Cognitive Abilities of school-aged Children with Cochlear Implants: A Systematic Review

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Abstract

It has been argued that children with CI might be at risk for cognitive delays, which may have negative consequences for academic success and social interaction with peers. In this systematic review it was found that most cognitive test have only been used to compare children with CI and children with TH in one or two studies. The stability of results across studies could therefore not be evaluated. Most studies did not control for language ability which makes it impossible to evaluate if differences in the cognitive domain might be explained by differences in language ability. Most studies also had low ecological validity. Future directions and possibilities to improve research on the cognitive abilities of children with CI are discussed.

Cognitive Abilities of school-aged Children with Cochlear Implants: A Systematic Review

Cognitive abilities are of importance for amongst others acquiring a language (Conway et al., 2011; Deocampo et al., 2018; Kidd & Arciuli, 2016; Tomasello, 2000), academic success (Chamorro-Premuzic & Furnham, 2008; Giofrè et al., 2017), and social interactions with peers (Channon & Watts, 2003; Hebert-Myers et al., 2006; Matthews et al., 2018). For children with cochlear implants (CI), it has been suggested that they might be at risk for delays in certain cognitive domains, like executive functions (Kral et al., 2016; Kronenberger, 2019), and implicit sequence learning (Conway et al., 2011). However, studying differences in cognitive abilities between children with CI and children with typical hearing (TH) is challenging due to heterogenetic and small samples. Summarizing and comparing research can help to detect if results are consistent across studies and which factors might influence the results of the single studies. If results from different labs are compared and taken together this will lead to a clearer picture concerning differences in the performance on cognitive tests between children with CI and children with TH.

Many deaf and hard of hearing (DHH) children are using CIs. A CI is a device that converts a sound into an electrical signal which is then transmitted to the auditory cortex. However, a lot of information from the incoming sound is lost. The input provided by a cochlear implant is sparser than in typical hearing. Compared to typical hearing, both frequency resolution is poorer (Loizou, 2006) and dynamic range is reduced (Zeng, 2004). The majority of DHH children are born to parents with TH (Mitchell & Karchmer, 2004). Their exposure to language often starts when their first CI is turned on as most parents with TH are not able to use sign-language. Due to the prior language deprivation, the language development of the children might be delayed. A high percentage of children with CIs has been found to have spoken language abilities below their age-norm when they start formal education (Geers et al., 2016) and some of them have a persistent delay in spoken language .

DHH children with DHH parents who receive sign language from birth are usually not found to experience such problems (Hall et al., 2019).

It has been argued that many children with CIs not only experience delays in terms of language but also in terms of cognitive ability, especially in executive functioning (Kronenberger, 2020) and implicit sequence learning (Conway et al., 2009). These delays have both been attributed to auditory (Conway et al., 2009; Kral et al., 2016; Kronenberger, 2020) and language deprivation (Hall et al., 2019). For most children with CIs auditory deprivation is confounded with language deprivation. Therefore, the different influences of language and auditory deprivation are not possible to study in this group.

Studies comparing cognitive skills of children with CI and children with TH can have the aim to evaluate if any real-life differences would be expected between the groups (applied approach). However, they can also aim to evaluate the cause of cognitive differences between the groups (theoretical approach). For the latter, it is important that the study design controls for confounding factors. Many verbal cognitive tests are administered auditory and might therefore be influenced by auditory perceptual abilities. A CI provides a poorer auditory quality than typical hearing (Loizou, 2006; Zeng, 2004) and this needs to be taken into consideration when comparing the performance of children with CI and children with TH on auditory administered cognitive measures. In addition, language ability has been found to influence the performance on cognitive measures (Baldo et al., 2005; Baldo et al., 2010; Christensen & Wright, 2010; Fatzer & Roebbers, 2013; Gentner, 2016; MacDonald & Christiansen, 2002). For non-verbal measures, this effect has been attributed to the use of verbal strategies (see for example: Fatzer & Roebbers, 2013). Children with CI are at risk for language delays (Geers et al., 2016). Therefore, when comparing the cognitive abilities of children with CI and children with TH the possible effect of differences in language ability needs to be taken into consideration. This can be either done by using measures that are

likely not or only very little influenced by language ability, or by matching the groups on language ability when investigating differences in cognitive abilities.

The focus group of this systematic review are school age children, not yet in adolescence (6;0-12;11 years of age) with CIs and typical hearing (TH). The aim is twofold. The first aim is to evaluate for which cognitive tests differences between children with CI and children with TH have been found and which of these results are consistent across studies. A second aim is to investigate how studies evaluating cognitive differences between children with CI and children with TH are designed and if they control for language ability.

Methods

Search Strategy

The PICO (Population, Intervention or Exposure, Comparison, Outcome) approach (Methley et al., 2014) was used to design the search terms. We were interested in children age 6 to 12 (Population; search term: “children”) with cochlear implants (Intervention or Exposure; search terms: “Cochlear Implant” OR “Sensory aid” OR “Bionic ear” OR “Cochlear prosthesis” OR “Auditory prosthesis”) compared to children with TH with the same age range (Comparison) on cognitive measures (Outcome; search terms: “Cognitive abilities” OR “Cognitive Skills” OR “Cognition” OR “Executive Function” OR “Executive Functioning” OR “Shifting” OR “Inhibition” OR “Working Memory” OR “Reasoning” OR “Planning” OR “sequence learning”).

Searches were conducted in three databases: Scopus, PubMed, and Web of Science. The full search term was (example from Scopus): (TITLE-ABS-KEY (“Cochlear Implant” OR “Sensory aid” OR “Bionic ear” OR “Cochlear prosthesis” OR “Auditory prosthesis”)) AND TITLE-ABS-KEY (*"sequence learning"* OR *"Cognitive abilities"* OR *"Cognitive Skills"* OR *"Cognition"* OR *"Executive Function"* OR *"Executive Functioning"* OR *"Shifting"* OR *"Inhibition"* OR *"Working*

105 *Memory" OR "Reasoning" OR "Planning") AND TITLE-ABS-KEY ("child" OR*
 106 *"children"))*

107

108 **Inclusion/ Exclusion Criteria**

109 Only empirical studies were included in the current systematic review. In addition,
 110 medical research on the cochlear or cochlear implants has been excluded. All studies that did
 111 not directly compare a group of children with CI to a group of children with TH were
 112 excluded. Only studies with children between 6;00 and 12;11 years of age were included.
 113 Evaluating areas in which specifically school-aged children have problems is important as
 114 these children are at the beginning of their school career and these early years are likely going
 115 to lead the way for their academic outcome (Rabiner et al., 2016). Studies including children
 116 with additional disabilities apart from being DHH were excluded. Studies with questionnaire
 117 or pure fMRI or EEG studies were excluded. Studies were excluded if the groups were
 118 smaller than 5 children per group or if single case designs were used. Publication in another
 119 language than English was a further exclusion criterion. Studies in which children received
 120 their implant after 4 years of age were excluded. This exclusion criterion might lead to the
 121 exclusion of older studies as the age at which children received their CI is likely going to be
 122 higher. Age at implantation has been reduced in several countries during the last years. In
 123 addition, this criterion might lead to the exclusion of studies from countries which do not use
 124 widespread newborn hearing screening and in which age at implantation might therefore be
 125 higher.

126 <figure 1 here>

127

Result and Discussion

128 The first search was conducted in Mai 2020 and the search was updated in October
 129 2020. In Figure 1 the PRISMA flow chart adapted from Moher et al. (2009) is presented.

Eight-hundred and forty-nine records have been screened and of those 100 full-text articles were assessed for eligibility. Eleven studies were included in the final review and in Appendix A the reason for exclusion is given for the remaining 89 studies. In addition, Appendix A includes details on whether the authors of the study were contacted to get additional necessary information. It was found that precise information about participant groups, like age-range, range of age at implantation, if and what language input the child received before getting a CI, or language mode used by the children (oral, sign language, sign support) was often not reported. In addition, many studies used diverse samples in terms of age, age at implantation, schooling, communication mode, prelingual/post lingual deafness, bilingual and unilateral CIs. Matching procedures were often not reported.

Eleven studies could be included in this systematic review (Akçakaya et al., 2019; Hall et al., 2018; López-Higes et al., 2015; Schouwenaars et al., 2019; Torkildsen et al., 2018; Volpato, 2020). Only six of them had the comparison of cognitive skills as their focus (Akçakaya et al., 2019; Engel-Yeger et al., 2011; Hall et al., 2018; Torkildsen et al., 2018; Volpato, 2020; Yucel & Derim, 2008). There is a lack of research on the cognitive abilities of school-aged children with CI. Many studies on the CI population use large age spans and include pre-school children, school-aged children, adolescence and sometimes even adults in the same study (e.g.: Al-Salim et al., 2020; AuBuchon et al., 2019; De Giacomo et al., 2013; Kronenberger et al., 2014). Large age spans make it impossible to evaluate which age group is driving the differences. This is especially problematic as CI technology and rehabilitation methods have changed during the years and a person with a CIs that was implanted 20 years ago is unlikely to be comparable to a person with a CIs implanted 5 years ago. Both in terms of implant technology, but also in terms of age at implantation and other factors like the use of sign language. The relation between age and outcome is not necessarily linear and not

finding significant correlations does not mean that differences might not be due to specific age groups or that differences in specific age-groups might go unnoticed.

In Table 1 a list of the cognitive tests used to assess the different cognitive domains in the eleven included studies is presented. In addition, Table 1 includes whether significant differences between children with CIs and children with TH were found in the respective study. In Table 2 information concerning the samples of the studies is presented. In Table 3 information concerning the matching procedures as well as results from the language measures used in the studies is presented. The quality assessment and estimation of bias was done according to AXIS (Downes et al., 2016) and the detailed analysis of each study is presented in Appendix B.

The task most often included in studies was the digital backwards span task (5 studies), a task measuring verbal working memory capacity. Two studies found a significant difference between children with CI and children with TH. However, while Schouwenaars et al. (2019) found a significantly higher performance of children with TH compared to children with CI, Pixner et al. (2014) found a significantly higher performance of children with CI compared to children with TH. López-Higes et al. (2015), Volpato (2020), and Akçakaya et al. (2019) did not find a significant difference between children with CI and children with TH on a backwards digit span test. In the study by Volpato (2020), this was the case both when comparing children with CI to chronologically-age matched children with TH, and when comparing them to language-matched children with TH. Akçakaya et al. (2019) used an aurally visual version of the backward digit span and the additional visual input might have led to a better performance of children with CIs as they did not have to rely solely on auditory information.

Both Schouwenaars et al. (2019) and Pixner et al. (2014) reported to compare children matched on hearing-age. However, in the study by Schouwenaars et al. (2019) the matching

procedure was not reported by the authors and it is unclear if the matching was controlled after the children with CI who did not pass the screening tests were excluded (12 of the children). In the study by Pixner et al. (2014) the children did not significantly differ in hearing age, however, the statistical comparison reported in the paper does not indicate that the groups are definitely matched ($p < .05$ see: Mervis & Klein-Tasman, 2004). It is therefore unclear for both Schouwenaars et al. (2019) and Pixner et al. (2014) if the comparison groups were matched on hearing-age and differences in the results might be explained by that. Another reason for differences might be the included children with CI. In the study by Schouwenaars et al. (2019) only prelingually deaf bilaterally implanted children were included, while this is unclear for the study by Pixner et al. (2014). However, Volpato (2020) also only included prelingually deaf children and did not find a significantly poorer performance on a backwards digit span test for children with CI compared to children with TH. It is important to note that Volpato (2020) did not report the exact statistical values of the comparison and the calculation of the appropriate effect size was not possible as a non-parametric test was used, but mean and SD were reported as descriptive statistics.

The different results concerning the backwards digit span might be explained by differences in non-verbal cognitive skills (IQ) between children with CI and children with TH. For the study by Pixner et al. (2014) the children with CI and children with TH did not differ significantly in terms of non-verbal intelligence. As the exact t-value is not given, it is unclear if the groups are definitively matched. However, Schouwenaars et al. (2019) did not measure non-verbal intelligence and it is therefore unclear if the significantly poorer performance of the children with CI in their study might be explained by differences in overall cognitive ability. If this would be the case, their result might be explained by a sample selection bias.

A difference between children with CIs and children with TH was found for non-word repetition, a measure of phonological short-term memory, in two of the included studies. Both Akçakaya et al., 2019 and Volpato, 2020 found a significantly poorer performance of children with CIs compared to children with TH. However, it must be considered that the performance on a non-word repetition task is not only influenced by short-term memory capacity, but also by hearing quality and phonological ability. Consistent with that, Akçakaya et al. (2019) found correlations to speech perception ability. However, they did not evaluate differences in speech perception ability between children with CI and children with TH and it is therefore not possible to evaluate if the group differences on the non-word repetition task might be explained by differences in speech perception ability. The auditory input of a CI is sparser than in TH and differences between the groups might be explained by this factor instead of differences in phonological short-term memory. This is even more likely as for another measure of short-term memory span which is not as depending on the quality of the auditory input, the forward digit span test, no difference in performance between children with CIs and TH was found by Volpato (2020). An additional reason for differences in non-word repetition ability could be lower phonological abilities of children with CIs due to missing the sensitive/critical period of phonology development (until 12 months of age: Ruben, 1997). This is not to say that differences on the non-word repetition task are not meaningful. Most likely the ability to better perceive the phonemes of spoken language is going to lead to improved ability to acquire spoken language. This is indicated by studies showing associations between spoken language ability and non-word repetition abilities for children with CIs (Dillon et al., 2004; Willstedt-Svensson et al., 2004). In addition, speech perception ability has been found to be a predictor for language development in typical developing infants (Kuhl et al., 2005). It is likely that this ability is also of importance for children with CIs. Therefore, using a non-word repetition task has both clinical and research relevance.

However, it must be considered that non-word repetition ability might be influenced by hearing quality and phonological processing ability. Research is needed which controls for these confounding factors and evaluates if differences are still present between children with CIs and children with TH.

The Non-verbal scale of the WISC-R was used in two studies (Akçakaya et al., 2019; Lopez-Higes et al., 2015). In both studies differences were reported to be non-significant. However, the p-value in the study by Akçakaya et al. (2019) was .05. The authors did not report the alpha level they used. Two studies used the Raven's matrices, with one reporting a significant difference between children with CI and children with TH (Bouton et al., 2011), and the other one not reporting significant differences between the groups (Torkildsen et al., 2018a). It must be taken into consideration that the sample size in the study by Bouton et al. (2011) was quite small and the sample included children attending special education. Bouton et al. (2011) found a significant difference for children with CI and children with TH matched on chronological age but not for children with CI and children with TH matched on reading age. Reading age is likely to be associated to language ability. More research is needed to evaluate if language ability might influence the performance on the Raven's matrices.

In general, most studies did not control for the influence of language ability on the performance on cognitive tests. For these studies it is unclear if some of the results are explained by differences in language ability between children with CI and children with TH. Most studies seem to have an applied approach and aim to evaluate if and not why differences in cognitive abilities between children with CI and children with TH exist. However, a lack of matching on core variables such as chronological age and non-verbal intelligence makes it difficult to evaluate if results are ecological valid.

Volpato (2020) used a language-matched comparison group and Torkildsen et al. (2018) used a non-verbal cognitive test that is unlikely to be influenced by language ability.

Both Schouwenaars et al. (2019) and Pixner et al. (2014) report to have matched the comparison groups on hearing age. Such a matching is likely to control in parts for differences in language ability. However, in both studies the matching procedure is not sufficiently reported, and it is unclear if the groups were definitely matched on hearing age. For future studies on children with CI it would be important to control for the influence of language ability. This is the only way to evaluate if children with CI are at risk for specific delays in the cognitive domain or if they perform as would be expected by their language ability. If latter was the case, improving language access and rehabilitation for children with CI is likely going to solve differences in the cognitive domain as well.

Conclusion

DHH children are a sensitive group at risk of experiencing a time of language deprivation and a subsequent language delay. In the literature, it has been discussed that auditory or language deprivation might lead to delays in the cognitive domain. However, research is lacking when it comes to the cognitive abilities of school-aged children with CIs. Only eleven studies could be included in the current systematic review and only six had the comparison of cognitive abilities as their focus. Only four cognitive tests were used in more than one study. Of these tests, results indicated a significantly poorer performance of children with CI compared to children with TH on a non-word repetition test (2 studies), no significant difference between children with CI and children with TH on the Non-verbal scale of the WISC-R (2 studies), and inconsistent result for the Raven's matrices (2 studies) and the backwards digit span test (5 studies). The latter result might be explained by differences in study design and by unclear matching in terms of language ability, hearing age, and non-verbal intelligence. Most studies included in this systematic review did not take the influence of language ability on the performance on cognitive tests into consideration. In general, many studies did not use a clear matching method and it is therefore hard to interpret results.

Future directions

Research on small populations is challenging and the research on DHH children with CIs is no exception. Many statistical methods are not possible to use as large sample sizes are unlikely to be achieved. In addition, samples are often highly heterogeneous and might be even considered to be rather a collection of single cases than a group. However, DHH children with CIs are a sensitive group as research results are likely going to be used to develop clinical practices and to give recommendations to parents and will thereby influence the lives of children. Therefore, it is of great importance to conduct research of high quality. To do so, collaborations are essential. Working together and adding the results from several studies can help to increase power and make analyses more reliable. However, to make this possible, guidelines are needed to assure researchers measure and report important variables, like age range, language experience, and use, and auditory measures. In addition, the development of an international test battery assessing both cognitive and language abilities is key. Basic processing skills, like speech processing, as well as higher order language skills, like expressive language skills, and higher order cognitive abilities, like executive functioning need to be included in such a test battery. This would make it possible to account for the influence of lower-level processes on higher order language and cognitive ability. Optimally results from research with children with CI should be accessible to the research community. The use of open data and a common database would make it possible for other researchers to add findings and could serve as a collaboration platform.

In addition, precise matching procedures should be encouraged as group comparisons are otherwise hard to interpret. If groups differ both on cognitive and language abilities, it is impossible to analyze what is causing what. If groups differ on verbal cognitive measures, but have not been matched on non-verbal cognitive ability, results are again hard to interpret.

304 More clean research designs that intend to measure differences in only one domain should be
305 preferred. For studies with an applied approach which mainly aim to evaluate if there are
306 difference and not why it needs to be made sure that the comparison is meaningful. If
307 comparison groups are not matched on core variables such as chronological age or non-verbal
308 intelligence, the real-life implications of the results are hard to evaluate.
309

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Figure 1: Graphical representation of the search and exclusion process. PRISMA flow chart adapted from Moher et al. (2009)

Table 1

This table lists the cognitive tests used in the studies included in the systematic review. In addition, the tested cognitive domain, the modality of the test, in which study the test was used, and the statistical comparison of children with CI and children with TH on the test are reported.

Cognitive Domain	Test used	Modality	Study	Statistical comparison
Verbal WM	Backward Digit Span (WISC-IV)	auditory	López-Higes et al. (2015)	non-significant, values not reported, $d = .122^*$
	Digit Span test backwards (Hamburg–Wechsler Intelligence Test for Children–Fourth Edition)	auditory	Schouwenaars et al. (2018)	$\beta = 0.7895$, $t = 3.526$, $p < .001$, $d = .968^{**}$ Direction: CI < TH (hearing age matched)
	Digit span test Backwards (TEMA)	auditory	Volpato (2020)	non-significant, values not reported CI vs. TH-LA: $d = .559^*$; CI vs. TH-CA: $d = .509^*$
	Backward Digit span (audio-visually version)	auditory/ visual	Akçakaya et al. (2019)	non-significant $F(1, 57) = 9.8$, $p = .07$, $partial \eta^2 = 0.06$
	Backward letter span (test-battery unclear)	Unclear	Pixner et al. (2014)	$t(92) = 5.43$; $p < 0.001$, $d = 1.117$ Direction: CI > TH (hearing age matched)
Phonological short-term memory	Short non-word repetition list (Akçakaya et al., 2018b)	auditory	Akçakaya et al. (2019)	$F(1, 57) = 1493.6$, $p < 0.001$, $partial \eta^2 = 0.84$, Direction: CI < TH
	Non-word repetition (Fabbro, 1999)	auditory	Volpato (2020)	CI vs. TH-LA: $U = 43$ $p = .012$, $d = .571^*$; No data for TH-CA group Direction: CI < TH
Verbal short-term memory	Digit span test Forward (TEMA)	auditory	Volpato (2020)	non-significant, values not reported, CI vs. TH-LA: $d = .725^*$; CI vs. TH-CA: $d = .302^*$
	Forward letter span (test-battery unclear)	Unclear	Pixner et al. (2014)	non-significant $t(92) = 1.33$; n.s., $d = .274$
Non-Verbal WM	Leiter International Performance Scale-Revised subtests Reverse Memory	visual	Torkildsen et al. (2018)	non-significant $t(66) = 1.65$, $p = .10$, $d = .38$

Non-Verbal short-term memory	Leiter International Performance Scale-Revised subtests Forward Memory	visual	Torkildsen et al. (2018)	non-significant $t(66) = 1.17, p = .25, d = .31$
	Children's memory scale-Dots immediate recall	visual	Engel-Yeger et al. (2011)****	$F(2,38) = 40.62, p < .001, d = 2.023$ Direction: CI < TH
	Children's memory scale-Faces immediate recall	visual	Engel-Yeger et al. (2011)	$F(2,38) = 45.09, p < .001, d = 2.134$ Direction: CI < TH
	Contextual Memory Test-CH-memory immediate recall	visual	Engel-Yeger et al. (2011)	$F(2,38) = 29.71, p < .001, d = 1.725$ Direction: CI < TH
	Picture Series Recall*****	visual	Bouton et al. (2011)*****	Accuracy TH-CA + CI_CS+: $t(50) = 4.47, p < .001$ TH-CA + CI_CS-: $t(50) = 5.74, p < .001$ Direction: TH > CI TH-RL + CI_CS+: $t(50) = 2.71, p < .05$ TH-RL + CI_CS-: $t(50) = 3.99, p < .01$ Direction: TH > CI Latency TH-CA + CI_CS-: $t(50) = 2.55, p < .05$ Direction: TH < CI TH-CA + CI_CS+: no sig. diff TH-RL + CI_CS+: $t(50) = 5.01, p < .001$ Direction: CI > TH TH-RL + CI_CS-: $t < 1$
Non-verbal long-term memory	Children's memory scale - Dots delayed recall	visual	Engel-Yeger et al. (2011)	$F(2,38) = 26.42, p < .001, d = 1.629$ Direction: CI < TH
	Children's memory scale - Faces delayed recall	visual	Engel-Yeger et al. (2011)	$F(2,38) = 47.66, p < .001, d = 2.185$ Direction: CI < TH
	Contextual Memory Test - CH-memory delayed recall	visual	Engel-Yeger et al. (2011)	$F(2,38) = 26.91, p < .001, d = 1.641$ Direction: CI < TH
	Contextual Memory Test - CH-memory recognition	visual	Engel-Yeger et al. (2011)	$F(2,38) = 17.16, p < .001, d = 1.936$ Direction: CI < TH
Sustained Visual Attention	Leiter International Performance Scale-Revised subtests	Visual	Torkildsen et al. (2018)	non-significant $t(66) = -.70, p = .95, d = .02$

	Attention Sustained (AS)			
	Gordon Diagnostic System (GDS): Vigilance Task (number correct)	Visual	Yucel & Derim, (2008)	$p = .004^{*****}$
Impulsivity	Gordon Diagnostic System (GDS): Vigilance Task (commission)	Visual	Yucel & Derim, (2008)	$p = .029^{*****}$
Visual Inattention	Gordon Diagnostic System (GDS): Vigilance Task (omission)	Visual	Yucel & Derim, (2008)	$p = .004^{*****}$
Non-verbal intelligence	Non-verbal scale of the WISC-R	visual	López-Higes et al. (2015)	non-significant $U = 161.50, p = .583, d = .300^*$
			Akçakaya et al. (2019)	$t(57) = 1.96; p = .05, d = .296;$ Direction: CI > TH
	Test of Nonverbal Intelligence–Fourth Edition	visual	Fortunato-Tavares et al. (2018)	$t(26) = 2.536, p = .018, r = .45$
	Grundintelligenztest Skala 2 - Revision (CFT 20-R)	Visual	Pixner et al. (2014)	non-significant $t(92) < 1; n.s., d = .04$
Analogical Reasoning	Raven's Matrices (standard score)	visual	Torkildsen et al. (2018)	non-significant $t(66) = -.61, p = .55, d = .15$
			Bouton et al. (2011)*****	TH-CA + CS+: $t(16) = 2.82, p < .01$ TH-CA + CS-: $t(16) = 3.25, p < .01$ Direction: TH-CA > CS TH-RL + CS+: $t(16) = 1.21, p > .20$ TH-RL + CS-: $t(16) = 1.18, p > .20$ Non-significant
	Matrix reasoning (WISC-IV)	visual	López-Higes et al. (2015)	non-significant, values not reported; $d = .39^*$
Categorical, abstract reasoning	Picture concepts (WISC-IV)	visual	López-Higes et al. (2015)	non-significant, values not reported; $d = .457^*$
Spatial visualization ability	Block design (WISC-IV)	visual	López-Higes et al. (2015)	non-significant, values not reported; $d = .062^*$

Non-verbal Implicit sequence learning	Implicit visual sequential learning of embedded triplets by Arciuli and Simpson (2011)	visual	Torkildsen et al. (2018)	non-significant $t(66) = 0.19, p = 0.85, d = .05$
	Artificial grammar learning task adapted from Conway et al. (2011)	visual	Hall et al. (2018)***	non-significant Learning phase: $F(1,40) = .267, p = .61, g = .176$ Learning score: $F(1,40) = .012, p = .914, g = .035$
	Serial Reaction Time (SRT) task (Nissen & Bullemer, 1987)	visual	Hall et al. (2018)***	non-significant Main effect: $F(1,39) = 0.0375, p = .847$ Group x Block: $F(4,156) = 2.24, p = .0664$ Group x TrialType: $F(1,156) = 0.0700, p = .793$

* effect size calculated based on mean and SD as other values not reported by authors; ** not possible to use g as mean and SD not reported (unequal sample size!); *** analysis was not part of the paper but was send to the author of this paper by Matthew Hall; **** this study included a meta-memory test which is not included here as it was measured with a questionnaire, ***** test statistic not reported, therefore not possible to calculate effect size; ***** CS: cued speech, CA: chronological age, RL: Reading age; *****test used as phonological short-term memory test, but test was visual and only phonological if a verbal strategy was used. No effect of phonological similarity of the words represented by the picture: unlikely that they used this strategy

Table 2

In this table the descriptive data of the samples used in the studies included in this systematic review are provided.

Study	N		Age range		Age at implantation	Audiological information (children with CI)	Language experience (children with CI)
Akçakaya et al. (2019)	CI	31	CI	7;0 - 10;4	Mean: 23 months	average free field threshold of 31 dB HL between 250 and 6000 Hz	monolingual in the home environment,
	TH	28	TH	7;0 - 10;4	SD: 7.3 months all before 3 years of age	Glendonald Auditory Screening Procedure (GASP) speech perception score of 90% or higher at word level	no further information
Bouton et al. (2011)	CI	18***	CI	7;11 – 11;0	1;10 - 3;6	used HA before CI	Nine early and intensive cued speech + oral (CS+)
	TH	18	TH	7;11 – 11;0			Six oral, two oral + LSF; one oral + signed French (CS-)
Engel-Yeger et al. (2011)	CI	20	CI	8 - 10	Not reported;	No information	Children with primarily oral communication and children with total communication included
	TH	20	TH	8 - 10	All younger than 3 years old*		
Fortunato-Tavares et al. (2018)	CI	13	CI	8;0 - 12;3	before age 4 (no detailed info)	prelingually deafened; severe-to-profound deafness; 7 unilateral CI; 6 bilateral CI; one child used CI + HA	participants of rehabilitation programs with an emphasis on residual hearing training and an auditory–oral approach; monolingual speakers of Brazilian Portuguese
	TH	15	TH	8;8 - 12;7			
Hall et al. (2018)	CI	11	CI	7;04-12;10	0;08 - 2;10	Severe or profound congenital deafness	Little accessible language input prior to cochlear implant, listening and spoken language emphasis at home and school
	TH	31	TH	7;0-12;11			

López-Higes et al. (2015)	CI TH	19 19	CI TH	8 – 12 8 – 12	Mean: 14.68 SD: 5.69 all before 2 years of age	severe or profound deafness (higher than 70 dB), diagnosed in prelingual phase (before 24 months) Bilateral CI: 47.0% Unilateral without HA: 31.8% Unilateral with HA: 21.1%	no information
Pixner et al. (2014)****	CI TH	45 49	CI TH	10;2 (12) 8;6 (16)	0;8 - 4;2	No information	14 children with CI in special school: might learn and/or use sign language
Schouwenaars et al. (2018)	CI TH	33 (21)** 36	CI TH	7;1 - 12;4 7;05– 10;09	0;6 - 3;3	prelingually deaf bilaterally implanted (63% simultaneously) 5 children HA experience	monolingual German
Torkildsen et al. (2018)	CI TH	34 34	CI TH	7;3–12;11 7;2–12;11	0;5-3;9	27 born deaf, rest became deaf during first two years of life hearing > 90dB bilateral except one (CI+HA)	34 oral Norwegian as main language, 1 child used both oral and sign language to communicate with family members
Volpato (2020)	CI TH- CA TH- LA	13 13 13	CI TH- CA TH-LA	7;9 - 10;8 7;5 - 10;8 5;0 – 7;9	1;9 - 3;4	profound bilateral sensorineural deaf since birth	oral Italian, none ever used Italian Sign Language all received speech-language therapy two or three times per week
Yucel & Derim (2008)*****	CI TH	15 36	CI TH	6;1 - 10;0 6;1 - 10;4	1;4 - 4;0	No information	attending an individual Auditory Verbal Therapy program regularly at least for one year

* information was sent to the author of this review by Engel-Yeger, ** only 21 children passed the screening and were part of the analysis; *** divided into two groups: CS- and CS+ of each 9 children; **** children in 3rd – 5th grade; ***** tested 30 children with CI, but only those with age at implantation < 4 included in this systematic review

Table 3

In this table it is reported how/if the comparison groups were matched and if the groups differed on a language measure

Study	Group Comparison Language/auditory domain	Matching procedure
Akçakaya et al. (2019)	Expressive Vocabulary Receptive Vocabulary	$t(57) = 6.48, p < .001, d = 1.7$ Direction: CI < TH $t(47.3) = 6.82, p < .001, d = 1.8$ Direction: CI < TH
Bouton et al. (2011)	Phonemic similarity judgment	Accuracy TH + CI_CS+: $t(50) = 1.11, p > .20$ TH + CI_CS-: $t(50) = 2.21, p < .05$ Direction: TH > CI Latency TH + CI_CS+: no sig diff TH + CI_CS-: $t(48) = 2.52, p < .05$ Direction: TH < CI
Engel-Yeger et al. (2011)	no measure used	No matching reported No-significant difference in terms of age IQ in normal range
Fortunato-Tavares et al. (2018)	Vocabulary Sentence comprehension (prosody manipulation)	$t(26) = 1.604, p = .121, r = .30$ Direction: CI < TH High attachment interpretation: ip, $t(26) = -2.984, p = .024, r = .51$; IPh, 0, $t(26) = -1.826, p = .032, r = .34$; and IPh, ip, $t(26)$

		$= -2.043, p = .016, r = .37$ Direction: CI < TH	
		Response Time $F(1, 19) = 1.540, p = .230, \eta^2 = .075$	
	Gap detection	$t(26) = 3.980, p < .001, r = .62$ Direction: CI < TH	
	Frequency discrimination	$t(26) = 3.518, p = .002, r = .57$ Direction: CI < TH	
Hall et al. (2018)	no measure used		age mean (unclear if on SD) education level of primary caregiver no significant difference in gender, but not matched ($p = .22$)
López-Higes et al. (2015)	Receptive Vocabulary (used equivalent age)	$U = 48.50; p < .001, d = 1.551^*$	no significant difference in age, but comparison not reported: unclear if matched; unclear if matched on non-verbal IQ ($p < .65$)
Pixner et al. (2014)	No measure used		non-verbal IQ and hearing age: difference non-significant but not matched although stated in paper
Schouwenaars et al. (2018)	Comprehension of "Which" questions: object questions Comprehension of "Which" questions: subject questions Comprehension of "Which" questions: passive questions	$\beta = 1.28, z = 2.988, p < .05$ Direction: CI < TH $\beta = 0.16, z = 0.239, p = .99$ $\beta = 0.70, z = 1.166, p = .83$	reported to be matched on hearing age (no statistical comparison or matching method reported)

Torkildsen et al. (2018)	Speech perception	$t(66) = 7.70, p < .001, d = 1.99$ Direction: CI < TH	pairwise matched on age and gender ($p = .95$) comparable in terms of education but no statistical test
Volpato (2020)	Relative clause comprehension	CI vs. TH-LA: $\chi^2(1) = 4.86, p < .03$ CI vs. TH-CA: $\chi^2(1) = 13.26, p < .001$ Direction: CI < TH	chronological age: matched on mean and range linguistic age: matched on language ability
Yucel & Derim (2008)	No measure used		no matching reported