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Maria Huber and Ulrike Kipman
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Cognitive Skills and Academic Achievement of Deaf Children with Cochlear Implants

Maria Huber, DPhil[1], and Ulrike Kipman, PhD, JD[2]

Sponsorships or competing interests that may be relevant to content are disclosed at the end of this article.

Abstract

Aim. To compare cognitive performance between children with cochlear implants (CI) and normal-hearing peers; provide information about correlations between cognitive performance, basic academic achievement, and medical/audiological and social background variables; and assess the predictor quality of these variables for cognition.

Design. Cross-sectional study with comparison group, diagnostic test assessment.

Setting. Data were collected in the authors' clinic (children with CI) and in Austrian schools (normal-hearing children).

Subjects and Methods. Forty children with CI (of the initial 65 children eligible for this study), aged 7 to 11 years, and 40 normal-hearing children, matched by age and sex, were tested with (a) the Culture Fair Intelligence Test (CFIT); (b) the Number Sequences subtest of the Heidelberger Rechentest 1-4 (HRT); (c) Comprehension, (d) Coding, (e) Digit Span, and (f) Vocabulary subtests of HAWIK III (German WISC III); (g) the Corsi Block Tapping Test; (h) the Arithmetic Operations subtests of the HRT; and (i) Salzburger Lese–Screening (SLS, reading). In addition, medical, audiological, social, and educational data from children with CI were collected.

Results. The children with CI equaled normal-hearing children in (a), (d), (e), (g), (h), and (i) and performed significantly worse in (b), (c) and (f). Background variables correlate significantly with cognitive skills and academic achievement. Medical/audiological variables explain 44.3% of the variance in CFT1 (CFIT, younger children). Social variables explain 55% of CFT1 and 24.5% of the Corsi test.

Conclusions. This study augments the knowledge about cognitive skills and academic skills of children with CI. Cognitive performance is dependent on the early feasibility to hear and the social/educational background of the family.

Keywords

cognitive skills, reading, arithmetic, hearing loss, pediatric cochlear implantation

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A consensus exists in pediatric cochlear implant (CI) research that the benefit of CI depends on the "hearing variables" of age at cochlear implantation,[1-5] duration of hearing loss before CI,[1] preoperative residual hearing,[2,3] bilateral cochlear implantation,[1] duration of implant use,[4] social and educational variables,[3,6] and possible additional handicaps.[7] However, the puzzle is still incomplete. All these variables are not sufficient to explain comprehensively why some children are more successful than others in their language development. In the past years, cognition has been postulated as a further potential link.

Working memory (WM) is considered essential for the cognitive system.[8-13] It is associated with selective attention (AT),[14-16] intelligence/neuropsychological skills,[13,17,18] and skills in language, reading, and mathematics of normal hearing children.[12,13,17, 9-21]

Studies on CI in children show high correlations between selective attention AT and the duration of implant use,[22] chronological age,[22,23] and nonverbal IQ.[23] Studies on WM and short-term memory (STM) of children with CI document close relationships between STM/WM capacities and age at CI,[24] vocabulary,[25] receptive language performance,[26-29]

[1]Department of Otorhinolaryngology, Head and Neck Surgery, University Clinic, Paracelsus Medical University, Salzburg, Austria
[2]UT SPSS Statistics, Hallein, Austria

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Corresponding Author:
Maria Huber, DPhil, Department of Otorhinolaryngology, Head and Neck Surgery, Landeskrankenhaus Salzburg, Universitätsklinikum, Müllner Hauptstr. 48, A 5020, Salzburg, Austria
Email: M.Huber@salk.at

reading skills,[25,30,31] and nonverbal IQ/neuropsychological skills.[25,26]

However, it remains an open question how cognitive skills are related to mathematical achievement of children with CI, as our knowledge about mathematic skills of children with CI is still poor.[32-35] Furthermore, the number of studies on IQ/neuropsychological skills of children with CI is still limited.[25,36-39]

The present study aims to survey cognitive abilities and basic academic achievement of children with CI to answer the following questions: Do children with cochlear implants differ in their cognitive skills compared with normal-hearing peers? Is cognitive performance related to hearing variables such as age at implantation? Do hearing variables predict cognitive performance? Is cognitive performance related to reading and arithmetic achievement?

Methods

Participants

Forty children with cochlear implants participated in the study (21 girls, 19 boys; mean [SD] age, 10.1 [1.3] years). Initially, 65 children with CI who were implanted in Salzburg had fulfilled our inclusion criteria: (a) aged 7 to 11 years, (b) onset of deafness in the first 24 months, (c) cochlear implantation in the first 60 months of life, and (d) at least 3 years of hearing experience with the first CI. However, the parents of 13 children declined to participate, 2 children refused, and 10 of the remaining 50 were unavailable because their address was unknown.

Table 1 shows medical, audiological, and social/educational background data of children with CI.

The comparison group consisted of 40 normal-hearing children from 2 Austrian schools, matched by age and sex (mean [SD] age, 10.1 [1.3] years).

Table 2 summarizes the educational background of parents for the 2 groups.

The 2 groups did not differ significantly in social background (educational and skill level of the parents, single-parent family, single child, employment of parents).

Instruments

The following instruments were employed to evaluate inductive and deductive reasoning, attention, auditory short-term memory, visual short-term memory, reading skills, arithmetic skills, and language skills of children with CI and normal-hearing children:

The Culture Fair Intelligence Test (CFIT)[40] is a measure of (nonverbal) fluid intelligence. We used the German version (CFT) of the CFIT to assess inductive reasoning. Children up to age 8.5 years were tested with the CFT1[41]; children older than 8.5 years were tested with the CFT 20.[42]

We used the CFT 20 and not the revised form CFT 20-R[43] because of practical reasons (to be able to compare current results with former results of the children), which is still allowed according to the test manual.[43]

The Heidelberger Rechentest (HRT)[44] is a test battery for primary school pupils and evaluates different mathematical capacities. We employed the Number Sequences and Arithmetic Operations subtests. The Number Sequences (NS) subtest is a measure of mathematical logical reasoning. It was employed to assess deductive reasoning. The child has to continue number sequences (eg, 1 3 2 4 3 5__ __). The Arithmetic Operations subtest is a measure of basic arithmetic achievement. The child has to solve the following basic arithmetic tasks: addition (RA), subtraction (RS), multiplication (RM), division (RD), ''bigger/smaller tasks'' (BS), and complement tasks (CT). There is also an ''operations total'' score. All tasks did not include math word problems.

The Hamburger-Wechsler Intelligenz-Test für Kinder (HAWIK),[45] the German version of the Wechsler Intelligence Scale for Children (WISC),[46] is a test battery for different nonverbal and verbal capacities. To compare the results of the present study with corresponding WISC III results of earlier studies,[25,39,47,48] we used the HAWIK III instead of the reversed HAWIK IV.[49] We employed the Coding, Digit Span, Comprehension, and Vocabulary subtests. Coding (Cod) is a measure of selective visual attention. The child has to transcribe rows of digit-symbol codes as quickly as possible (according to a key). Digit Span (DS) is a measure of short-term memory and auditory-verbal working memory. The child has to repeat a dictated series of digits forward (DSf) or backward (DSb). The series begins with 2 digits and increases in length. Comprehension (Com) is a measure of commonsense reasoning. The child is asked (oral) questions to solve everyday problems or to understand social rules and concepts. Vocabulary (Voc) is a measure of language skills. The child is asked questions to define a set of words.

The Corsi Block Tapping Test (CORSI)[50] is a measure of visual memory span for children and adults. The examiner points at a sequence of 9 blocks, which are irregularly positioned on a monitor or fixed on a board. The respondent has to tap the same blocks in the same order (2 sessions).

The Salzburger Lese–Screening (SLS) is an Austrian test to assess basic reading skills of primary (SLS 1-4)[51] and secondary (SLS 5-8) pupils.[52]

All tests except CORSI have (standardized) age norms (CFIT, HAWIK) or class norms (HRT, SLS).

Procedures

Children with CI were tested individually in our clinic. Test sessions lasted approximately 2 hours per child. All children of the comparison group were examined anonymously in groups (CFIT, HRT, SLS) and parts of the group (randomly selected) also individually (CORSI, HAWIK III).

Statistics

We compared mean percentages and means of children with CI with mean percentages and means of matched normal-hearing children using χ^2 tests, t tests for independent samples, and multivariate analyses of variance (MANOVAs). To find out if there is any correlation between background variables (medical and audiological variables [see **Table 1**];

Table 1. Medical, Audiological, and Social/Educational Background Variables of 40 Children with Cochlear Implants Participating in the Study

Girls	21 (52.5)
Boys	19 (47.5)
Age, y, mean (SD)	10.1 (1.3)
Causes of deafness, No.	
Meningitis	3
Genetic (connexin 26)	20
Otosclerosis	1
Unknown	16
Congenital hearing loss	34 (85)
Normal imaging of temporal bone	38 (95)
Full insertion of electrodes at implantation	40 (100)
Indication for distinct developmental delay, No.	1
Age at first fitting of hearing aids, mo, mean (SD)	12.5 (11.4)
Benefit of hearing aids (minimal perception of acoustic stimuli with hearing aids) prior to implant	13 (33)
Age, y, at first implantation, mean (SD)	2.3 (1.2)
Duration, y, of first implant use, mean (SD)	7.8 (1.3)
Unilateral cochlear implantation	25 (62.5)
Bilateral cochlear implantation	15 (37.5)
Age, y, at second implantation, mean (SD)	5 (2.4)
Use of CI[a]	38 (95)[b]
Interimplant interval, y, mean (SD)	3.2 (2.3)
Duration, y, of second implant use, mean (SD)	5.6 (2)
Speech perception outcomes, %	
Numbers, mean (SD)	98 (4.6)
Monosyllables, mean (SD)	66 (19.7)
Sentences, mean (SD)	75 (27.3)
Early intervention before age 3 years	30 (75)
Mainstream schools	27 (67.5)
Special school for persons with hearing loss	10 (25)
Other schools	3 (7.5)
Co-teacher in classroom	22 (55)
Communication mode at school: oral/total/oral and total	26 (65)/ 5 (12.5)/ 9 (22.5)
Good/middle competence of sign language	19 (47.5)
Exclusive use of oral language	21 (52.5)
Only child	10 (25)
Single-parent family	8 (20)
Father unemployed	4 (10)
Migration background	8 (20)

Values presented as No. (%) unless otherwise indicated.
[a]Uses the cochlear implant (CI) continuously during the day, changes battery, and informs about damage.
[b]2 children do not change batteries

social and educational variables [see **Tables 1** and **2**]) and cognitive skills/academic achievement in children with CI, we computed Pearson, Spearman, and point-biserial correlations as well as partial correlations and a 1-way analysis of variance (ANOVA). Furthermore, we did regression analyses to investigate the impact of medical/audiological and social background variables on the test results.

Table 2. Educational Level and Employment Skills of 40 Parents of Cochlear Implant (CI) Users and 40 Parents of Normal Hearing Peers Participating in the Study

	CI Users	Hearing
Educational level, father		
Secondary school	19 (51)	20 (49)
Vocational school	11 (30)	8 (20)
Grammar school	3 (8)	10 (26)
College or university	4 (11)	2 (6)
Employment skills,[a] father		
0	0	0
1	6 (16)	6 (14)
2	29 (76)	32 (81)
3	3 (8)	2 (6)
Educational level, mother		
Secondary school	23 (57.5)	24 (59)
Vocational school	10 (25)	4 (9)
Grammar school	4 (10)	7 (18)
College or university	3 (7.5)	6 (15)
Employment skills,[a] mother		
0	7 (18)	9 (22)
1	7 (18)	7 (17)
2	22 (56)	19 (47)
3	3 (8)	6 (14)

Values presented as No. (%). Key for employment skills: 1 = unskilled work, 2 = jobs demanding vocational/training qualifications up to college level, 3 = jobs demanding college/university degrees, 0 = others. Orientation ISCO 88 International Standard Classification of Occupation (International Labor Office 1990).[67]
[a]The higher the number the higher the parents' skill level.

Ethics Committee

The study was approved by the Ethics Committee in Salzburg.

Results

Cognitive Capacities of Children with CI vs Normal-Hearing Children

Tables 3 and **4** show the percentage of children who scored average, below average, and above average on the CFT1, CFT20, HAWIK-Coding (Cod), HAWIK–Digit Span (DS), HAWIK-Comprehension (Com), HAWIK-Vocabulary (Voc), HRT, and SLS. The percentage of children who scored above average was significantly higher for hearing children on the Vocabulary and HRT Complement (CT) tests. The percentage of children who scored below average was significantly higher for children with CI on the Comprehension, Vocabulary, HRT-Subtraction (RS), and HRT-CT tests. **Tables 5** and **6** show the test outcomes with means and standard deviations (SD) for the CI group and the comparison group. Children with CI scored significantly worse on the Comprehension, Vocabulary, and Number Sequences (NS) tests. They also performed worse on the SLS; however, the difference is not significant. In all other tests, performance did not differ significantly between the

Table 3. Test Results for the CFT1, CFT20, HAWIK Coding, Digit Span, Comprehension, Vocabulary, HRT-Number Sequences, and SLS

Test	CFT1	CFT 20	HAWIK Coding	HAWIK Digit Span	HAWIK Comprehension	HAWIK Vocabulary	HRT Number Sequences	SLS
CI group, No.	14	25	39	39	38	27	27	36
Average, %	50	56	61	67	37	48	48	36
Above average, %	36	32	31	5	18	0	15	36
Below average, %	14	12	8	28	45	52	37	28
Hearing group, No.	19	21	17	17	40	17	40	40
Average, %	16	24	52	64	52	41	54	44
Above average, %	63	71	28	12	36	53	33	43
Below average, %	21	5	20	24	12	6	13	13
CI group vs hearing group, χ^2								
Above average	.01	.06	.10	.79	1.85	9.81***	1.67	.32
Below average	.25	.75	.25	.13	5.65**	17.97****	3.72	2.79

Table includes the percentage of children who scored average, below, and above average in the cochlear implant (CI) group according to the test norms compared with the normal-hearing group. Abbreviations: CFT, Culture Fair Test; HAWIK, Hamburger-Wechsler Intelligenz-Test für Kinder; HRT, Heidelberger Rechentest; SLS, Salzburger Lese–Screening.
$^{**}P < .05$. $^{***}P < .01$. $^{****}P < .001$.

Table 4. Test Results for the HRT Arithmetic Operations: Percentage of Children Who Scored Average, Below, and Above Average in the Cochlear Implant (CI) Group According to the Test Norms Compared with the Normal-Hearing Group (Only Primary School Children)

HRT	RA	RS	RM	RD	CT	BS	Op. Tot.
CI group, No.	28	28	22	21	28	28	28
Average, %	46.5	54	46	71	32	43	53
Above average, %	7	7	18	5	25	18	11
Below average, %	46.5	39	36	24	43	39	36
Hearing group, No.	40	40	31	31	40	40	40
Average, %	34	67	54	64	70	50	57
Above average, %	23	15	23	13	10	25	18
Below average, %	43	18	23	23	20	25	25
CI group vs hearing group, χ^2							
Above average	1.04	.30	1.00	.13	4.77**	.01	.49
Below average	.03	4.01**	.34	.01	3.00	.94	.86

Abbreviations: CT, Complement tasks; BS, Bigger-Smaller tasks; HRT, Heidelberger Rechentest; RA, Addition; RD, Division; RM, Multiplication; RS, Subtraction.
$^{**}P < .05$.

Table 5. Test Results for the CFT1, CFT20 (IQ in Mean, SD), CORSI SLS (Reading IQ in Mean, SD), and HAWIK Coding, Digit Span, Comprehension, and Vocabulary (Mean Scores, SD) Subtests for the Cochlear Implant (CI) Group Compared with the Normal-Hearing Group

	CFT		HAWIK						CORSI		SLS
Subtest	1	20	DSf	DSb	DStot	Cod	Com	Voc	1	2	R-IQ
CI, No.	14	25	39	39	39	39	38	27	40	40	36
Mean (SD)	102.7 (13.7)	104.2 (12.8)	6.5 (1.6)	5 (1.5)	9.1 (2.3)	11.1 (2.6)	8.6 (4)	7.4 (3.3)	6 (0.7)	12.6 (2.1)	101.3 (18.3)
Hearing, No.	19	21	17	17	17	40	17	17	17	17	40
Mean (SD)	102.5 (14.9)	107.0 (9.8)	7.2 (1.7)	4.8 (1.7)	9.4 (2.2)	9.8 (2.5)	10.5 (3.0)	12.7 (3.0)	5.7 (0.9)	11.9 (2.2)	108.2 (15.2)
t	0.05	0.79	1.43	0.40	0.88	0.96	2.45**	5.34****	1.38	1.12	1.80

Abbreviations: CFT, Culture Fair Test; Cod, Coding; Com, Comprehension; CORSI, Corsi Block Tapping Test; DSb, Digit Span backward; DSf, Digit Span forward; DStot, Digit Span total; HAWIK, Hamburger-Wechsler Intelligenz-Test für Kinder; SLS, Salzburger Lese–Screening; Voc, Vocabulary.
$^{**}P < .05$. $^{****}P < .001$.

Table 6. Test Results for the HRT Arithmetic Operations and HRT Number Sequences (NS) for the Cochlear Implant (CI) Group Compared with the Normal-Hearing Group (Only Primary School Children)

HRT	RA	RS	RM	RD	CT	BS	Op. Tot.	NS
CI group, No.	25	25	19	18	25	25	25	24
Mean (SD)	34.4 (24.8)	39.0 (27.6)	44.0 (26.2)	46.5 (26.7)	39.6 (32.4)	40.3 (31.2)	36.4 (27.8)	42.0 (25.2)
Hearing group, No.	40	40	31	31	40	40	40	40
Mean (SD)	40.9 (28.8)	47.0 (24.2)	48.1 (26.7)	47.2 (23.6)	45.4 (23.3)	47.5 (30.6)	43.3 (28.1)	56.5 (25.8)
CI group vs hearing group								
t	0.10	1.42	1.34	0.47	0.11	0.29	1.04	2.15**

Abbreviations: CT, Complement tasks; BS, Bigger-Smaller tasks; HRT, Heidelberger Rechentest; Op. Tot., Operations total; RA, Addition; RD, Division; RM, Multiplication; RS, Subtraction.
**$P < .05$.

CI group and normal-hearing group. Results of the MANOVAs show the same results: Children with CI differ significantly from normal-hearing children on the Comprehension (F = 4.30, P = .045), Vocabulary (F = 26.40, P = .000), and Number Sequences (F = 6.05, P = .017) tests.

Medical and Audiological Background Variables and Cognitive Performance (Children with CI)

For the study group, we analyzed to what extent medical/audiological background variables listed in **Table 1** correlated with the test outcomes (see cognitive performance in **Table 5**).

Interimplant interval and duration of second implant use did not correlate significantly with any test outcome (all $P > .05$). All other correlations between medical or audiological variables (**Table 1**) and the test outcomes are shown in **Table 7**.

We found the following:

- The earlier the fitting of hearing aids and the earlier the age at first implantation, the better did children with CI perform on the CFT 1(IQ), Digit Span, and Vocabulary tests, if confounding variables are controlled.
- The longer the duration of first implant use, the better did children with CI perform on the Digit Span forward task and the CORSI (this correlation is not significant, when controlling confounding variables).
- Bilateral CI was related to better performance on the Digit Span forward task, if confounding variables are controlled.
- The earlier the age at second implantation, the better did children with CI perform on the Comprehension test, if confounding variables are controlled.
- Audiological speech test results were positively correlated with performance on the CFT 20 (IQ), Digit Span, Comprehension, Vocabulary, and HRT–Number Sequences tests, if confounding variables are controlled.

The variables of age at first fitting of hearing aids, benefit of hearing aids, age at first CI, and duration of first CI use explain 44.3% of the variance of the CFT1 results. For all other tests, the explained variance was <10%.

Further results: The performance on the Comprehension test is strongly correlated (r = 0.70) with the Vocabulary skills test.

Children with connexin 26 as the etiology for hearing loss performed significantly better on the CFT (CFT 1: t = 2.28, $P < .05$; CFT 20: t = 2.31, $P < .05$) than did other children with CI.

Social and Educational Background Variables and Cognitive Performance (Children with CI)

Parents' education and skill level (**Table 2**) correlated significantly with the Comprehension test: The higher the level, the better were the scores. If there was a co-teacher in class (**Table 1**), children with CI scored better on the Digit Span, Comprehension, Vocabulary, and the CORSI tests (correlations are smaller but still significant, when controlling confounding variables). Competence of sign language (**Table 1**) did not correlate significantly with the cognitive performance of the children. All correlations can be seen in **Table 8**.

Pupils of mainstream schools (**Table 1**) scored significantly better than pupils of special schools for the hearing impaired on the Comprehension test (t = 2.34, $P < .05$).

To see whether test performance is related to the mode of communication at school (**Table 1**), we did a 1-way ANOVA: There were significant differences in test performance between children communicating "auditory oral" and children communicating "total" in HAWIK Coding (P = .026), HAWIK Comprehension (P = .021), and the SLS (P = .012), as well as between children communicating oral and children communicating "oral and total" in the SLS (P = .022).

Explanation of variance by social background variables (school education, skill level of mother and father, migration background) was >10% for the CFT1, CORSI1, CORSI2, and the HRT-Division tests: CFT1 = 55%, CORSI1 = 19%, and CORSI2 = 24.5%.

Further results: Girls scored significantly better than boys on the Coding test (t = 4.90, $P < .001$).

Table 7. Results for Children with Cochlear Implants (CI)

	CFT 1	CFT 20	HAWIK DSf	HAWIK DSb	HAWIK DStot	HAWIK Cod	HAWIK Com	HAWIK Voc	CORSI1	CORSI2
Age at first fitting of HA[1]	–0.58** (14)	–0.03 (24)	–0.12 (37)	–0.03 (37)	–0.36** (37)	–0.11 (38)	–0.25 (37)	–0.44** (25)	–0.07 (38)	0.16 (38)
Benefit of HA prior to CI[2]	0.42 (13)	0.05 (21)	0.21 (33)	0.21 (33)	0.18 (33)	0.02 (34)	0.06 (32)	0.29 (22)	0.19 (34)	0.53*** (34)
Age at first CI[1]	–0.74***(14)	–0.11 (25)	–0.20 (39)	–0.01 (39)	–0.43*** (39)	0.04 (39)	–0.20 (39)	–0.46** (27)	0.01 (40)	–0.06 (40)
Duration of first CI use[1]	0.39 (14)	0.05 (25)	0.44*** (39)	0.29** (39)	0.14 (39)	0.11 (39)	0.22 (38)	0.16 (27)	0.29 (40)	0.46*** (40)
Unilateral/bilateral CI[3]	0.16 (14)	0.24 (25)	0.38** (39)	0.15 (39)	0.20 (39)	0.01 (39)	0.20 (39)	0.26 (27)	0.05 (40)	0.21 (40)
Age at second CI[1]	n too small	–0.19 (11)	0.22 (14)	0.14 (14)	0.04 (14)	0.38 (13)	–0.55** (14)	–0.45 (11)	0.35 (14)	–0.09 (14)
Speech test, numbers[1]	0.31 (10)	0.13 (23)	0.36** (33)	0.41** (33)	0.50*** (33)	–0.03 (33)	0.20 (32)	0.51*** (22)	0.00 (33)	0.13 (33)
Monosyllables[1]	0.14 (10)	0.35 (22)	0.42** (32)	0.57*** (32)	0.58*** (32)	0.06 (32)	0.57*** (31)	0.61*** (21)	0.14 (32)	0.31 (32)
Sentences[1]	0.29 (10)	0.59*** (19)	0.56***(29)	0.46*** (29)	0.58*** (29)	0.18 (29)	0.60*** (28)	0.57*** (18)	0.26 (29)	0.35* (29)

All correlations between medical and audiological background variables and cognitive skills as assessed with the Culture Fair Test 1 (CFT1) and CFT20; Hamburger-Wechsler Intelligenz-Test für Kinder (HAWIK) Digit Span (forward [DSf], backward [DSb], and total [DStot]), Coding (Cod), Comprehension (Com), and Vocabulary (Voc) subtests; Corsi Block Tapping Tests (CORSI1 and 2); and Heidelberger Rechentest (HRT) Number Sequences. Values represent correlation coefficients (n): 1 = Pearson correlation, 2 = Spearman correlation, 3 = point-biserial correlation. Abbreviation: HA, hearing aid.
*$P < .1$ (non significant); **$P < .05$; ***$P < .01$.

Table 8. Results for Children with Cochlear Implants (CI)

	CFT 1	CFT 20	HAWIK DSf	HAWIK DSb	HAWIK DS	HAWIK Cod	HAWIK Com	HAWIK Voc	CORSI1	CORSI2
Education mother[2]	0.32 (14)	0.16 (24)	–0.04 (38)	0.08 (38)	0.12 (38)	–0.10 (38)	0.35** (37)	0.26 (27)	0.01 (39)	0.06 (39)
Education father[2]	–0.01 (14)	0.19 (22)	–0.14 (36)	–0.03 (36)	0.04 (36)	–0.14 (36)	0.40** (35)	0.21 (25)	–0.37** (37)	–0.24 (37)
Skill level mother[2]	0.34 (14)	–0.34 (25)	–0.10 (39)	–0.18 (39)	0.32** (39)	–0.09 (39)	0.31* (38)	0.36* (27)	–0.15 (40)	–0.16 (40)
Skill level father[2]	0.53** (14)	0.37* (23)	0.23 (37)	0.28* (37)	0.37** (37)	0.24 (37)	0.59*** (36)	0.23 (25)	0.06 (38)	0.17 (38)
Migration background[3]	–0.16 (14)	–0.45** (25)	–0.28* (39)	–0.28* (39)	–0.22 (39)	–0.18 (39)	–0.27 (38)	–0.27 (27)	–0.14 (40)	–0.08 (40)
Sign language[2]	–0.08 (13)	0.21 (23)	0.16 (36)	0.29* (36)	0.19 (36)	0.20 (36)	0.32* (35)	–0.13 (25)	0.23 (37)	0.21 (37)
Co-teacher at class[3]	0.44 (10)	0.45* (19)	0.58***(29)	0.44** (29)	0.64*** (29)	0.18 (29)	0.41** (28)	0.51** (20)	0.13 (30)	0.36** (30)
Early intervention[3]	–0.69 (14)	0.25 (24)	–0.15 (38)	0.16 (38)	–0.30* (38)	–0.01 (38)	–0.25 (37)	–0.40** (26)	0.04 (39)	0.18 (39)

All correlations between social and educational background variables and cognitive skills, as well as reading and cognitive skills, as assessed with the Culture Fair Test 1 (CFT1) and CFT20; Hamburger-Wechsler Intelligenz-Test für Kinder (HAWIK) Digit Span (forward [DSf], backward [DSb], and total [DStot]), Coding (Cod), Comprehension (Com), and Vocabulary (Voc) subtests; Corsi Block Tapping Tests (CORSI1 and 2); and Heidelberger Rechentest (HRT) Number Sequences. Values represent correlation coefficients (n): 1 = Pearson correlation, 2 = Spearman correlation, 3 = point-biserial correlation.
*$P < .1$ (non significant); **$P < .05$; ***$P < .01$.

Arithmetic and Reading Achievement and Cognitive Performance (Children with CI)

We also investigated whether cognitive skills of children with CI are related to their arithmetic (total score of HRT–Arithmetic Operations) and reading (SLS score) achievement. Arithmetic achievement was correlated significantly and strongly only with deductive reasoning (r = 0.52, $P < .01$). Reading achievement was significantly and positively correlated with performance on the Vocabulary (r = 0.65, $P < .01$), Comprehension (r = 0.59, P = .001), Digit Span (forward: r = 0.50, $P < .01$; total: r = 0.56, P = .01), and Number Sequences (r = 0.43, $P < .05$) tests. (Correlations are smaller, but still significant, when controlling confounding variables.) None of the other cognitive measures correlated significantly with arithmetic or reading achievement. Reading and arithmetic achievement are positively correlated (r = 0.39, $P < .05$).

Discussion

We compared cognitive performance of 40 children with cochlear implants (of the initial 65 eligible for this study) with performance of (matched) normal-hearing children. Furthermore, we analyzed relations between hearing, medical/audiological, and social/educational background variables and cognitive performance, as well as relations between academic skills and cognitive performance. Finally, we assessed to what extent various background variables explain cognitive performance.

Children with CI performed at an average level, compared with the 40 matched normal-hearing children, in inductive reasoning (‘‘nonverbal IQ’’), auditory STM, visual STM, and selective visual attention. They performed worse in commonsense knowledge, vocabulary, and deductive reasoning (mathematical logical reasoning). Auditory STM, commonsense knowledge, and deductive reasoning correlated with reading and arithmetic achievement. Cognitive performance of children with CI was strongly connected to hearing variables such as age of fitting the hearing aids, age at first and second implantation, duration of first implant use, bilateral implantation, and social background variables.

Early hearing, provided by hearing aids[53] and CI,[1-5] promotes the early development of oral language in deaf children, and in this case, the first language acquisition may be very similar to that of normal-hearing children. Because normal-hearing children use strategies of inductive reasoning to learn general linguistic rules (eg, flexion rules for the conjugation of verbs),[54] inductive reasoning is trained simultaneously to language acquisition, which may also be the case for early hearing children with CI. In addition (in the case of hearing-impaired children with normal-hearing parents), oral language acquisition in time may prevent the development of reasoning and learning deficits due to a lack of experience in the hearing world.[55] As in the normal-hearing population, IQ test performance is influenced by social/educational background variables.[56]

Children with CI with connexin 26 as the etiology for hearing loss scored better in inductive reasoning/nonverbal IQ than other children with CI. According to Green et al[57] and Pierson et al,[58] children with this etiology have an advantage in their cognitive development[58] and in reading[57] compared with children with other etiologies. Our results add to these findings.

Children with CI performed age equivalent in auditory STM. The earlier the time of implantation of the first CI and the longer the duration of CI use, the better were the outcomes. The importance of the (early) capability to hear is also shown by correlations with the age at first fitting of hearing aids, bilateral implantation (see also Wass et al[24]), and auditory performance of the children. In addition, the outcomes are not independent of the social background of the children.

Our results are in contrast to earlier findings,[24-30,47,48,59] in which the same measure was used in some studies,[25,47,48] with results below average. A possible reason for this contrast is that the children in these studies[25,47,48] were implanted later and used their implant for a shorter period of time compared with the children in our study.

Children with CI also performed age equivalent in visual-spatial STM, as in earlier studies.[24,26,39]

In selective visual attention, the performance of children with CI was age equivalent to that of children with CI in Wu et al,[39] where the same measure was used. These results can best be interpreted by the theory of Dye et al.[60,61] According to these authors, performance of hearing-impaired persons (with and without CI) on selective attention tasks is modulated by the focus (deficient performance with central presentation vs enhanced performance with peripheral presentation) and allocation of attention (deficient performance with allocation in time vs enhanced performance with allocation in space). In the Coding task, performance was average for children with CI because attention was allocated in space and no focus on a central vision was required (see also previous studies[22,60-65]).

Children with CI performed below average in commonsense reasoning, similar to the children with CI in Wu et al,[39] where the same measure was used. Outcomes are tightly connected to the lexical skills of the children. Mainstream pupils and children with an early CI in the second ear and with satisfactory auditory performance will achieve better results. Obviously, the ability to hear and communicate easily with persons belonging to the hearing world is important for deaf children (at least with hearing parents).

Auditory STM, visual STM, and commonsense reasoning correlated with the availability of a second teacher in the classroom. A second teacher may promote the verbal communication and the active attendance at school, compensate for loss of information in the classroom, and prevent passivity of children with CI. The positive effect of parents' educational level may be explained by a similar mechanism.

As in earlier studies,[25,30,31] reading correlated with auditory STM, as well as with commonsense reasoning, deductive reasoning (mathematical logical reasoning), and lexical skills, in this study. However, unlike earlier studies,[2,6,25,66] reading was not associated with nonverbal IQ/neuropsychological skills. A possible reason for this is that we employed the "culture fair" CFIT, which is independent of cultural skills such as reading and mathematics.

The unavoidable connection to language is also shown by the correlation of arithmetic and (language-based) reading achievement. As expected, arithmetic achievement in this study also correlated with deductive (mathematical logical) reasoning.

However, our sample was too small to control the influence of the type of deafness and etiological variables such as meningitis as the cause of deafness or complications such as developmental delay, which may also affect the outcomes. Other open questions address the education of the children. Children with CI with mainstream education have fewer problems in commonsense reasoning than children with CI with special school education, despite the fact that the groups do not differ in their lexical skills. Further studies may also be necessary to investigate the influence of a second teacher in the classroom on the performances of children with CI and the role of social aspects. We still cannot determine if the problems of children with CI in commonsense reasoning are also based on social deficits. Another question addresses the migration background. Furthermore, it remains unanswered to what extent deaf children with CI are disadvantaged in orally presented tasks (Digit Span, Comprehension, Vocabulary).

Conclusion

Our study augments the knowledge about cognitive skills and academic skills of children with CI. Our results demonstrate very clearly the benefits of early fitting of hearing aids, early cochlear implantation, mainstream school education, co-teachers, and a high educational level of the parents for the cognitive development of children with CI.

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Author Contributions

Maria Huber, literature research, conception and design of the study, request for research funds, request for acknowledgment of ethics committee, organization, management and monitoring of the acquisition of data, interpretation of results, drafting the article (text, tables, references), and final approval of the paper; **Ulrike Kipman**, conception and design of the study, analysis of data, chart review and final version of the tables, revising the article critically, and final approval of the paper.

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