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Concept Formation Skills in Long-Term Cochlear Implant Users

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Abstract

This study investigated if a period of auditory sensory deprivation followed by degraded auditory input and related language delays affects visual concept formation skills in long-term prelingually deaf cochlear implant (CI) users. We also examined if concept formation skills are mediated or moderated by other neurocognitive domains (i.e., language, working memory, and executive control). Relative to normally hearing (NH) peers, CI users displayed significantly poorer performance in several specific areas of concept formation, especially when multiple comparisons and relational concepts were components of the task. Differences in concept formation between CI users and NH peers were fully explained by differences in language and inhibition–concentration skills. Language skills were also found to be more strongly related to concept formation in CI users than in NH peers. The present findings suggest that complex relational concepts may be adversely affected by a period of early prelingual deafness followed by access to underspecified and degraded sound patterns and spoken language transmitted by a CI. Investigating a unique clinical population such as early-implanted prelingually deaf children with CIs can provide new insights into foundational brain–behavior relations and developmental processes.

Concept formation is a complex cognitive process encompassing a wide range of functions including categorization, abstraction, derivation of semantic-linguistic meaning, and development of cognitive representations for complex thoughts, behaviors, and events (Medin & Smith, 1984). Although specific definitions, hypothesized components, and explanatory theories of concept formation vary somewhat, concept formation is generally regarded as the categorization and differentiation of stimuli based on their perceptual, relational, and functional features (Hills, Maouene, Maouene, Sheya, & Smith, 2009). Concept formation is a core foundational component of human information processing that underlies many higher-order cognitive and linguistic functions such as controlled attention, reasoning, abstraction, and the ability to compare (Vygotsky, 1986). Language, along with experience and reasoning skills, plays an important role in how children learn and form concepts (Nelson, 1996). In support of this view, Yoshida and Smith (2003) showed that the language that young children are exposed to and learn (e.g., English vs. Japanese) affects how they use novel words to form categories for ambiguous objects.

Conceptual awareness is influenced in toddlers and preschool-aged children by other types of language experience such as explicit parental labeling of categories and modeling of hierarchical category structure, much of which is conveyed in the context of daily experiences and activities. For example, everyday discourse between parents and children about driving to the grocery store, getting a flat tire repaired, and riding a school bus may provide subordinate and relational superordinate instances about the category “vehicle” (e.g., cars and buses both take people places, both have wheels, buses go to schools but cars are driven by parents and go to many other places).

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Initially, the models supplied by parents provide only a partial representation about the category "vehicle." Later in childhood, more formal and explicit teaching of language, math, and scientific concepts in school provide the developing child with more systematic training and experiences with many different types of concept formation activities and tasks. Children also learn everyday concepts from interactions and activities with their sensory environment and these fundamental concepts serve to scaffold learning of more abstract complex scientific concepts upon entering formal schooling (Richards, 2013; Vygotsky, 1986).

Academically, concept formation is necessary for activities such as reading comprehension, written expression, and mathematics. In reading, for example, conceptual thought underlies the formulation of complex relationships between specific ideas, characters, and/or plotlines (Guthrie et al., 2004; Langer, 1967), as well as providing an overall gestalt of the meaning(s) and purpose(s) of the reading material. Reading has been described as a "vehicle for acquiring concepts" (Chase, 1969), and, in fact, children's conceptual skills are strongly associated with measures of their reading comprehension (Braun, 1963) and vocabulary knowledge (Langer, 1967). Written expression also involves organization of ideas conceptually, so that the writing progresses in a logical way and adheres to a central theme. Comprehension and completion of mathematics problems ranging from operations (e.g., addition) to math applications also require an understanding of the concepts that the operations and applications represent. Previous research reveals that children's mathematical conceptual skills upon school entry are highly predictive of long-term academic achievements (Duncan et al., 2007). Early literacy and mathematical conceptual skills also have a long-term impact on quality of life, and studies of adults have linked these core abilities with employability and wages (Bynner, 1997; Rivera-Batiz, 1992).

Concept formation is also involved in information processing beyond the academic realm. Social interaction requires shared conceptual thinking in order to understand and relate to the perspectives of others. Verbal communication is based on the transmission of concepts using language; hence, concept formation skills are critical for the development of adequate verbal communication. Organization of materials, ideas, and plans is a core foundational component of executive functioning (Gioia, Isquith, Guy, & Kenworthy, 2000) and is guided by the general concepts that provide an overarching framework for the specific details that must be organized, whether in a calendar, a play area, or a professional presentation. Reasoning and logic are closely dependent, in part, on the development and manipulation of abstract concepts; not surprisingly, then, many intelligence tests incorporate a significant component of concept formation (Hammill, Pearson, & Wiederholt, 2009; Wechsler et al., 2004). In general, the ability to form, apply, and manipulate concepts is universally applied in everyday functioning, making concept formation an essential core foundational cognitive function. Because concept formation is an integrated component of adaptive functioning across a broad span of cognitive, social, and academic domains, understanding and enhancing the development of concept formation in vulnerable populations is critically important for enhancing both clinical and normal developmental functional outcomes.

Because concept formation is learned largely through direct perceptual and sensory experiences (Gelman, 2009; Mandler, 2008) as well as language-based social and formal learning experiences and activities (Nelson, 1996), children with sensory and/or language delays and disorders may be at high risk for disturbances in the development of concept formation. Myklebust (1960) was among the first researchers to describe how the altered perceptual world of the profoundly deaf might have cascading neurocognitive effects in other domains:

> A sensory deprivation limits the world of experience. It deprives the organism of some of the material resources from which the mind develops. Because total experience is reduced, there is an imposition on the balance and equilibrium of all psychological processes. When one type of sensation is lacking, it alters the integration and function of all of the others. Experience is now constituted differently; the world of perception, conception, imagination, and thought has an altered foundation, a new configuration (p. 1).

Prelingually deaf children with cochlear implants (CIs) have several of these risk factors because they experience a period of early auditory deprivation followed later by exposure to degraded auditory input from the CI; these limitations on early auditory experience and activities have been shown to impact their neurocognitive, language, and executive functioning (Geers & Sedey, 2011; Hauser & Marschark, 2008; Peterson, Pisoni, & Miyamoto, 2010; Pisoni, Kronenberger, Roman, & Geers, 2011) and, ultimately, may also affect the development of concept formation skills. Investigating the relation between early sensory experience and conceptual thinking using clinical populations such as children with prelingual deafness has the potential to further our understanding of typical cognitive development in innovative ways not possible through direct experimental manipulations.

CIs are biomedical devices approved by the Food and Drug Association that provide deaf children and adults who have bilateral severe-to-profound sensorineural hearing loss (>71 dB HL) with access to sound by stimulating the surviving spiral ganglion cells of the auditory nerve (Pisoni et al., 2008). Without medical intervention, individuals with severe-to-profound hearing loss have extremely limited access to the sounds of spoken language as typical conversational speech occurs between 45 and 60 dB. Following cochlear implantation, many deaf children show large improvements in speech intelligibility, speech perception, and spoken language skills (May-Mederake, 2012). However, there still remains an amount of individual variability in performance outcome after cochlear implantation that is not attributable to the device itself but is related to other factors such as foundational underlying neurocognitive processes including attention, working memory, and self-regulation that affect everyday learning and communication. Recent research supports this view and indicates that, compared to age-matched normally hearing (NH) peers, even high-functioning deaf children with CIs who have no additional developmental, neurological, or cognitive conditions other than hearing loss are at elevated risk for disturbances in areas of language, executive control, and working memory (e.g., Beer, Kronenberger, & Pisoni, 2011; Harris et al., 2013; Hauser & Marschark, 2008; Kronenberger, Beer, Castellanos, Pisoni, & Miyamoto, 2014; Kronenberger, Pisoni, Henning, & Colson, 2013; Nittrouer, Caldwell, Lowenstein, Tarr, & Holloman, 2012; Pisoni, Conway, Kronenberger, Henning, & Anaya, 2010) that may have downstream implications for the development of concept formation skills and other aspects of cognition and language processing.

Because the formation of concepts is linked to perceptual experience and activities, including auditory experience with sounds and sound patterns, and because concept formation is linguistically mediated, we hypothesize that deaf children with CIs may develop concepts differently than NH peers as a result of (a) a period of auditory deprivation during infancy prior to receiving a CI, which may impact perceptual experiences and activities upon which early basic concepts are based, (b) limited early language experiences within everyday activities from which spontaneous concepts develop, and (c) language delay reflecting poorly specified semantic categories upon which abstract/scientific concepts are explicitly taught.

Most of the early research carried out on concept development in deaf populations has focused on academic concepts in youths who do not use CIs. For example, Furth (1961) examined relational concepts (same, symmetric, opposite) in deaf children aged 7–12 years who used sign language for communication in three tasks requiring nonverbal responses. Deaf children and NH children performed comparably on several tasks requiring knowledge of the concept of sameness and symmetry. However, deaf children performed significantly worse than NH children when the task required knowledge of the concept of opposites. In this task, the experimenter displayed four disks of varying diameters on the table, pointed to a disk, and then asked the child to point to its opposite. If, for example, the experimenter pointed to a disk with the smallest diameter, the child was required to point to a disk with the largest diameter. Although performance on this concept formation task only required pointing (no vocal response was necessary), deaf children who used sign language displayed delays in conceptualizing opposites in this procedure.

An understanding of relational concepts is particularly important in mathematics, and research has shown that compared to NH peers, oral-deaf children and deaf children who use sign language have more difficulties with relational mathematical concepts that involve changing, combining, and comparing items and elements (e.g., x is more than y but less than z; Zevenbergen, Hyde, & Power, 2001). In a cross-sectional study, Pettifor (1968) found that the nonverbal conceptual skills (as assessed by a dimensional card sorting task) of deaf children with moderate-to-profound hearing loss improved with age but remained delayed compared to NH peers. Relative to NH children, deaf children also display delays in performing several classic Piagetian conversation tasks (Furth, 1964).

Deaf youths also display delays in problem-solving verbal tasks such as the "Twenty questions" game (Marschark & Everhart, 1999) and nonverbal visual–spatial tasks such as the "Tower of Hanoi" puzzle (Luckner & McNeill, 1994). In the "Twenty questions" game, participants are presented with 42 familiar images (e.g., animals, buildings, and automobiles) and instructed to correctly identify, within the constraint of 20 yes or no questions, the image selected by the experimenter. Participants who exhibited sophisticated problem-solving techniques (i.e., could correctly identify the selected image in as few questions as possible) were children who formed concepts from among the images and inhibited guesses such as "Is it a dog?" and instead asked constraint-seeking questions that eliminated a large number of nontarget images such as "Is it living?" (Marschark & Everhart, 1999). The "Twenty questions" game is a proxy measure of verbal problem solving requiring conceptual and executive functioning skills. Marschark and Everhart's (1999) pioneering problem-solving research suggests that deaf children aged 7–14 years who use sign language, compared to their NH peers, are delayed in these critical areas. Additional research has shown that deaf children with CIs have delays and disturbances in memory and learning and manipulating nonverbal sequential information (Conway, Pisoni, & Kronenberger, 2009). These delays and disturbances in cognitive control were strongly correlated with receptive language delays (Conway, Pisoni, Anaya, Karpicke, & Henning, 2011).

To date, there has been no research that has examined the characteristics of verbally mediated visual concept formation skills (e.g., concept formation with visual stimuli, which could be mediated with verbal labels) in deaf children who use CIs. The present study investigated two primary questions concerning the visual concept formation skills of long-term CI users: First, are long-term CI users, compared to their NH peers, delayed in this type of concept formation? Second, if long-term CI users display delays in these core visual concept formation skills, can these delays be explained by language, working memory, and/or executive control difficulties? In addition to increasing our understanding of the role of language and the effects of early sensory experience on concept formation, the present study also provides a better description of the types of concept formation skills that may be at risk in deaf children with CIs.

Methods

Participants

CI sample

Participants in the CI sample were 57 children, adolescents, and young adults (Table 1) who met the following inclusionary criteria: (a) have severe-to-profound prelingual hearing loss (>70 dB HL in the better-hearing ear prior to age 3 years) severely limiting their access to spoken language prior to cochlear implantation, (b) have received a CI prior to age 7 years, (c) have used their CI for 7 years or more, (d) use a currently available state-of-the-art multichannel CI system, (e) live in a household with spoken English as the primary language, and (f) pass a screening performed by licensed speech-language pathologists prior to testing, confirming no additional developmental, neurological, or cognitive conditions were present other than hearing loss.

Hearing history variables obtained for the CI sample are shown in Table 1 and include age at onset of deafness (defined as the age at which deafness was identified or age at the time of a known event causing deafness), age at time of implantation, duration of CI use at time of testing, preimplant residual hearing (mean unaided pure-tone average in the better-hearing ear for the frequencies 500, 1,000, and 2,000 Hz in dB HL), communication mode (coded on a 1 [*mostly sign*] to 6 [*auditory verbal*] scale, with values of 1–3 reflecting simultaneous communication strategies [sign and speech to varying degrees of emphasis] and 4–6 reflecting oral communication strategies [speech used exclusively with no formal sign language other than gestures]; Geers & Brenner, 2003), and etiology of deafness. Etiology of deafness included unknown (N = 35), familial (at least one immediate family member also had deafness, N = 8), meningitis (N = 7), auditory neuropathy (N = 3), Mondini malformation (N = 2), ototoxicity (N = 1), and large vestibular aqueduct (N = 1).

NH control sample

Participants in the NH control sample were 74 children, adolescents, and young adults who passed a basic audiometric hearing screening (headphones were used to test each ear individually at frequencies of 500, 1,000, 2,000, and 4,000 Hz at 20 dB HL) and reported no significant developmental, neurological, or cognitive delays.

Characteristics of the NH sample are also summarized in Table 1. NH and CI samples were matched on nonverbal intelligence (IQ) and demographic variables including age, gender, family income (coded by income ranges on a 1 [under $5,500] to 10 [$95,000 and over] scale, with values of 4, 6, and 8 corresponding to income values of $15,000–$24,999, $35,000–$49,999, and $65,000–$79,999, respectively), and race/ethnicity.

Table 1. Participant demographics and hearing history

	Hearing status			
	CI (N = 57)		NH (N = 74)	
	M (SD)	Range	M (SD)	Range
Onset of deafness (months)	3.23 (8.02)	0.00–36.00	NA	
Age at implantation (months)	36.82 (20.41)	8.28–75.76	NA	
Age at testing (years)	15.43 (4.97)	7.80–27.37	16.01 (4.90)	7.08–25.30
Duration of CI use (years)	12.36 (3.88)	7.08–22.43	NA	
Preimplant PTA[a]	107.61 (10.62)	85.00–118.43	NA	
CMRS[b]	4.71 (.79)	2.00–5.00	NA	
Nonverbal IQ[c]	56.04 (6.27)	42.00–68.00	56.32 (6.86)	38.00–70.00
Income level[d]	7.13 (2.46)	2.00–10.00	7.04 (2.60)	1.00–10.00
	Count (% of CI sample)		Count (% of NH sample)	
Hearing device[e]				
Bilateral CI	19 (33.3%)		NA	
Unilateral CI	36 (63.2)			
CI and HA	2 (3.5)			
Etiology of hearing loss				
Meningitis	7 (12.3)		NA	
Other/unknown	50 (87.7)			
Processor/strategy[f]				
Nucleus 22/SPEAK	8 (14.0)		NA	
Nucleus 24/ACE	32 (56.1)			
Nucleus 24/SPEAK	2 (3.5)			
Nucleus System 5/ACE	7 (12.3)			
Clarion/MPS	2 (3.5)			
Clarion HF/MPS	1 (1.8)			
Clarion/HiRes	2 (3.5)			
Sonata/CIS	1 (1.8)			
Combi 40+/CIS	2 (3.5)			
Gender				
Female	26 (45.6)		45 (60.8)	
Male	31 (54.4)		29 (39.2)	
Race				
Asian	1 (1.8)		3 (4.1)	
Black	1 (1.8)		11 (14.9)	
Multiracial	3 (5.3)		5 (6.8)	
White	52 (91.2)		55 (74.3)	
Ethnicity				
Hispanic	2 (3.5)		3 (4.1)	
Not Hispanic	55 (96.5)		71 (95.9)	

Note. NA = not applicable; NH = normally hearing.
[a]Preimplant unaided pure-tone average (PTA) in the better ear for the frequencies 500, 1,000, and 2,000 Hz in dB HL.
[b]CMRS = Communication Mode Rating Scale.
[c]WASI Matrix Reasoning Subtest I-score for Nonverbal Intelligence.
[d]Income level is coded on a scale from under $5,000 (coded 1) to $95,000 and over (coded 10) with a code of 7 = $50,000–$64,999 and a code of 8 = $65,000–$79,999.
[e]CI = cochlear implant, HA = hearing aid.
[f]Processor/strategy for bilateral users is coded for the most recent implant/upgrade.

Procedure

All study procedures were reviewed and approved by the local Institutional Review Board, and written informed consent was obtained for all participants or parents prior to initiation of study procedures. The CI sample was recruited from a research volunteer registry and from patient populations receiving clinical services at a large hospital-based CI clinic. Recruitment approaches included contacting all eligible patients who had previously volunteered for research (or who were enrolled in active longitudinal research projects) and informing patients at clinical appointments of the opportunity to participate in the current study. The project was also advertised locally to professionals and schools who are in contact with CI users. The NH control sample was recruited from the community using flyers and advertisements posted in the same institutions and geographic areas from which the CI sample was recruited, including e-mail and internet sites affiliated with the CI clinic and university.

Licensed speech-language pathologists evaluated all participants with CIs and administered language tests in the participant's mode of communication used at school or (for those not in school) in the participant's preferred mode of communication (either oral communication or total communication). Speech-language pathologists or experienced psychometric technicians also evaluated the NH participants. All examiners were supervised by a licensed clinical psychologist (W. G. Kronenberger) and completed a training process consisting of mutual observation and scoring of tests and discussion of administration procedures.

Measures

Nonverbal intelligence

The Matrix Reasoning subtest of the *Wechsler Abbreviated Scale of Intelligence* (WASI; Wechsler, 1999) was used as a measure of global nonverbal intelligence. This subtest requires participants to complete a pattern of geometric designs based on an underlying concept. WASI Matrix Reasoning T-scores were used to assess global nonverbal intelligence.

Concept formation

The Concept Formation subtest of the *Woodcock-Johnson Tests of Cognitive Ability, Third Edition* (WJ-III-Cog; Woodcock, McGrew, & Mather, 2001) was used as a measure of categorical reasoning and inductive logic. Participants were presented with visual puzzles containing circles and squares outside and inside a box and were asked to identify and verbalize the underlying concept/rule(s) for inclusion inside the box (see Figure 1 for examples of a similar concept formation task). Possible inclusion rules included dimensions such as *magnitude* (big or small), *quantity* (one or two), *shape* (square or circle), and/or *color* (red or yellow). The Concept Formation subtest contained 40 test items distributed across three categories: (a) *Single Comparison, Single Rule* (7 test items) showed a single comparison (e.g., only one box with a criterion stimulus inside) and had a single dimensional rule for inclusion in the box (e.g., only one of the rules listed above, such as color, differentiated the item inside the box from the item(s) outside the box), (b) *Multiple Comparisons, Single Rule* (12 test items) showed multiple comparisons (multiple boxes, each with one criterion stimulus inside, requiring the participant to identify commonalities and differences among several criterion stimuli) and had a single dimensional rule for inclusion in the box, and (c) *Multiple Comparisons, Multiple Rules* (16 test items) contained multiple comparisons and multiple dimensional rules, joined with either an "and" or an "or" relational concept, such as "red and two." Following the test manual protocol, participants were administered test items according to standard basal and ceiling rules, and thus, not all participants completed all of the earlier and later test items on the Concept Formation subtest. Correct answers were scored as 1 and incorrect answers scored as 0. Item scores were analyzed as measures of specific types and complexities of conceptual reasoning (perceptual, relational), and the subtest standard score was used to obtain an aggregate measure of global Concept Formation skills.

Language and executive functioning composite scores

Composite scores were created for Language, Verbal Working Memory, Inhibition–Concentration, and Fluency-Speed by standardizing and aggregating participants' scores from a broad range of "gold standard" neurocognitive assessments (see the Composite Score Derivation in the Data Analyses section for additional information). The specific assessments used to measure executive functioning (verbal working memory, inhibition–concentration, and fluency-speed) were selected because they place very limited demands on audibility and also included several nonverbal measures (see below for additional information regarding these assessments).

Language. Language skills were assessed using the standard score of the *Peabody Picture Vocabulary Test—Fourth Edition* (Dunn & Dunn, 2007) and the Core Language standard score of the *Clinical Evaluation of Language Fundamentals Fourth Edition* (CELF-4; Semel, Wiig, & Secord, 2003). The PPVT-4 is a one-word receptive vocabulary test used to measure word knowledge. The PPVT-4 requires participants to choose one of four pictures that match a spoken word produced by the examiner. The Core Language score of the CELF-4 is a measure of general receptive and expressive language skills, derived from several subtests depending on the participant's age. Both the PPVT-4 and the CELF-4 were also administered in Signed Exact English for children using simultaneous communication.

Verbal Working Memory. Verbal working memory was assessed using the Digit Span (DS) subtest of the *Wechsler Intelligence Scale for Children, Third Edition* (WISC-III; Wechsler, 1991 1999) and the

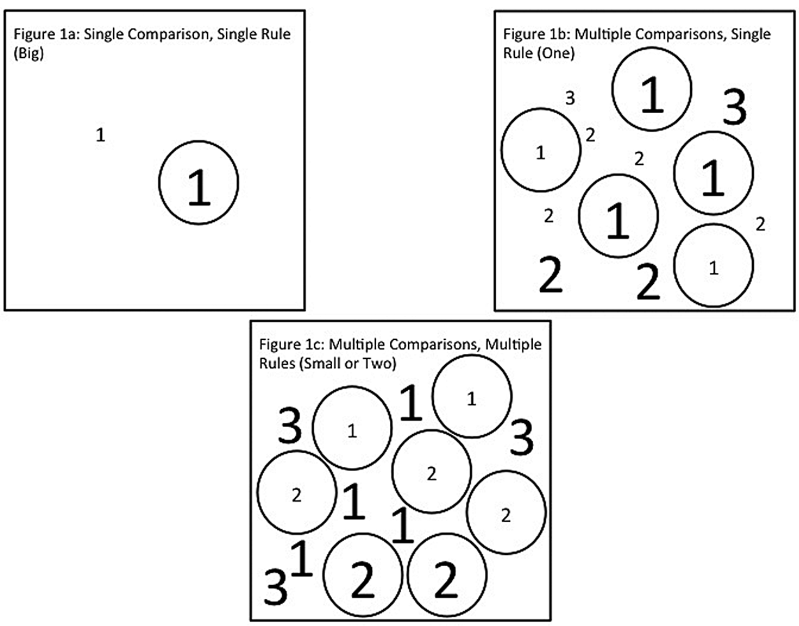

Figure 1. (a) Single Comparison, Single Rule (Big). (b) Multiple Comparisons, Single Rule (One). (c) Multiple Comparisons, Multiple Rules (Small or Two).

Visual Digit Span (VDS) subtest of the *Wechsler Intelligence Scale for Children, Fourth Edition—Integrated* (WISC-IV-I; Wechsler et al., 2004). The WISC-III DS subtest requires participants to reproduce a sequence of spoken digits presented in forward (Digit Span Forward; DSF) or backward (Digit Span Backward; DSB) order, whereas the WISC-IV-I VDS subtest requires repetition of a series of visually presented digits in forward order. Scaled scores for the DSF, DSB, and VDS were used to derive the composite measure of Verbal Working Memory.

Inhibition–Concentration. Inhibition–Concentration skills were measured using the Color-Word condition of the *Stroop Color–Word Test* (Golden, Freshwater, & Golden, 2003), the Number–Letter Switching (NLS) condition of the *Trail-Making Test* (Delis, Kaplan, & Kramer, 2001), and the omissions, commissions, and response time variability scores of the *Test of Variables of Attention* (TOVA; Leark, Dupuy, Greenberg, Corman, & Kindschi, 1996). The *Stroop Color–Word Test* requires participants to inhibit a highly overlearned/automatic process (word reading) in favor of a more effortful/controlled process (naming ink color) for a series of color words (i.e., red, blue, and green) that are printed in ink colors that are incongruent with the words. The NLS condition of the *Trail-Making Test* requires participants to connect a series of numbers and letters randomly spaced on a page by drawing a line alternating between numbers and letters (e.g., 1-A-2-B). The TOVA requires participants to press a button when presented with a target stimulus (a square at the top of a screen) but not when presented with a distractor stimulus (a square at the bottom of a screen). The Stroop Color–Word T-score, NLS scaled score, and standard scores for the TOVA Response Time Variability (variation in response speed across all target stimuli), TOVA Omissions (failing to respond to a target), and TOVA Commissions (responding inaccurately to a distractor) were used to derive the composite measure of inhibition and concentration.

Fluency-Speed. Fluency-Speed skills were assessed with the Retrieval Fluency, Pair Cancellation, and Visual Matching subtests of the WJ-III-Cog (Woodcock et al., 2001), and the Coding and Coding Copy subtests of the WISC-IV-I. Standard scores for Retrieval Fluency, Pair Cancellation, and Visual Matching, and scaled scores for Coding and Coding Copy were used to derive the composite measure of fluency and speed skills. The Retrieval Fluency subtest requires participants to rapidly generate words from specific semantic categories (e.g., first names, animals). The Pair Cancellation and Visual Matching subtests require participants to rapidly identify pictures or match numbers (respectively) within visual stimulus arrays. The Coding subtest requires participants to rapidly reproduce a sequence of visual symbols based on a corresponding sequence of numerals (each numeral corresponds to a unique symbol). Finally, the Coding Copy subtest requires participants to rapidly reproduce visual symbols from the Coding subtest, without the corresponding numerals.

Data Analyses

Composite score derivation

Principal components analyses were used to evaluate the relations between individual scores on the composite measures of Language, Verbal Working Memory, Inhibition–Concentration, and Fluency-Speed. These analyses (available upon request from the authors) demonstrated that the Language, Verbal Working Memory, Inhibition–Concentration, and Fluency-Speed composite scores were each well represented by a single component score with high loadings for each measure. *z*-Transformed scores for Language, Verbal Working Memory, Inhibition–Concentration, and Fluency-Speed were computed using the mean and standard deviation (*SD*) of the pooled sample of CI and NH participants. Aggregate composite scores were then obtained using sums of *z*-transformed scores of each measure (see Geers, Brenner, & Davidson, 2003, for an example and support of this technique).

Relations between concept formation, hearing status (CI vs. NH), and composite scores

In order to evaluate differences in Concept Formation item scores based on Hearing Status, Fishers' Exact Tests were used to compare the performance of the CI and NH samples on individual items (correct vs. incorrect). Items that were not administered to specific participants due to basal/ceiling rules were treated as missing data and were not included in the Fishers' Exact Tests of the *Concept Formation* subtest items.[1] Two-tailed independent samples *t*-tests were then conducted to assess differences in Concept Formation standard scores. Next, relations between the four composite scores and Concept Formation standard scores were evaluated using Pearson correlations of Concept Formation scores with Language, Verbal Working Memory, Inhibition–Concentration, and Fluency-Speed composite measures. These correlational analyses were carried out separately for the CI and NH participants.

Regression models predicting concept formation—moderator analyses

Moderator analyses were used to examine if a third variable affects the strength or direction of the relationship between two variables (Baron & Kenny, 1986). In order to evaluate whether the composite scores for Language, Verbal Working Memory, Inhibition–Concentration, and Fluency-Speed moderate the relation between Hearing Status (CI, NH) and Concept Formation scores, a hierarchical regression analysis was conducted with Concept Formation scores as the criterion variable and blocks of variables entered sequentially as follows: Block 1 consisted of Hearing Status (CI, NH); Block 2 consisted of composite scores of Language, Verbal Working Memory, Inhibition–Concentration, and Fluency-Speed; and Block 3 (Moderator Effects) consisted of the interactions (product terms) of Block 1 (Hearing Status) and each of the composite scores from Block 2 (Language, Verbal Working Memory, Inhibition–Concentration, and Fluency-Speed; in order to reduce multicollinearity, product terms were tested one at a time, with only significant product terms retained in the equation). These regression equations were used to test the extent to which the relationship between Hearing Status and Concept Formation differs depending on scores for Language, Verbal Working Memory, Inhibition–Concentration, or Fluency-Speed. A statistically significant product term in Block 3 would demonstrate that the effect of Hearing Status on Concept Formation is partially or completely dependent on (e.g., moderated by) Language, Verbal Working Memory, Inhibition–Concentration, and Fluency-Speed (see Holmbeck, 1997; Figure 2).

Regression models predicting concept formation—mediator analyses

Mediator analyses were used to examine if the predictor variable affects the criterion variable by working through another variable (Baron & Kenny, 1986). In order to evaluate if the composite scores for Language, Verbal Working Memory, Inhibition–Concentration, and Fluency-Speed mediate the effect of Hearing Status (CI, NH) on Concept Formation scores, three additional regression analyses were also carried out. We followed Baron and Kenny's (1986) model for testing mediating effects. The first regression equation tested for a direct relation between Hearing Status and Concept Formation scores. The second set of regression equations tested for direct relations between Hearing Status and each composite score of Language, Verbal Working Memory, Inhibition–Concentration, and Fluency-Speed using four bivariate regressions with Hearing Status predicting each of the four composite scores. Finally, the third regression equation tested the full mediating model with simultaneous entry of Hearing Status, Language, Verbal Working Memory, Inhibition–Concentration, and Fluency-Speed as predictors of Concept Formation scores (Figure 3).

Results

Associations Between Concept Formation, Hearing Status (CI vs. NH), and Composite Scores

CI and NH samples did not differ on age ($t(129) = -0.67$, $p = .50$; $d = .12$), nonverbal IQ scores ($t(129) = -0.25$, $p = .80$; $d = .04$), family income ($t(115) = 0.18$, $p = .86$; $d = .03$), or gender ($p = .11$ by Fisher's Exact Test; Table 1). Language, Verbal Working Memory, Inhibition–Concentration, and Fluency-Speed scores are reported in Table 2. Ninety-eight percent of the participants in the NH sample were able to complete all 40 items of the WJ-III-Cog Concept Formation subtest, whereas only 84% of the participants in the CI sample completed all 40 items. CI users displayed significantly poorer Concept Formation standard scores than NH participants ($t(129) = -4.86$, $p < .0001$; $d = .85$). The mean Concept Formation standard score was 98.07 ($SD = 14.63$) for the CI users and 109.66 ($SD = 12.65$) for the NH participants. Concept Formation standard scores of 85 or below (1 *SD* below the normed mean[2]) indicate low average or lower performance (19.3% of the CI sample vs. 4.1% of the NH sample) and standard scores of 70 or below (2 *SD*s below the normed mean) indicate very low performance (5.3% of the CI sample vs. 0% of the NH sample).

CI users scored significantly lower than NH participants on 16 Concept Formation test items, with most of the group differences occurring when the items involved complex multiple

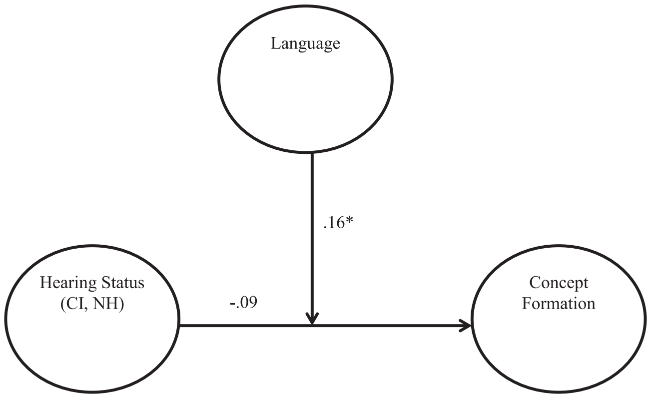

Figure 2. Moderator model predicting concept formation.
Note. Values are standardized regression coefficients. $^{*}p < .05$.

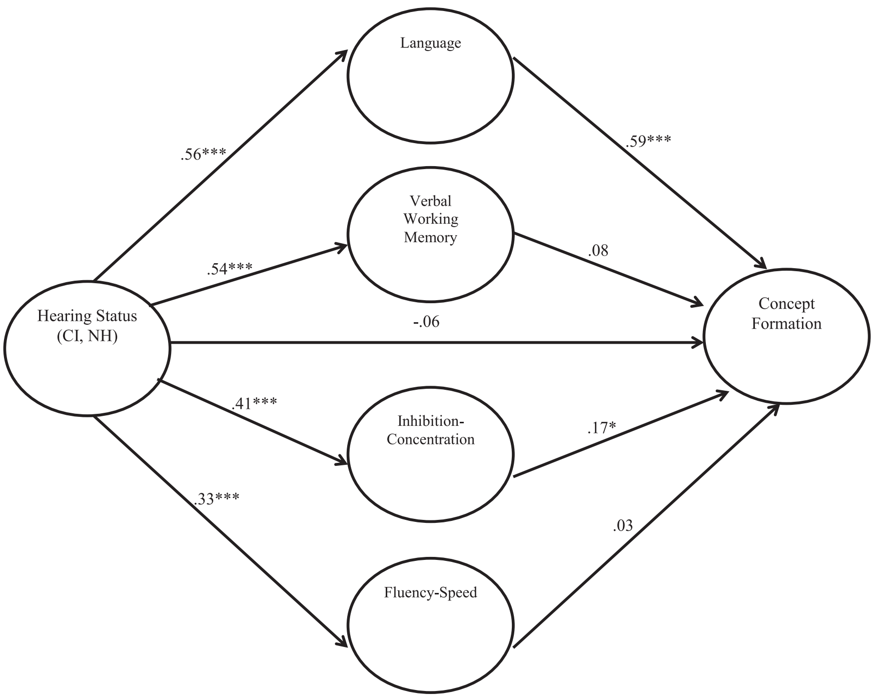

Figure 3. Mediating model predicting concept formation.
Note. Values are standardized regression coefficients. $^{*}p < .05$; $^{***}p < .001$.

comparisons (Table 3). When presented with test items requiring multiple comparisons to abstract a single rule, CI users performed significantly worse than NH participants on 58% (7/12) of the test items. When presented with items requiring multiple comparisons to abstract multiple rules, CI users performed significantly worse than NH participants on 56% (9/16) of the items. CI users consistently had more difficulty on test items that required the abstraction of an "or" rule, performing significantly worse than NH participants on 73% (8/11) of these items (Table 3).

Table 2. Descriptive statistics on Language, Verbal Working Memory, Inhibition–Concentration, and Fluency-Speed scores

	Hearing status	
	CI (*N* = 57)	NH (*N* =74)
	M (*SD*)	*M* (*SD*)
Language		
PPVT-4	91.09 (20.23)	111.46 (15.03)
CELF-core	89.96 (24.20)	112.72 (9.41)
Verbal Working Memory		
WISC-III Digit Span Forward	6.72 (2.64)	10.49 (2.91)
WISC-III Digit Span Backward	8.91 (2.80)	10.36 (3.32)
WISC-IV-I Visual Digit Span	8.72 (3.10)	11.85 (2.16)
Inhibition–Concentration		
Stroop Color–Word	49.18 (10.48)	53.41 (12.84)
NLS Trial-Making Test	9.12 (3.23)	11.03 (2.16)
TOVA Response Time Variability	86.09 (22.11)	95.26 (17.06)
TOVA Omissions	76.47 (27.19)	92.81 (20.56)
TOVA Commissions	84.24 (24.53)	99.63 (13.25)
Fluency-Speed		
WJ-III Retrieval Fluency	92.63 (12.74)	101.58 (10.10)
WJ-III Pair Cancellation	98.63 (10.40)	101.22 (10.62)
WJ-III Visual Matching	92.68 (15.94)	104.23 (13.65)
WISC-IV-I Coding	9.04 (2.93)	10.30 (3.04)
WISC-IV-I Coding Copy	9.84 (3.14)	10.92 (3.02)

Note. CI = cochlear implant; NH = normally hearing; NLS = Number–Letter Switching; TOVA = Test of Variables of Attention. Language Composite Measure = Peabody Picture Vocabulary Test-4 (PPVT-4) and Clinical Evaluation of Language Fundamentals Fourth Edition Core Language (CELF-core); Verbal Working Memory Composite Measure = WISC-III subtests: DSF = Digital Span Forward and DSB = Digital Span Backward. WISC-IV subtest: VDS = Visual Digital Span; Inhibition–Concentration Composite Measure = D-KEFS Trail-Making Test Number/Letter Switching, Stroop Color, and Word Test, Test of Variable of Attention: Reaction Time Variability, Commissions, and Omissions; Fluency-Speed Composite Measure = WISC-IV subsets: Coding and Coding Copy. WJ-III subtests: Visual Matching, Retrieval Fluency, and Pair Cancellation.

Correlations of the composite scores from the four neurocognitive domains with Concept Formation standard scores are summarized in Table 4. Language, Verbal Working Memory, Inhibition–Concentration, and Fluency-Speed were all highly correlated with Concept Formation scores for CI users ($p < .01$). However, only Language, Verbal Working Memory, and Inhibition–Concentration were correlated with Concept Formation scores for NH participants.[3] The correlation between Concept Formation and Verbal Working Memory was much stronger in the CI sample ($r = 0.65$) than in the NH sample ($r = 0.29$; z-test comparing magnitude of these correlations = 2.64, $p < .01$), whereas correlations of Concept Formation with Language and Inhibition–Concentration were similar between both samples.

Regression Models Predicting Concept Formation—Moderator Analyses

Table 5 displays a summary of the results of the regression analysis using Language, Verbal Working Memory, Inhibition–Concentration, and Fluency-Speed as moderators of the relationship between Hearing Status (CI vs. NH) and Concept Formation. In Block 1, Hearing Status accounted for 16% of the variance in Concept Formation scores ($p < .001$). In Block 2, composite scores of Language and Inhibition–Concentration added significantly to the relation obtained between Hearing Status and Concept Formation scores, and the overall equation with Hearing Status, Language, Verbal Working Memory, Inhibition–Concentration, and Fluency-Speed accounted for 55% of the variance in Concept Formation scores ($p < .001$). In Block 3, the product of Hearing Status and Language further added to the contribution of all of the individual variables in predicting Concept Formation scores ($\beta = .16$, $p < .05$): Language was more strongly associated with Concept Formation scores for the CI users than for the NH

Table 3. Number of concept formation test items that differ for CI and NH participants

	Item rules				
	Size	Color	Shape	Quantity	Total
Single Comparison, Single Rule					
Nonsignificant	3	1	2	1	7
Significant	0	0	0	0	0
% Significant	0.00	0.00	0.00	0.00	0.00
	Item rules				Total
	Size	Color	Shape	Quantity	
Multiple Comparisons, Single Rule					
Nonsignificant	1	1	3	0	5
Significant	1	1	3	2	7
% Significant	0.50	0.50	0.50	1.00	0.58
	Item rules				Total
	And, 2 parts	Or, 2 parts	Or, 3 parts		
Multiple Comparisons, Multiple Rules					
Nonsignificant	4	0		3	7
Significant	1	5		3	9
% Significant	0.20	1.00		0.50	0.56

Note. Fishers' Exact Tests were conducted to compare the performance of the cochlear implant and normally hearing sample on individual Concept Formation test items (correct vs. incorrect). % Significant = percent of test items in which the samples are statistically different.

Table 4. Correlations between composite scores and concept formation standard scores for CI and NH participants

	Concept formation standard scores	
	Hearing Status	
	CI (N = 57)	NH (N =74)
Composite scores		
Language	.69***	.65***
Verbal Working Memory	.65**	.29*
Inhibition–Concentration	.45***	.38**
Fluency-Speed	.51***	.13

Note. CI = cochlear implant; NH = normally hearing. Language Composite Measure = Peabody Picture Vocabulary Test-4 and Clinical Evaluation of Language Fundamentals Fourth Edition Core Language; Verbal Working Memory Composite Measure = WISC-III subtests: DSF = Digital Span Forward and DSB = Digital Span Backward. WISC-IV subtest: VDS = Visual Digital Span; Inhibition–Concentration Composite Measure = D-KEFS Trail-Making Test Number/Letter Switching, Stroop Color, and Word Test, Test of Variable of Attention: Reaction Time Variability, Commissions, and Omissions; Fluency-Speed Composite Measure = WISC-IV subsets: Coding and Coding Copy. WJ-III subtests: Visual Matching, Retrieval Fluency, and Pair Cancellation.
*p < .05; **p < .01; ***p < .001.

Table 5. Regression model predicting concept formation

	Concept formation standard scores (N = 131)
Block 1	
Hearing Status	.39***
R^2	.16***
Block 2	
Hearing Status	−.06
Language	.59***
Verbal Working Memory	.08
Inhibition–Concentration	.17*
Fluency–Speed	.03
R^2	.55***
Block 3	
Hearing Status	−.09
Language	.52***
Verbal Working Memory	.08
Inhibition–Concentration	.15[a]
Fluency-Speed	.04
Hearing Status × Language	.16*
R^2	.56***

Note. Values are standardized regression coefficients.
[a]p < .10; *p < .05; ***p < .001.

participants (Figures 2 and 4). No other product terms (Block 3) were significant in these equations, indicating that Verbal Working Memory, Inhibition–Concentration, and Fluency-Speed did not moderate the relations between Concept Formation and Hearing Status.

Regression Models Predicting Concept Formation—Mediator Analyses

Figure 3 displays a summary of the results of the regression analysis using Language, Verbal Working Memory, Inhibition–Concentration, and Fluency-Speed as mediators for the effect of Hearing Status (CI, NH) on Concept Formation scores. The direct relationship between Hearing Status and Concept Formation scores was significant (β = .39, p < .000), independent of any mediated effects. The relations

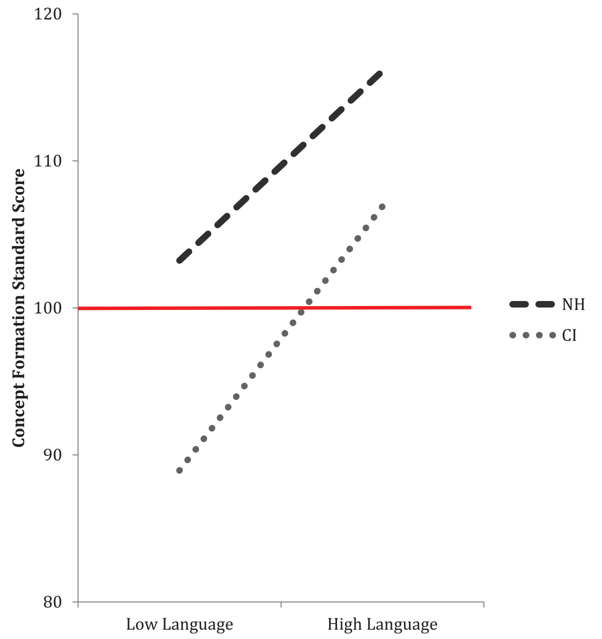

Figure 4. Language skills (low, high) moderating the relationship between hearing status (CI, NH) and concept formation.
Note. Reference line indicates the normed mean (100) Concept Formation standard score.

between Hearing Status and each of the composite scores of Language, Verbal Working Memory, Inhibition–Concentration, and Fluency-Speed were also significant. The overall equation revealed that Language (β = .59, p < .000) and Inhibition–Concentration (β = .17, p < .05) mediate the effect of Hearing Status (CI, NH) on Concept Formation scores. Verbal Working Memory and Fluency-Speed played no mediating role in the model. Finally, the direct relation between Hearing Status and Concept Formation was significantly attenuated with the addition of the composite scores in the overall equation (p > .05), indicating their mediating effect.

Discussion

Language and sensory-perceptual experiences and activities provide core fundamental information for the development of concept formation in children. As a result, early sensory disturbances have the potential to propagate and cascade to higher processing levels (Johnston, 2004; Luria, 1973). Indeed, our data suggest that a period of early auditory sensory deprivation followed by degraded auditory input via a CI and compromised access to spoken language has far-reaching effects on language, executive control, and ultimately specific aspects of conceptual thinking and cognition such as higher-order relational concepts. Our findings document the importance of using clinical populations with sensory delays and disorders to test hypotheses that ultimately inform our understanding of typical developmental processes. Feldman (2007) describes the benefits of using a developmental cognitive neuroscience approach for understanding normal development by stating that "…clinical conditions [are] naturalistic experimental manipulations, selectively altering factors in the language-learning situation that could not otherwise be ethically manipulated in a research study" (p. 586). Children who have experienced a period of early auditory deprivation and then gain access to speech sounds through a CI offer scientists the unique opportunity to investigate developmental timing and offer the equivalent of the "forbidden experiment" in which cognitive consequences of sensory deprivation in humans may be tested experimentally.

Given that deaf children with CIs experience a period of early auditory deprivation, have ongoing exposure to highly degraded and underspecified auditory information via their CI, and have language delays, it is not surprising that our group of long-term prelingually deaf CI users was also delayed in formulating and using concepts compared to our NH sample. Although our samples did not differ on nonverbal IQ scores, the CI sample performed significantly below their NH peers on a normed, standardized measure of concept formation and failed to perform conceptual tasks at levels that are commensurate with their own IQ scores. Individual differences in underachievement were observed and a subgroup (5.3%) of our CI participants were identified as showing very severe deficits of 2 *SDs* below the nationally representative normative mean, a rate that is double what would be expected in a normal distribution. Concepts involving multiple comparisons between visual objects as well as comparisons involving the relational concept of "or" were particularly difficult for our sample of CI users relative to the comparison group of NH participants.

Mediating and Moderating Models of Conceptual Thinking

In the regression models that were used to assess the moderating and mediating effects of language and executive functioning on the relations between Hearing Status and Concept Formation, we found that Hearing Status significantly predicted Concept Formation, but this effect was mediated completely by the relationship of Hearing Status with Language and Inhibition–Concentration, both of which significantly predicted Concept Formation scores. Furthermore, Language skills moderated the relations between Hearing Status and Concept Formation, such that Language was more strongly related to Concept Formation in deaf children with CIs than in children with NH, once the direct effects of Language and Executive Functioning on Concept Formation were taken into account.

Taken together, these findings suggest that the poorer Concept Formation skills in children with CIs observed in this study can be explained by their delays in Language and Inhibition–Concentration skills. Understanding the cascading effects of an early period of auditory deprivation followed by degraded underspecified auditory input from a CI on the development of Language, Executive Functioning, and ultimately Concept Formation is critically important not only for guiding and implementing clinical interventions in low-performing CI users but also for understanding and explaining the enormous variability and individual differences in speech and language outcomes universally observed in all CI centers around the world.

The WJ-III-Cog concept formation task used in our study presented all concepts visually and had no requirements for auditory perception. All of the concepts could be verbally encoded using very simple vocabulary (e.g., big, small, round, red, and one), and only a brief verbal response was required to answer all questions. In the visual concept formation task from the WJ-III-Cog, the concepts were limited to four perceptual dimensions (magnitude, quantity, shape, and color) that are easily mastered by NH typically developing school-aged children. Therefore, given the age of our long-term CI users (M = 15.43 (4.97), range = 7.80–27.37), we expected that knowledge of these early-learned and basic concepts would be well established and possibly overlearned. Our results supported this prediction. No differences were found between the CI and NH groups on single comparisons based on single perceptual dimensions (Table 3); both groups achieved scores of 88–99% correct on those simple elementary concept formation items. Therefore, any differences in Concept Formation observed between the two groups were not a result of difficulty with the vocabulary, task instructions, or understanding of the conceptual labels or perceptual dimensions (magnitude, quantity, shape, and color) assigned to the stimuli. Differences in performance on Concept Formation only occurred when the CI users were required to *combine* and *integrate* similarities or differences across several stimuli (multiple comparisons) or when the CI users were explicitly required to apply higher-order relational concepts involving "and" or "or." The pattern of these findings suggests that encoding and maintaining complex information in mind (for multiple comparisons) or understanding and using language for relational concepts (use of "and" and "or") are the primary concept formation areas that differ between the long-term CI users and the NH comparison control group.

Although a basic understanding of the verbal labels (e.g., vocabulary) for the four perceptual dimensions on the concept formation task did not explain the differences in performance observed between the CI and NH groups in concept formation skills, an aggregate measure of language processing skills both mediated and moderated the observed relations between hearing status and concept formation performance. It may be that fluency in language processing allows for better concept formation skills as a result of placing fewer demands on executive functions such as working memory capacity, inhibition–concentration, and fluency-speed during the process of carrying out the concept formation task. Alternatively, executive functioning skills may mediate the relationship between language and concept formation, allowing for better cognitive control over language processing operations as more complex verbal concepts are formed and maintained in active verbal working memory.

In support of these hypotheses, the observed relation between Verbal Working Memory and Concept Formation in CI users (r = 0.65) was substantially greater than the relation observed between Verbal Working Memory and Concept Formation in the NH group (r = 0.29). Furthermore, in a recent study on executive functioning, Kronenberger, Colson, Henning, and Pisoni (2014) reported moderate-to-strong correlations (r = 0.38–0.64) between language skills and executive functions in long-term CI users. The correlations they found between several types of executive functions and language skills were also stronger for the long-term CI users than for NH participants. Thus, in children, adolescents, and young adults with CIs, language skills and executive functioning are closely coupled, and these relations may be inseparable for encoding, storing, and processing multidimensional visual stimuli in order to understand complex relational concepts regardless of sensory modality.

Multiple Dimensional Rules Require More Cognitive Control

Children, adolescents, and young adults with CIs, compared to their NH peers, showed significantly poorer performance on complex concept formation items that required an understanding of multiple concepts (perceptual and relational dimensional rules, Table 3). These test trials increased participants' cognitive load, were more taxing on working memory capacity and attentional resources, and required more conscious effortful executive control processes. Our findings fit nicely with the standard cognitive view that simple perceptual categories are easily mastered in early development, whereas higher-order relational categories require more advanced cognitive processing (Sheya & Smith, 2006). Correlational analyses (Table 4) demonstrated that verbal working memory and fluency-speed were both more strongly related to concept formation in the CI users than in the NH sample, suggesting a greater role for these types of compensatory executive control processes in complex concept formation tasks for CI users.

The differences we observed in this study may also reflect the contribution of processing speed and working memory capacity for supervising and managing higher cognitive loads in children, adolescents, and young adults with CIs in concept formation tasks compared to the lower cognitive load required by their NH peers. Previous research has demonstrated that children with CIs, compared to their NH peers, have significant working memory delays and deficits (Harris et al., 2013; Pisoni et al., 2011; Pisoni & Geers, 2000). Based on clinical findings obtained from patients who have frontal lobe damage and amnesia, Delis, Squire, Bihrle, and Massman (1992) suggested that visual concept formation tasks like those used in the present study rely heavily on explicit declarative memory functioning. Similarly, other researchers have reported that disturbances in working memory dynamics are also related to delays in processing mathematical concepts (e.g., magnitude, quantity) in children with Mathematical Learning Disabilities (Geary, 2004 2005) and deaf children (Bull, 2008). Hence, vulnerabilities in language, verbal working memory, and information processing speed may significantly reduce the ability of prelingually deaf long-term CI users to rapidly carry out processing operations in high-load verbally mediated concept formation tasks.

Our regression models also revealed that along with language, inhibition–concentration skills were also strong predictors of concept formation skills. Inhibition–concentration mediated the relation between hearing status (CI, NH) and concept formation skills, such that higher inhibition–concentration scores were predictive of better concept formation scores. This finding is also consistent with the cognitive-load hypothesis suggested above: Concentration and inhibition of competing impulses, thoughts, and responses allow for more efficient processing of more complex information by allocating more mental effort and resources to the specific information processing task demands at hand (see also Johnsrude et al., 2013).

Conclusions

Children's conceptual knowledge gradually matures across development, and changes in conceptual thinking coincide with other aspects of neurocognitive development (van der Veer, 1994). An understanding of which underlying neurocognitive factors (e.g., working memory, executive control) contribute to concept formation is vital—especially in populations at risk for concept formation delays, such as clinical samples of deaf children with CIs who have experienced a period of early auditory sensory deprivation followed by experience with highly degraded, underspecified, sparsely coded acoustic-phonetic information about speech and spoken language via their CI. The ability to conceptually reason broadly impacts success and quality of life in academic, social, and cognitive areas. Our findings on basic conceptual formation skills suggest that delays and weaknesses in language and executive functioning contribute to concept formation delays in children, adolescents, and young adults with CIs, in some cases with greater magnitude than observed in NH peers. Therefore, downstream effects on concept formation should be evaluated in long-term CI users who show language or executive function delays, and novel interventions to improve language and executive function skills should be developed to address the mediating effects of these core neurocognitive functions on basic concept formation skills. High-load complex concept formation tasks might be better managed in long-term CI users by targeting improvements in working memory capacity, inhibition–concentration, and information processing speed and may be integrated with other behaviorally based interventions that explicitly teach strategies for acquiring and communicating complex concepts (see Stone, 1980, for more information on teaching strategies).

There are several limitations to the present study. First, we used a cross-sectional, correlational design, and thus, the direction of causality cannot be determined. Language skills appear to be a critical component in the development of conceptual thinking; however, additional research is necessary to disentangle the effects of hearing loss on language, executive control, and conceptual thinking and reasoning. Second, our sample of CI users was relatively small and homogeneous, limiting our ability to generalize findings more broadly. Future research should investigate other neurocognitive processes that are associated with early CI use that may predict concept formation skills in deaf individuals postcochlear implantation. In the present study, correlations between Concept Formation standard scores and Onset of Deafness ($r = -.05$, $p = .73$) and Age at Implantation ($r = -.21$, $p = .13$) were nonsignificant, which is not surprising given how homogeneous our sample was in terms of early hearing loss detection and cochlear implantation. However, duration of CI use ($r = -.313$, $p = .02$) was significantly correlated with Concept Formation standard scores, suggesting that more recently implanted CI users score higher on concept formation relative to CI users implanted more than a decade ago. These findings are consistent with our prior research demonstrating that CI users who use their implant for 15 years or more are a unique cohort who are more likely to have an etiology of meningitis, have worse preimplant residual hearing levels, were implanted at older ages, and have CIs with older processing technologies (Ruffin, Kronenberger, Colson, Henning, & Pisoni, 2013). Third, our sample consisted of children, adolescents, and young adults with CIs who ranged in age from 7 to 27 years old. Although recruiting CI users is difficult because they are a small unique clinical population, future research should make attempts to recruit participants from a reduced age range. Fourth, our regression models examined the unique contribution of Language and Executive Function constructs on Concept Formation by removing shared variance (see Figure 3 for heuristic model). However, other models of Concept Formation are possible, and future research should examine possible indirect effects of Executive Function through Language (and vise versa) on Concept Formation. Finally, we examined how a specific type of visual concept formation task is affected by a period of early auditory deprivation followed by cochlear implantation; future research should expand and broaden this study and examine if other forms of thinking and conceptual functioning are also at risk in this clinical population and explore other methods for measuring concept formation using nonverbal responses in long-term CI users.

In summary, the present findings provide the first insights into how a period of early auditory deprivation followed by cochlear implantation affects the visual concept formation skills of long-term prelingually deaf CI users. Specifically, this study demonstrated that children, adolescents, and young adults with CIs exhibit significant delays relative to their NH peers in conventional concept formation tasks. Our findings suggest that early-implanted long-term CI users might think and act upon concepts in a manner that is fundamentally different from their NH peers and that this difference can be explained, in part, by delays and disturbances in more basic underlying language and executive functioning processes. We suggest that concepts are taught through the use of spoken language, executed through inhibition and concentration processes, and maintained in long-term memory for retrieval and that these specific areas of neurocognitive functioning are at risk in long-term CI users (Kronenberger, Beer, 2014). Interventions to address delays and/or disturbances in these specific areas hold promise for improving concept formation skills in CI users at an early age when neural plasticity and brain reorganization are more likely to occur. The present findings illustrate how inferring function from dysfunction has both theoretical and clinical value for understanding basic underlying neurocognitive mechanisms.

Conflicts of Interest

No conflicts of interest were reported.

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Notes

1. All subsequent analyses were conducted using Concept Formation standard scores.
2. WJ-III-Cog norm scores are derived from a nationally representative U.S. sample.
3. In order to ensure that variability in sample scores did not affect our results, we z-transformed all composite scores separately for the CI and NH samples and reran correlations between z-transformed scores and Concept Formation. Results indicate that for CI participants, Concept Formation remained significantly correlated with Language (r = .69, p = .000), Verbal Working Memory (r = .65, p = .000), Fluency-Speed (r = .51, p = .000), and Inhibition–Concentration (r = .45, p = .000), even after composite scores were corrected for variability present within the group. Similarly, for NH participants, Concept Formation remained significantly corrected with Language (r = .66, p = .000), Verbal Working Memory (r = .29, p = .01), and Inhibition–Concentration (r = .40, p = .000). Therefore, correlations using separate z-score transformations for each sample were comparable with correlations using z-score transformations computed from pooled variance across samples.

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