to be strongly affected by the age of the child. Second order partial correlations were also performed where age and each of the demographic variables at a time were partialled out. Significance-levels of .05 and below are reported.

RESULTS

The results are presented in two sections. First, we report the descriptive statistics from the cognitive tests. For each test measure, the results are presented at a group level where the 19 children with CI in all ages are analyzed as one group and compared with a comparison group of 48 children with normal hearing in the same age range. The comparison group has been grade-matched to the group of children with CI in order to have similar proportions of children in each grade. Therefore, since we have children with CI in each of the grades 0-2, for most of the tests, the comparison group has 10 children in each of these grades. We have 3 children with CI and 9 with normal hearing in grade 4, 2 children with CI and 6 children with normal hearing in grade 5, 1 child with CI and 3 children with normal hearing in grade 6. For each test measure, we further compare the performance of subgroups of children with CI in each grade to their

respective grade-matched comparison group. In these subgroup analyses, the comparison groups are all constituted of 10-12 children with normal hearing in each grade. The results from the analyses of the groups with all ages included are presented in Table 2. The results from the sub-group comparisons are presented in Table 3 for the tests on WM and phonological skills and in Table 4 for the tests of lexical access. The results of individual children with CI in each grade are reported in Table 5 together with means and standard deviations of their respective comparison groups.

The significant differences between children with CI and children with normal hearing reported in the text refer to the Mann-Whitney exact tests, displayed in tables 2 (all ages), 3 (subgroup analyses of WM and phonological skills) and 4 (subgroup analyses lexical access). For every test, the number of children with CI who perform within 1 standard deviation of the mean of the children with normal hearing in their respective grade, are presented in table 2 and is further commented in the text. Test abbreviations are presented in Table 1.

Secondly, we present the first order partial correlations, with age partialled out, between the different tests, for each group separately. These partial correlations are performed on the group of children with CI with all ages included and their grade-proportion matched comparison group. The partial correlations referred to in the text are presented in Table 6 (children with CI) and Table 7 (children with NH). Only the significant correlations are further commented in the text.

The boys and girls did not differ significantly in performance in any of the cognitive tests, neither in the group of children with CI nor in the group of children with normal hearing. Therefore gender differences will not be further discussed.

Descriptive statistics

In two tests, Wordspotting- and Non-word Repetition, the results from two children with an accuracy-level of zero were excluded. The Non-word Repetition and Non-word Discrimination tests were not completed by all of the children with CI younger than 9 years of age, since these tasks were considered to be too complex for some of these children.

Phonological Working Memory

At the group level with all ages included, the children with CI had a significantly lower performance level than the children with normal hearing on all of the measures of phonological WM. However, in the Serial Recall of Non-words task, with less phonologically complex non-words, 1-4 children performed within 1 SD of the mean of their respective age-matched comparison group, depending on the scoring criteria used. Further analyses of the grade-matched subgroups (see Table 3) indicated that the differences between the children with CI and the NH children were also significant for all of the subgroups except for grade 4, where the children with CI did not perform significantly poorer on the psa (percent suprasegmental accuracy) measure of the Serial Recall of Non-words task, which is less demanding from a developmental perspective.

Table 2. Descriptive statistics at the group level with all ages included. Test abbreviations are explained in table 1.

	Children w CI							Children w normal hearing (NH)					Mann-Whitney U (1-tailed)	Effect size (r)	
	N	m	SD	Median	Min	Max	Children w CI within 1 SD from age-matched NH mean	N	m	SD	Median	Min			Max
Visuospatial WM															
MP	19	4.1	1.4	4.0	2	7	14/19	48	4.5	1.3	4.0	2	7	379 n.s.	-.13
General WM															
SCR	14	8.3	3.2	8.25	2.0	13.0	3/14	48	11.8	2.8	12.0	6.0	17.5	142.0**	-.42
Phonological WM															
SR pnc	15	9.8	7.2	10.0	0	26	2/16	47	42.7	15.3	40	17	69	13.0**	-.71
SR pcc	15	25.8	9.8	29.0	9	46	1/16	47	56.2	13.1	55	24	77	27.0**	-.68
SR psa	16	37.8	14.4	37.0	4	67	4/16	47	66.0	15.1	67	21	88	70.5**	-.61
NWR pcc	13	42.0	12.1	39.0	17.5	60.8	0/13	37	90.0	6.4	91.7	72.5	100	.000**	-.75
Lexical access															
PN latency	18	2380	415	2312	1785	3077	8/18	48	2091	363	2082	1393	3072	265.0**	-.30
PN accuracy	18	5.8	2.25	6.50	2	9	4/18	48	8.6	.71	9	7	9	97.0**	-.65
WS latency	14	1382	188	1375	1025	1752	6/14	48	1229	140	1207	902	1579	163.5**	-.37
WS accuracy	14	3.7	2.1	3.5	1	8	3/14	48	7.4	1.4	8	4	9	49.0**	-.62
SD latency	18	1401	202	1345	1179	1984	9/18	48	1223	164	1181	919	1705	193**	-.42
SD accuracy	18	26.7	2.6	27.0	22	30	6/18	48	29	1.2	29	25	30	183.5**	-.46
Phonological sensitivity															
ND latency	12	3630	145	3671	3324	3789	9/12	38	3577	192	3583	3103	4034	174.0 n.s.	-.17
ND accuracy	12	5.7	2.5	6.0	1	8	4/12	38	7.97	.16	8	7	8	78.5**	-.72

*p<.05

*p<.01

Table 3. Grade-matched subgroup-analyses, tests of WM and phonological skills.

Tests of Working Memory and Phonological Skills							
Test		NH Median (range)	CI Median (range)	Mann-Whitney U (Exact significance, 1-tailed)	Z	Effect size (r)	Number of children w. CI performing within 1 SD of NH mean
SRpnc	Grade 0: NH N=10 CI N=3	3.01 (24-62)	10.0 (9-26)	2.5 (.017)	-2.12	-.59	1/3
	Grade 1: NH N=10 CI N=4	39.0 (17-50)	8.5 (5-24)	3.0 (.007**)	-2.42	-.65	1/4
	Grade 2: NH N=10 CI N=3	46.5 (19-69)	4.0 (0-14)	0.0 (.003**)	-2.55	-.71	0/3
	Grade 4: NH N=10 CI N=3	49.0 (29.0-69.0)	10.0 (10-11)	0.0 (.003**)	-2.54	-.70	0/3
	Grade 5-6: NH N=14 CI N=2	52.0 (36.0-64.0)	3.5 (2-5)	0.0 (.008**)	-2.24	-.56	0/3
SRpcc	Grade 0: NH N=10 CI N=3	48.5 (39-71)	24.0 (19-46)	4.5 (.049*)	-1.78	-.49	1/3
	Grade 1: NH N=10 CI N=4	54.5 (24-62)	24.0 (13-37)	3.0 (.007**)	-2.42	-.65	0/4
	Grade 2: NH N=10 CI N=3	58.0 (24-77)	20.0 (9-29)	1.0 (.007**)	-2.37	-.66	0/3
	Grade 4: NH N=10 CI N=3	58.0 (43.0-71.0)	32.0 (30-33)	0.0 (.003**)	-2.56	-.71	0/3
	Grade 5-6: NH N=14 CI N=2	64.0 (52.0-77.0)	23.5 (17-30)	0.0 (.008**)	-2.23	-.56	0/3
SRpsa	Grade 0: NH N=10 CI N=3	62.0 (48-79)	38.0 (36-56)	2.0 (.014)	-2.21	-.61	1/3
	Grade 1: NH N=10 CI N=4	60.0 (21-76)	35.5 (26-52)	7.0 (.034*)	-1.85	-.49	2/4
	Grade 2: NH N=10 CI N=3	70.0 (26-88)	33.0 (4-38)	2.0 (.014*)	-2.20	-.61	0/3
	Grade 4: NH N=10 CI N=3	64.5 (55.0-83.0)	50.0 (44-67)	5.5 (.059 n.s.)	-1.62	-.45	1/3
	Grade 5-6: NH N=14 CI N=3	80.0 (55.0-88.0)	29.6 (29-31)	0.0 (.001**)	-2.66	-.65	0/3

NWRpcc	Grade 0:	-	-	Test not performed by this age group	-	-	
	Grade 1: NH N=10 CI N=4	84.6 (72.5-96.7)	38.25 (33-48)	0.0 (.001**)	-2.84	-76	0/4
	Grade 2: NH N=10 CI N=3	88.8 (80.8-97.5)	32.5 (17.5-35.8)	0.0 (.003**)	-2.55	-71	0/3
	Grade 4: NH N=10 CI N=3	95.8 (77.4-100.0)	40.0 (38.3-52.5)	0.0 (.003**)	-2.55	-68	0/3
	Grade 5-6: NH N=14 CI N=3	92.5 (86.7-96.7)	59.2 (51.7-60.80)	0.0 (.001**)	-2.67	-65	0/3
SCR	Grade 0: NH N=10 CI N=1	8.25 (6.0-11.5)	8.5 (8.5-8.5)	4.5 (.55 n.s.)	-.159	-.048	1/1
	Grade 1: NH N=10 CI N=4	11.8 (7-14.5)	8.25 (2-13)	12.5 (.16 n.s.)	-1.07	-.29	1/4
	Grade 2: NH N=10 CI N=3	11.8 (9-15)	7.0 (4.5-8)	0.0 (.003**)	-2.55	-.71	0/3
	Grade 4: NH N=11 CI N=3	13.5 (11.0-17.0)	7.0 (5-10)	0.0 (.003**)	-2.58	-.69	0/3
	Grade 5-6: NH N=15 CI N=3	14.5 (10.5-17.5)	11.0 (11-13)	5.0 (.02*)	-2.09	-.49	1/3
MP	Grade 0: NH N=10 CI N=4	3.0 (2-4)	3.0 (2-4)	17 (.466 n.s.)	-.477	-.13	3/4
	Grade 1: NH N=10 CI N=5	4.0 (3-6)	4.0 (3-5)	24 (.51 n.s.)	-.13	-.034	4/5
	Grade 2: NH N=10 CI N=4	4.5 (2-7)	2.5 (2-4)	8.0 (.051 n.s.)	-1.73	-.46	2/4
	Grade 4: NH N=11 CI N=3	5.0 (4.0-7.0)	6.0 (4-7)	13.5 (.42 n.s.)	-.49	-.13	2/3
	Grade 5-6: NH N=15 CI N=3	5.0 (3.0-8.0)	5.0 (5-6)	22.0 (.52 n.s.)	-.06	-.01	3/3
ND accuracy	Grade 0:	-	-	Test not performed by this age group	-	-	
	Grade 1: NH N=10 CI N=3	8.0 (7-8)	3.0 (1-6)	0.0 (.003**)	-3.10	-.86	0/3
	Grade 2: NH N=10 CI N=3	8.0 (8-8)	5.0 (2-6)	0.0 (.003**)	-3.43	-.95	0/3
	Grade 4: NH N=11 CI N=3	8.0 (8-8)	8.0 (7-8)	11.0 (.214n.s.)	-1.92	-.51	2/3

	Grade 5-6: NH N=15 CI N=3	8.0 (8-8)	8.0 (6-8)	15.0 (.167 n.s.)	- 2.24	-.53	2/3
ND latency	Grade0:	-	-	Test not performed by this age group	-	-	
	Grade 1: NH N=10 CI N=3	3569 (3522- 3844)	3701 (3324- 3724)	14 (.46 n.s.)	-.17	-.047	2/3
	Grade2: NH N=10 CI N=3	3603 (3103- 3812)	3576 (3394- 3640)	12.0 (.35 n.s.)	-.51	-.14	3/3
	Grade 4: NH N=11 CI N=3	3513 (3314- 4034)	3722 (3594- 3722)	7.0 (.08 n.s.)	- 1.48	-.40	3/3
	Grade 5-6: NH N=15 CI N=3	3516 (3097- 3822)	3776 (3596- 3789)	5.0 (.02*)	- 2.07	-.49	1/3

*p<.05

*p<.01

Table 4. Grade-matched subgroup-analyses, tests of lexical access.

Test		NH Median (range)	CI Median (range)	Mann-Whitney U (Exact test, 1-tailed)	z	Effect size (r)	number of children w. CI performing within 1 SD of NH mean
PN accuracy	Grade 0: NH:N=10 CI N=4	8.0 (7-9)	7.0 (3-8)	8 (.065 n.s.)	-1.79	-.48	1/4
	Grade 1: NH N=10 CI N=5	9.0 (7-9)	4.0 (2-6)	0.0 (0.0**)	-3.33	-.86	0/5
	Grade 2: NH N=10 CI N=4	9.0 (7-9)	6.0 (3-7)	2.0 (.006**)	-2.75	-.73	0/5
	Grade 4: NH N=11 CI N=3	9.0 (8-9)	8.0 (5-9)	7.5 (.093 n.s.)	-1.77	-.47	2/3
	Grade 5-6: NH N=15 CI N=2	9.0 (8-9)	8.0 (7-9)	9.0 (.14 n.s.)	-1.21	-.29	½
PN latency	Grade 0: NH N=10 CI N=4	2333 (2026- 2750)	2469 (2274- 2863)	13 (.19 n.s.)	-.990	-.26	2/4
	Grade 1: NH N=10 CI N=4	2180 (1679- 2463)	2714 (1921- 3077)	12 (.065 n.s.)	-1.59	-.42	2/5
	Grade 2: NH N=10 CI N=4	2217 (1730- 3072)	1951 (1785- 2999)	17 (.367)	-.42	-.11	¾
	Grade 4: N=11 CI N=3	1760 (1509- 2243)	2168 (2077- 2749)	2.0 (.011*)	-2.26	-.60	0/3

	Grade 5-6: N=15 CI N=2	1978 (1393- 2436)	2182 (1910- 2454)	9.0 (.221 n.s.)	-.89	-.22	1/2
WS accuracy	Grade 0: NH N=10 CI N=3	6.0 (4-9)	4.0 (1-5)	3.0 (.024*)	-2.07	-.57	1/3
	Grade 1: NH N=10 CI N=4	7.0 (5-8)	4.0 (2-6)	4.0 (.014*)	-2.31	-.62	1/4
	Grade 2: NH N=10 CI N=2	8.5 (6-9)	2.0 (1-3)	0.0 (.015*)	-2.25	-.65	0/2
	Grade 4: N=11 CI N=2	8.0 (7.0-9.0)	2.0 (1-3)	0.0 (.013*)	-2.30	-.64	0/2
	Grade 5-6: N=15 CI N=3	9.0 (7-9)	5.0 (5-8)	3.0 (.007**)	-2.57	-.61	1/3
WS latency	Grade 0: NH N=10 CI N=3	1236 (902- 1420)	1427 (1382- 1456)	1.0 (.007**)	-2.37	-.66	1/3
	Grade 1: NH N=10 CI N=4	1332 (1118- 1579)	1464 (1293- 1752)	12.0 (.15)	-1.13	-.30	2/4
	Grade 2: NH N=10 CI N=2	1202 (1008- 1272)	1160 (1025- 1295)	9.0 (.46)	-.22	-.06	1/2
	Grade 4: N=11 CI N=2	1208 (1046- 1423)	1506 (1430- 1581)	0.0 (.013*)	-2.17	-.60	0/2
	Grade 5-6: N=15 CI N=3	1158 (1010- 1398)	1208 (1201- 1368)	9.0 (.065 n.s.)	-1.60	-.38	2/3
SD accuracy	Grade 0: NHN=10 CI N=4	29 (26-30)	29 (22-30)	18 (.382 n.s.)	-2.91	-.078	3/4
	Grade1: NH N=10 CI N=4	29 (25-30)	26 (24-28)	4.5 (.015*)	-2.23	-.60	2/4
	Grade 2: NH N=10 CI N=4	30 (26-30)	26 (23-27)	2.0 (.004**)	-2.68	-.72	0/4
	Grade 4: N=11 CI N=3	30 (29-30)	28 (22-30)	8.0 (.09 n.s.)	-1.45	-.39	0/3
	Grade 5-6: N=15 CI N=3	29 (27-30)	28 (27-29)	8.0 (.06 n.s.)	-1.86	-.44	1/3
SD latency	Grade 0: NH N=10 CI N=4	1145 (1042- 1360)	1402 (1236- 1984)	2.0 (.004**)	-2.55	-.68	1/4
	Grade 1: NH N=10 CI N=4	1257 (973- 1705)	1291 (1179- 1460)	18 (.42 n.s.)	-.28	-.07	4/4
	Grade 2: NH N=10 CI N=4	1264 (1100- 1434)	1471 (1276- 1786)	5.0 (.018*)	-2.12	-.57	1/4
	Grade 4: N=11 CI N=3	1181 (919- 1598)	1308 (1291- 1426)	7.0 (.08 n.s.)	-1.48	-.40	2/3
	Grade 5-6: N=15 CI N=3	1176 (974- 1433)	1302 (1235- 1409)	7.0 (.038*)	-1.84	-.43	1/3

*p<.05
*p<.01

Table 5. Results of individual children with CI, and grade-matched comparison groups. Test abbreviations are explained in table 1.

School grade level	0	1	2	4	5-6
NH - n (total)	10	10	10	11	15
CI - n (total)	4	5	4	3	3
SR pnc NH mean (sd)	35.1(12.3)	34.2(11.9)	44.6 (18.5)	47.4 (12.4)	51.2 (10.3)
SR pnc Individual CI-scores	a= 26, g= 10 , j=missing, k= 9	b= 24, o=missing, p= 5 , q= 7 , r= 10	d= 14 ,e= 4 , f= 0 , s=missing	c= 10 , h= 10 , n= 11	i= 0 , l= 2 , m= 5
SR pcc NH mean (sd)	50.8 (9.2)	49.9 (11.72)	55.8 (16.42)	58.2 (9.6)	64.9 (8.6)
SR pcc Individual CI-scores	a=46, g= 24 , j=missing, k= 19	b= 37 , o=missing, p= 13 , q= 18 , r= 30	d= 29 ,e= 20 , f= 9 , s=missing	c= 30 , h= 32 , n= 33	i= 0 , l= 17 , m= 30
SR psa NH mean (sd)	63.3 (8.51)	55.7 (15.74)	66.5 (18.8)	68(10.4)	75.7 (11.4)
SR psa Individual CI-scores	a=56, g= 36 , j=missing, k= 38	b=52, o=missing, p= 26 , q=40, r= 31	d= 16 ,e= 9 , f= 1 , s=missing	c= 50 , h=67, n= 44	i= 30 l= 31 , m= 29
NWR pcc NH mean (sd)	test not given to this age group	85.6 (7.1)	89.17 (4.5)	92.4 (7.6)	92.8 (3.2)
NWR pcc Individual CI-scores	test not given to this age group	b= 37.5 , o=missing, p= 39 , q= 33 , r= 48	d= 35.8 ,e= 32.5 , f= 17.5 , s=missing	c= 38.3 , h= 52.5 , n= 40	i= 59 , l= 61 , m= 52
SCR NH mean (sd)	8.75 (1.8)	11.2 (2.18)	11.6 (1.6)	13.2 (1.9)	14.6 (1.9)
SCR Individual CI-scores	a=missing, g= 8.5, j=missing, k=missing	b=13, o=missing, p= 2 , q= 8.5 , r= 8	d= 7 ,e= 4.5 , f=missing, s= 8	c= 7 , h= 5 , n= 10	i=13, l= 11 , m= 11
MP NH mean (sd)	3.2 (0.63)	4.2 (0.92)	4.3 (1.6)	5.36 (0.92)	5 (1.35)
MP Individual CI-scores	a=3, g=3, j=4, k= 2	b=4,o=5 p= 3 , q=5, r=4	d=3, e= 2 , f= 2 , s=4	c= 4 , h=6, n=7	i=5, l=6, m=5
ND accuracy NH mean (sd)	Test not given to this age group	7.9 (0.32)	8.0 (0.0)	8.0(0.0)	8.0 (0.0)
ND accuracy individual CI scores	Test not given to this age group	b=missing, o=missing, p= 3 , q= 6 , r= 1	d= 6 ,e= 2 , f=missing, s= 5	c= 7 , h=8, n=8	i=8, l=8, m= 6
ND latency NH mean (sd)	Test not given to this age group	3644 (140)	3561.5 (236)	3544 (210)	3481.7 (189)
ND latency individual CI scores	Test not given to this age group	b=missing, o=missing, p= 3701, q= 3724, r= 3324	d=3576,e= 3394, f=missing, s= 3640	c= 3594, h= 3722, n= 3722	i= 3789 , l=3596, m= 3776
PN accuracy NH mean (sd)	8 (0.82)	8.7(0.67)	8.5 (0.85)	8.8 (0.4)	8.8 (0.41)
PN accuracy Individual CI scores	a=8, g= 3 , j=7, k=7	b= 6 , o= 2 , p=6, q=4, r= 2	d=7, e= 5 , f= 3 , s=7	c=9, h=8, n= 5	i=9, l=7, m=missing
PN latency NH mean (sd)	2329.3 (252.3)	2097.4 (260)	2274.7 (442)	1787.7 (222)	1941.1 (282)
PN latency Individual CI scores	a= 2863 , g=2274, j= 2351, k= 2588	b=1921, o=2215, p= 2714 , q= 2799 , r= 3077	d= 2065, e= 1836, f= 2999 , s=1785	c= 2077 , h= 2168 , n= 2749	i= 2454.3 , l=1910.1, m=missing
WS accuracy NH mean (sd)	6.5 (1.78)	6.6 (1.07)	8.0 (1.15)	8.1 (0.7)	8.6 (0.6)
WS accuracy individual CI scores	a= 4 , g=5, j=missing, k= 1	b=6, o=missing, p= 5 , q= 2 , r= 3	d= 3 ,e= 1 , f=missing, s=missing	c= 3 , h=missing, n= 1	i=8, l=5, m= 5
WS latency NH mean (sd)	1226 (156.5)	1332 (160)	1189.6 (73.4)	1212 (126)	1157.3 (109.5)
WS latency individual CI scores	a=1382, g= 1427 , j=missing, k= 1456	b=1293, o=missing, p= 1300, q= 1627 , r= 1752	d=1025,e= 1295 , f=missing, s=missing	c= 1430 , h=missing, n= 1581	i=1201, l=1208, m= 1368
SD accuracy NH mean (sd)	28.3(1.42)	28.6 (1.6)	29.3 (1.25)	29.5 (0.52)	29.1 (0.83)
SD accuracy individual CI scores	a=30, g=30, j=28, k= 22	b=28, o=missing, p=27, q= 24 , r= 25	d= 27 ,e= 26 , f= 23 , s= 26	c= 28 , h= 30 , n= 22	i=29, l= 28 , m= 27
SD latency NH mean (sd)	1176.2 (96.2)	1278.3 (211)	1267.4 (108)	1203 (204)	1165.8 (134)
SD latency individual CI scores	a= 1406 , g= 1236, j= 1984 , k= 1397	b= 1179, o=missing, p= 1288, q= 1460, r= 1293	d= 1381 ,e= 1276, f= 1561 , s= 1786	c= 1426 , h= 1291, n= 1308	i= 1302 , l= 1409 , m=1235

BOLD –below range of NH

General Working Memory

The children with CI generally obtained significantly lower scores than the children with normal hearing on the Sentence Completion and Recall test taxing the capacity to simultaneously process and store phonological/semantic/lexical information. Three out of 14 children with CI performed within 1 SD of the mean of their grade matched comparison group. These differences between children with CI and NH children were also found in the subgroup analyses (see table 3), except for in grade 1, where no significant difference was found.

Visuospatial Working Memory

The two groups did not differ significantly in performance on the Matrix Patterns test, which measures visuospatial working memory capacity. These results were consistent in the all-age group analysis and in the analyses of all grade-matched subgroups. Fourteen out of 19 children with CI performed within 1 SD of the mean of their grade matched comparison group mean on this test.

Phonological skills

At the group level with all ages included, the children with CI had significantly lower performance than the children with normal hearing on the accuracy measure but not the latency measure of the Non-word Discrimination test. On the accuracy measure of the test, 4 out of 12 children performed within 1 SD of their grade-matched comparison group mean whereas 9 out of 12 children reached the corresponding level on latency measure. The subgroup analyses further revealed significant differences between children with CI and children with NH in grade 1 and grade 2 for the accuracy measure. For the latency measure, a significant difference between the groups was found only in the grade 5 and 6.

Lexical access skills

When the age groups were analyzed together, the children with CI had a significantly lower level of accuracy, and they also had longer response latencies, than the children with normal hearing on all three measures of lexical access: Passive Naming, Wordspotting and Semantic Decision Making. However, almost 50 percent of the children with CI performed within 1 SD of their respective comparison group mean on

the latency measures of these tests. The corresponding proportions of children performing within 1 SD on the accuracy measures of these tests, was 21-22 percent for the Passive Naming and Wordspotting tests and 33 percent for the Semantic Decisions test. A few more children performed just below 1 SD of their respective comparison group. Further analyses of the subgroups revealed that the differences between the children with CI and the children with NH were only significant in grade 1 and grade 2 on the Passive Naming accuracy measure and in grade 4 on the latency measure of this test. In the Wordspotting test, the group differences were significant in all grade subgroups for the accuracy measure. In the Semantic Decisions test, significant differences between CI and NH groups were found only in grade 1 and grade 2 for the accuracy measure and for grade 0 and grade 2 for the latency measure.

In summary, the children with CI generally had a lower performance on the measures of phonological WM. When the most lenient scoring criterion of the Serial Recall test was used, the difference between the groups was not significant in grade 4 and at the all-age group level. Four children out of 16 performed within 1 SD of their respective NH comparison group mean on this measure. On the test of general WM, significant differences between the groups were found both in the all-age group analyses and in all subgroup analyses except for grade 1. No significant differences between the groups were found for the visuospatial WM test, neither in the all-age group analysis nor in the subgroup analyses. At the group level with all ages included, the children with CI had a significantly poorer performance than the children with NH on the accuracy measure of the Non-word Discrimination test, measuring phonological skills. Subgroup analyses indicated that these differences were not found for all school grades. There were no significant differences between the two groups on the response latency measure of this test. In the lexical access tests, significant differences between the groups were found at the group level with all ages included but not in all of the subgroup analyses.

Correlation analyses

The first-order partial correlations with age partialled out are the correlations referred to in the text if nothing else is stated. We also performed second order partial correlations where the variables age plus age at diagnosis, age plus age at implantation of the first CI, and age plus speech perception respectively, were partialled out. The results from these

analyses are not presented since they did not differ appreciably from the pattern found in the first order partial correlations.

Phonological WM - General WM

In the group of children with CI, general WM (Sentence Completion and Recall) was found to be significantly correlated with one of the measures of phonological storage (the pnc measure of the Serial Recall of Non-words test). No significant correlations between general and phonological WM were found in the group of children with normal hearing.

Phonological WM - Phonological skills

Significant correlations between the accuracy measure of the Non-word Discrimination test and the Serial Recall of Non-words task were found in the group of children with CI, but not in the group with normal hearing.

No significant correlations, for any of the groups were found between the tests of Non-word Repetition and Non-word Discrimination, which had exactly the same non-word items.

In the Non-word Discrimination test, where both response latencies and correct answers were recorded, a significant positive correlation was found between response latency and accuracy for the children with CI, i.e. children with longer response latencies had more correct answers. This correlation was not significant for the children with normal hearing.

Table 6. Partial correlations with age partialled out for the whole group of children with CI. Test abbreviations are explained in table 1.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1. age at diagnosis(mts)	1																	
2. age at implant. CI 1(mts)	.37	1																
3. Age at impl. CI2 (mts)	-.76*	.55	1															
4. Time between CI1– CI2	.10	-.62	.39	1														
5. PN latency	.07	.37	-.30	-.61	1													
6. PN accuracy	.05	-.11	-.73*	.04	-.28	1												
7. WS latency	-.53	-.06	.20	-.11	.65*	-.56	1											
8. WS accuracy	.40	.17	-1.0*	-.54	-.08	.23	-.39	1										
9. SD latency	-.06	-.09	.18	.14	-.16	.30	-.01	-.34	1									
10. SD accuracy	.32	-.06	-1.0*	-.21	-.41	.46	-.51	.76**	-.10	1								
11. MP	-.16	.13	-.33	-.52	-.09	-.12	.44	.03	.08	.08	1							
12. ND latency	.19	.27	-1.0*	-.69	.23	.46	-.09	.39	.18	.17	.39	1						
13. ND accuracy	-.19	.19	-.58	-.79	.004	.66*	-.12	.13	.53	.37	.61*	.66*	1					
14. SCR	-.39	.17	.002	.06	.07	-.10	.12	.42	.03	-.005	.30	.15	.33	1				
15. SR pcc	-.18	.16	.73*	.27	-.10	.41	.07	.17	-.42	.44	.36	.03	.51	.55	1			
16. SR pnc	-.14	.21	1.0**	.48	-.20	.58*	-.21	.39	-.48	.45	.27	.18	.85**	.70*	.92**	1		
17. SR psa	-.05	-.08	.76*	.42	-.36	.55*	.11	-.19	-.34	.43	.45	.20	.78**	-.04	.75**	.73**	1	
18. NWR,pcc	-.09	-.04	-1.0*	-1.0*	-.11	.39	.02	.63	-.36	.70*	.51	.01	.05	.24	.47	.35	.40	1

* Correlation is significant at the 0.05 level (2-tailed).
 ** Correlation is significant at the 0.01 level (2-tailed).

Table 7. Partial Correlations with age partialled out for the whole group of children with normal hearing (age-matched proportions in each grade). Test abbreviations are explained in table 1.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. PN latency	1													
2. PN accuracy	-.123	1												
3. WS latency	.045	-.197	1											
4. WS accuracy	-.012	-.127	-.233	1										
5. SD latency	.353*	.049	.602**	-.201	1									
6. SD accuracy	.129	-.155	.195	.300*	.157	1								
7. MP	-.149	-.19	.006	.056	.008	.229	1							
8. ND latency	.216	.15	.387**	-.094	.677**	.025	-.199	1						
9. ND accuracy	-.059	-.15	-.042	.008	.044	.057	.163	-.171	1					
10. SCR	-.084	.316*	-.255	.008	-.089	-.075	.282	-.093	.175	1				
11. SR pcc	.437**	-.055	-.101	.020	-.046	.036	.033	-.116	.050	.225	1			
12. SR pnc	.400**	.005	-.127	.007	-.030	.079	.043	-.159	.066	.202	.893**	1		
13. SR psa	.445**	-.067	-.078	-.144	.045	-.115	.065	-.063	-.095	.144	.742**	.630**	1	
14. NWR pcc	.253	-.358*	-.140	-.066	.076	.177	.329*	-.061	.204	.183	.294*	.179	.349*	1

* Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed).

Lexical access

Several of the measures of lexical access were found to be significantly inter-correlated for both groups of children, although these correlations had smaller magnitudes in the group of children with normal hearing.

Phonological WM – Lexical access

Phonological WM, i.e. the Non-word Repetition test and the Serial Recall of Non-words test, was found to be significantly correlated with measures of lexical access. The Passive Naming test was significantly correlated with the Serial Recall test in both groups of children. Non-word Repetition was found to be significantly correlated with the Passive Naming test in the NH group and with the Semantic Decisions test in the CI group.

Phonological skills – Lexical access

In the group of children with CI, the accuracy measure of the Non-word Discrimination test was significantly correlated with lexical access (accuracy of the Passive Naming test). In the comparison group, the latency measure of the non-word discrimination was significantly correlated with the latency measures of the Semantic Decisions test and the Wordspotting test.

General WM - Lexical access

General WM was significantly correlated with the accuracy measures of the Passive Naming test in the group of children with normal hearing, but not in the children with CI.

In sum, associations found in both groups of children were generally stronger in the group of children with CI. Significant correlations between measures of lexical access and phonological WM were found for both groups of children. A few significant correlations between measures of lexical access and general working memory were found in the group of children with normal hearing but not in the group of children with CI. General and phonological WM were found to be significantly correlated in the children with CI but not in the group with normal hearing. The measures of latency and

accuracy were only significantly correlated in one of the tests, the Non-word Discrimination task for the children with CI.

Demographic Factors – Cognitive Skills

Age at diagnosis and age at implantation

Age at diagnosis did not correlate with any of the cognitive measures, neither when age was the only variable partialled out nor in the second order partial correlation where age and age at implantation of the first CI were partialled out. Age at implantation of the first CI was not found to correlate with any of the cognitive measures neither when age nor age plus age at diagnosis were partialled out.

Age at implantation of the second CI and time interval between first and second CI

A few significant correlations were obtained between cognitive skills and age at implantation of the second CI, and between cognitive skills and time between the implantations of the first and second CI. However, since the population of children with 2 CIs was small and very heterogeneous, we refrain from reporting these correlations. A median split analysis was performed where children were divided into separate groups depending on whether they had received their second implant before or after the age of 6;3 yrs. Frequency analyses revealed that similar proportions in both groups performed above the mean for the whole group of children with 2 CI on most of the cognitive tests. This pattern was also found when comparing groups with time intervals between first and second implantation of greater than or less than 4.1 yrs.

Communication Mode and School Setting

The children with CI were roughly subdivided into two groups according to their main communication mode; one group who used oral communication only (10 children) and one group (9 children) who were mainly oral but who, according to parental reports, sometimes needed signed support in their daily lives. Significant differences between the groups were found on the accuracy measure of the Passive Naming test, where the children who used oral communication only had a higher performance, $t(16) = 2.6$, $p < .05$ (see Geers, in press, for similar results), and on the psa measure of the Serial Recall of Non-words test $t(14) = 2.7$, $p < .05$. The children with CI were also compared in terms of school setting, mainstream education (10 children) versus education programs

for children with severe or profound hearing impairment (9 children), respectively. No significant differences between the groups were found on any of the cognitive measures.

In summary, the children with CI who used oral communication only were found to have a higher performance level on the Passive Naming accuracy measure of lexical access and on the psa measure of phonological WM than those children who to some extent used signed speech. There was no difference in performance between children attending different school settings.

DISCUSSION

The purpose of the present study was to examine different aspects of WM capacity, lexical access and phonological skills in children with CI, in comparison to age-matched children with normal hearing. A second purpose was to study the relations between the cognitive measures and investigate how these cognitive measures are related to demographic variables. Generally, the children with CI had a lower level of performance than the children with normal hearing on all of the cognitive tests, except for the visuospatial WM test and the response latency measure of the test on phonological skills. A more detailed analysis at the subgroup level where the children with CI were compared with their grade-matched comparison group, revealed that these differences were not significant for all grades and that their performance was relatively poorer in the tests of phonological WM.

Phonological Working Memory

A Non-word Repetition task and a Serial Recall of Non-words task were used to measure the phonological storage component of working memory. Neither of these tests is believed to involve any support from long-term memory, which is the case in span tests with digits or real words.

The Serial Recall of Non-words test and the Non-word Repetition tests may be considered to tap the capacity of the phonological loop according to Baddeley's model of WM (Gathercole & Pickering, 2000). Alternatively, these tests may be considered to measure the functioning in all three components (the phonological input buffer, the output buffer and the conversion mechanism in between) of the model by Jacquemot & Scott (2006). The difference between Non-word Repetition test and the Serial Recall test

is that non-words in the former test have more complex syllable structures than the non-words used in the latter task. Furthermore, in the Non-word Repetition test, the child should make use of the different stress patterns and intonations of the non-words. The non-words of the Serial Recall test, on the other hand, have a simple CVC-structure and the non-words are reproduced in series with up to 5 items and therefore this test is considered to measure the maximum capacity of either the phonological loop (Baddeley, 2000) or the components of Jacquemot's & Scott's (2006) model. The children with CI had a lower performance level than the children with normal hearing on both tasks of phonological WM. When the most lenient scoring measure of the Serial Recall of Non-words test was used, 4 children out of 16 performed within 1 SD of their respective comparison group mean. Furthermore, the difference between children with CI and their NH comparison group was not significant for grade 4. These results suggest that children with CI may experience relatively less problems in tasks assessing phonological storage, when a lower level of detail for the phonological representations to be stored is required.

General WM

At the all-age group level, the children with CI had a lower performance than the children with NH on measures of general working memory. Subgroup analyses indicated that this difference was not significant in grade 1. These results are in line with the findings from Burkholder & Pisoni (2003). A relatively larger proportion of children with CI had higher performance on the general working memory test as compared to their performance level in the tests on phonological WM, Serial Recall of Non-words (the 2 more conservative scoring criteria of this test) and Non-word Repetition. This may be an indication that children with CI have more specific problems related to the phonological storage aspects of working memory than to the more the general aspects, including both processing and storage of information. These findings are also in line with findings from children with mild / moderate hearing impairment (Hansson, Forsberg, Löfqvist, Mäki-Torkko & Sahlén, 2004; Sahlén & Hansson, 2006) who were found to differ significantly from children with normal hearing on measures of phonological working memory, but who performed comparably to their controls on the measures of general working memory.

Another explanation for the pattern of results may be found in the tasks used to measure the specific aspects of working memory. Since real words were used in the test on

general working memory, support from phonological, semantic and lexical representations in long-term memory should improve the children's performance (Gathercole, 1999). Children with CI may benefit more from support from long-term representations, and the use of top-down processing strategies than children with normal hearing, since this would make them rely less on auditory perception. The tests on phonological storage, on the other hand, should not allow for support from long-term representations since non-words were used in these tests. This may explain the relatively lower performance of the children with CI on the phonological working memory tests as compared to their general working memory performance. Burkholder & Pisoni (2003) found a strong correlation between general working memory and speaking rate in CI-users, but not in children with normal hearing. They interpreted this as an indication that the lower working memory capacity in children with CI may be caused by reduced speed and efficiency in the processes of subvocal rehearsal and serial scanning. The fact that children with normal hearing in the Burkholder & Pisoni (2003) study did not display a relation between general working memory and speaking rate was seen as an indication that backward digit span is more taxing for the central executive functioning in this group of children, while the phonological component of working memory is more taxed in children with CI. The lower general working memory performance, found in the children with CI may also be related to slower sub-vocal rehearsal processes since there was a significant correlation between our measure of general WM and phonological WM in this group. The correlation between general and phonological WM was not significant for the children with normal hearing in our study. This finding was somewhat unexpected since complex working memory has been found to be dependent on the phonological loop for storage of the information to be remembered in children with normal hearing (e.g. Alloway et al. 2004; Gathercole & Pickering, 2000).

Visuospatial Working Memory

The children with CI performed on a level with the children with normal hearing on the task tapping visuospatial WM. These results corroborate previous findings from children with hearing impairment (Mayberry, 1992), that working memory capacity should not be impaired relative to that of children with normal hearing in tasks without a phonological component. This finding seems reasonable since children with CI have been exposed to visuospatial information to the same extent as children with normal hearing. Different results were, however, found in a study by Cleary, Pisoni & Geers (2001), where

children with CI had a lower performance level than children with normal hearing in tasks tapping both the visuospatial and the phonological components of working memory. The interpretation was that children with CI have atypical development of both phonological and visuospatial components of working memory. The reason for the results found by Cleary et al. (2001) may be found in their test procedure, where a task on visual WM was always presented in an audio-visual condition before the visual-only condition. This may have primed the children to rely on phonological coding of the stimuli even in the visual-only condition. Assuming that children with CI have relatively more difficulties with storing of phonological than visuospatial information, reliance on a phonological coding strategy in this test may explain their lower performance relative to the children with normal hearing. The pattern of filled and unfilled matrix cells used in our study may be hard to translate into phonological form and no similar audio-visual test was presented before the test. Therefore, the procedure adopted in the present study may be considered a relatively pure measure of visuospatial working memory.

Visuospatial working memory tasks have previously been suggested to place significant demands on the processing component of general working memory for individuals with normal hearing (Wilson et al., 1987). The results from the present study may therefore be interpreted as an indication that children with CI have a general processing component of working memory, which is of the same capacity as that of children with normal hearing. However, the test on general working memory may not tap exactly the same capability in children with CI and the comparison group. Since the test used to assess general working memory capacity was presented in linguistic form, phonological working memory capacity (storage only) may restrict performance for the children with CI, as they seem to have specific problems with this component of working memory. For the children with normal hearing, the test on general working memory may to a greater extent measure the simultaneous storage and processing of information.

Phonological skills

Non-word Discrimination was used to assess phonological skills. This task may be considered to tap the phonological input buffer according to Jacquemot & Scott (2006) since no output is required. At the group level with all ages included, the children with CI had a lower performance level than the children with normal hearing, on the accuracy measure but not the response latency measure of the test. Further subgroup analyses

indicated that 75 percent of the children performed within 1 SD of their grade-matched comparison group mean on the latency measure. Thirty-three percent performed within 1 SD of the NH mean on the accuracy measure and the differences between children with CI and children with NH were not significant in several of the age-matched subgroups. These results suggest that the children with CI may often process phonological information as rapidly as children with normal hearing when their representations of the phonemes used in the task are distinct (Elbro, 1998). No significant correlations were found between the tests of Non-word Repetition and Non-word Discrimination, neither for children with CI, nor for children with NH. When interpreted according to the theoretical model by Jacquemot & Scott (2006), this pattern of results may indicate that poor performance in the Non-word Repetition task is not necessarily a product of impaired function in the phonological input buffer. Instead, it may be a result of problems in either the phonological output buffer or in the conversion mechanism converting phonological input into output. Possibly, the functioning of these components of the model may be affected by the limited auditory stimulation experienced by children with CI before they received their implants.

The results further suggest that children with CI may be able to differentiate between different speech sounds but that they have problems reproducing these sounds, which may be a consequence of problems in the conversion mechanism or the output buffer in Jacquemot's & Scott's (2006) model.

Lexical access skills

Problems in finding and retrieving verbal labels from long-term memory have been interpreted as the result of difficulties encoding the full segmental phonological representations of words leading to less distinct phonological representations of words in long-term memory (Elbro et al., 1998). These problems have also been interpreted as difficulties in processing the encoded representations in order to retrieve the required name on demand (Swan & Goswami, 1997; Plaza & Cohen, 2003). The children with CI had significantly lower performance than the children with NH when the groups with all ages included were compared. Fifty percent of the children with CI, however, performed within 1 SD of their respective grade-matched comparison group on the latency measures and 20-30 percent performed within 1 SD of the NH mean on the corresponding accuracy measures. Analyses of the grade-matched subgroups further

revealed that the differences between children with CI and children with NH were not significant in all grades for the accuracy measures. The finding that so many children with CI had a relatively high speed of lexical access for known words may be interpreted as an indication that children with CI can access their phonological- and semantic representations of words in long-term memory at a high speed, when the quality of these representations is high, i.e. when the words are highly familiar to them. On the other hand, when the phonological representations or the speech signals are less distinct, the process of matching the incoming speech signal to the correct phonological representations in the mental lexicon may be slower and often fail (Elbro et al., 1998).

The measures of phonological WM and lexical access were found to be significantly correlated in both groups of children. Speculatively, this correlation may imply causation, and a causal relation between these skills may go in both directions. The phonological storage may be necessary in the process of encoding phonological information in long-term memory in order to acquire distinct phonological representations (Gathercole et al., 2005). On the other hand, it may be necessary for these phonological representations to be distinctive so that they could easily be matched with an incoming speech signal in situations demanding quick access to phonological representations (Elbro et al. 1998).

The correlation between the Non-word Discrimination test of phonological skills and the measures of lexical access, found in both groups, may indicate that tasks on lexical access are highly dependent on phonological processing, in the sense of discriminating between different speech sounds.

The correlations between measures of lexical access and general working memory, found in the group of children with normal hearing, were expected since the processing component of the working memory test required the child to quickly access words from long-term memory in order to complete the sentences. Therefore, those children who could quickly and easily access their long-term representations may have had more resources left to store the words they had previously filled in. The fact that these correlations were not found in the group of children with CI was somewhat surprising since children with CI might have lower quality of the incoming speech signal and

therefore their performance in the general working memory task may be expected to be more dependent on lexical access in this particular task.

It should be noted that there is an absence of valid tests on auditory perception for children in Sweden. It should also be noted that this may be a problem for hearing research on this population. The situation is that all of the tests that are used clinically to test auditory perception are linguistic in nature and require the repetition of words or sentences, where perfect pronunciation of the words is required to receive full credit. These tests may be clinically useful measures of how the children manage in some situations requiring speech perception. However, when used for a research purpose, we cannot be certain to which extent the results from these tests are measures of auditory perception or of cognitive skills. The performance level of a child tested with these measures may be a composite measure of their auditory perception, articulation skills, phonological WM, vocabulary and/or lexical skills (since the child needs to be familiar with the words used). These characteristics of the tests may make them particularly uninformative when used for children with motor- and/or cognitive problems. A further potential problem is that some of the most commonly used tests contain words that are rare in modern Swedish vocabulary. Because of this situation we have not been able to relate the cognitive performance of the children with measures of auditory perception. Some hints about how auditory perception may influence performance on the cognitive measures may be found in the tests of Non-word Repetition and Non-word Discrimination, since these tests use the same non-words as test items. In the former test the task is to repeat exactly the same non-words which are to be discriminated in the latter task. In the non-word discrimination task, the children's auditory perceptual skills are assessed when they are asked to discriminate between non-words differing by one single phoneme. This test does not pose any requirements on their speech production skills since they are asked to respond by pressing a button. The fact that we did not find a significant correlation between the measures of discrimination and repetition of the non-words may be seen as an indication that (at least) phonological working memory performance, assessed in the non-word repetition task, is not dependent on the ability to discriminate between the phonemes of the non-words. Since these two tests use non-words, the influence of vocabulary/lexical skills should not be a confounding variable as it may be in conventional tests on auditory perception, even though both tests pose certain demands on phonological WM. As mentioned before, the relation between the

Non-word Repetition and Non-word Discrimination tests may only give us a hint about the influence of auditory perception, since they are not designed to measure auditory perception but should be seen as tests on phonological WM and phonological skills respectively. Therefore, we need to develop non-linguistic tests of auditory perception to be able to learn more about the influence of auditory perception on the cognitive skills of Swedish children with CI.

To sum up, at the group level with all ages included, the children with CI performed at a lower level than the children with NH on all of the cognitive tests, except for the visuospatial WM test and the response latency measure of the test on phonological skills. These differences between the groups were not found in all of the subgroup analyses and a number of children with CI performed within 1 SD of the mean of their grade-matched comparison group on all of the cognitive tests. The children with CI seemed to have specific problems with phonological WM and phonological skills as compared to other cognitive skills (e.g. general and visuospatial components of WM and lexical access skills).

Demographic Factors

Before a further discussion of the results with respect to the demographic data, it should be noted that the demographic variables must be regarded as less precise compared to the other variables as they are constituted by parental reports.

Age at diagnosis and age at implantation of the first CI

Neither age at diagnosis nor age at implantation of the first CI correlated with any of the cognitive measures. These tendencies may point in the same direction as results reported by Geers (2002) who did not find any significant contribution of age at implantation on speech perception and production when nonverbal intelligence was held constant. On the other hand, other studies have found higher levels of language skills to be associated with a higher age at onset of deafness (e.g. Geers, 2002; Richter et al., 2002), and early age at implantation (Geers, 2003, Tomblin et al., 2005).

Communication mode and School setting

When the children with CI were subdivided into two groups according to their main communication mode, a significant difference between the groups was found only for

one of the cognitive measures (the accuracy measure of the Passive Naming test) where the children who used oral communication had a higher performance. When the children with CI were subdivided according to their educational setting (individually integrated into mainstream education versus attending education programs for children with severe or profound hearing impairment) we did not see any differences between the groups on any of the cognitive variables. These tendencies are interesting since some authors (e.g. Archbold, Nikolopoulos, Tait, O'Donoghue, Lutman & Gregory, 2000) stress the importance of the communication mode in school for the outcome. However the tendencies reported here must be interpreted with extreme caution for these variables in particular since the situation of communication modes and school settings is extremely complex for Swedish children with CI. They have at least four kinds of educational settings to choose between. Some children with CI attend schools for the deaf, where teaching is mainly in sign language. Others attend hearing classes in special schools for children with hearing impairment and receive their instruction mainly in oral language. Children with CI may also be integrated in mainstream education attending a hearing class. Swedish sign language (a system comparable to American Sign Language) has a unique position since all deaf children in our country are exposed to it, but the use of sign language is seldom a static phenomenon. In a longitudinal case study of four Swedish children with CI, the authors conclude that the children with CI and their parents successively drop sign language as oral language develops (Nelfelt & Nordqvist, 2004). The present situation in Sweden thus makes it very hard to control for the amount of auditory input in children with CI. In our study, the children attended different educational settings with different communication modes, which also changed over time. Although most children included in the present study were mainly oral they were also to some extent 'bilingual'. This means that they were exposed to oral language at home and at school at the time of testing, often with signed support. Our results from the analyses of communication mode and school setting should be interpreted with caution, with the previous discussion in mind. We did, however, not find any differences in performance measures between the children attending mainstream schools and those attending education programs for children with severe or profound hearing impairment. This result does point in the same direction as results from Geers (2002), suggesting that the main communication mode used at home and at school is more important for the language development of children with CI than the type of school setting per se.

Conclusions

The children with CI had poorer performance than the children with normal hearing on the tests of phonological and general WM, phonological skills (accuracy) and lexical access. No significant differences between the groups were found in the test of visuospatial WM. For most of the cognitive tests, group differences were not found in all of the subgroup analyses. The children with CI were found to have relatively more problems in the tasks with higher demands on phonological WM and phonological skills. We interpret these results as an indication that general working memory capacity of children with CI is not impaired relative to children with normal hearing. The more phonologically complex information that is used in tests on working memory capacity, the more difficulties children with CI do experience. The difficulties with phonological WM experienced by children with CI may be caused by problems in the phonological loop of working memory according to Baddeley's (2000) model. These difficulties may also, according to Jacquemot & Scott (2006), stem from problems in the output buffer and/or the input-output conversion mechanism rather than by problems in the input buffer. The reason for this interpretation is that these children performed relatively high on the phonologically demanding Non-word Discrimination task without requirements on output phonology. Less developed motor aspects of articulation may also be a possible cause for these difficulties.

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