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New Research Findings:

Executive Functions of Adolescents Who Use Cochlear Implants

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Speech, language, and other cognitive outcomes for children who are deaf and use cochlear implants (CIs) can vary due to a number of factors. Understanding and predicting this variability are critically important to families, clinicians, educators, and researchers. Such information can help to establish expectations and contribute to providing effective interventions and educational resources.

A shorter period of auditory deprivation, auditory-oral rehabilitation, and greater residual hearing are known to be associated with improved speech and language outcomes, but the presence of any of these factors does not ensure that a child with hearing loss will achieve developmental outcomes similar to peers with typical hearing (Geers & Brenner, 2003). Successful cochlear implant use throughout the lifespan requires learning how to perceive, process, and integrate auditory information in a meaningful way, thus relying on domain-general processes such as attention, working memory, executive functions, and processing speed (for a glossary of related terms, see "Assessment and Intervention Resources").

It is reasonable to assume that individual differences experienced by CI users in domain-specific outcome areas such as language, reading comprehension, and problem-solving may be explained by examining the development of these more general cognitive processes and understanding how they are affected by a period of auditory deprivation and language delay.

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Assessment and Intervention Resources
BRIEF®. Neuropsychological assessment for ages 2 through 90. Parent and teacher report of behavioral manifestations across several domains of executive function.
Cogmed Working Memory Training. A computer-based training program for children and adolescents with poor working memory and or attention deficits.
"Boss Your Brain." Strategies for students that help them remember, organize, and retrieve information they hear and read. Robbins, A.M. (2005, July/August). *Volta Voices,* 38–40.
Executive Skills in Children and Adolescents. A guidebook for parents and educators that includes practical and detailed procedures for designing and implementing interventions to promote executive skills. Dawson, P., & Guare, R. (2004). *Executive skills in children and adolescents. A practical guide to assessment and intervention*. NY: Guilford Press.
Study Strategies. A resource book for students in grades 6 through 12 that includes activities and exercises that focus on improving organizational skills, time management, reading comprehension, vocabulary development, communication, how to study for tests effectively, and memorization skills. Davis, L., & Sirotowitz, S. (1997). *Study strategies made easy.Plantation, FL:* Specialty Press.
Collaborative Intervention Strategies. A practical guide for clinicians and speech-language pathologists that provides collaborative approaches to assessment and intervention in the areas of executive function, cognition, behavior, and communication and social skills. Ylvisaker, M., & Feeney, T. (1998). *Collaborative brain injury intervention: Positive everyday routines.* Clifton Park, NY: Thomson Delmar Learning.

For example, children with poor working memory also have difficulty with reading comprehension (Pisoni & Geers, 2000). Identification of how executive function, attention, and working memory may be linked to language, social, cognitive, emotional, and academic outcomes throughout the lifespan can help clinicians develop targeted treatment goals for rehabilitation and help educators meet the longer-term academic needs of children who use cochlear implants.

Neurocognitive Approach

The traditional approach to CI evaluation typically focuses on assessing speech perception and production, vocabulary acquisition, and/or receptive and expressive language—conceptualized as "products" of the auditory access provided by a CI (Pisoni, Conway, Kronenberger, Henning, & Anaya, 2010). As a consequence of this focus, information typically is not available that would provide a more detailed understanding of general cognitive processes such as working memory, attention, and executive functions, which may contribute to differences in individual performance on these measures.

Rapidly accumulating evidence suggests that other central cortical and subcortical neurobiological and neurocognitive processes that are not assessed by the traditional battery of speech and language measures contribute additional sources of variance to favorable outcomes. These processes are involved in linking and coordinating multiple brain systems to form a functionally integrated information-processing system (Ullman & Pierpont, 2005). Children who are deaf and use CIs—especially poor performers—may have other neural, cognitive, and affective sequelae resulting from a period of deafness and auditory deprivation combined with a delay in language development before implantation (Pisoni et al., 2010; Pisoni et al., 2008).

In our research center at the Indiana University School of Medicine we have been using a range of neurocognitive tests to study the performance of children with CIs and with typical hearing. Compared to children with typical hearing and development, children with CIs had smaller immediate memory capacity, slower verbal rehearsal speed, slower scanning of short-term memory, shorter memory spans, delays in executive functions (EFs), and poor sequence learning. All of these neurocognitive factors were associated with the children's performance on at least one traditional speech-language measure (for a review, see Pisoni, Conway, Kronenberger, Henning, & Anaya, 2010).

Based on these findings, we propose the following four key areas—collectively referred to as executive-organizational-integrative processes (EOI)—that are involved in the development of spoken language:

- Working memory
- Fluency-efficiency-speed
- Concentration-vigilance-inhibition
- Organization-integration

These abilities allow spoken language to be processed rapidly into meaningful symbolic units, stored in working memory, and actively assigned meaning while the child maintains a focus on the relevant stimulus information and resists distracting impulses.

Executive Functions

EFs are one of the core neurocognitive areas involved in the development of speech and language processes in children after cochlear implantation. EF is an umbrella term for a collection of interrelated processes such as attention, inhibitory control, working memory, flexibility, self-regulation, and planning that are responsible for purposeful, goal-directed behavior. We can think of the EFs as a set of control processes that organize and direct our cognitive activities, behavior, and emotions (Gioia, Isquith, & Guy, 2001). Baddeley (2003) provides a historical review of working memory models that explicate the relationship between working memory and executive control.

Development of the executive system parallels neurological development. As a consequence, the development of particular component processes of EFs and the relation among them will vary across individuals and over time. Furthermore, reliance on particular executive domains will vary due to differences in the day-to-day experiences and expectations of children of different ages. Three separate, but integrated, foundational EFs that emerge around age 3 years are:

- Response inhibition—the ability to refrain from acting on an impulse.
- Working memory—the ability to maintain and manipulate information in mind over a brief period of time.
- Shifting—the ability to alternate attention flexibly during problem-solving.

These processes become more finely coordinated and integrated between ages 3 to 5 years with changes in the development of controlled attention (Garon, Bryson, & Smith, 2008). The unity and diversity model of EFs suggests that these three processes are actually separable constructs; however, they are moderately correlated, suggesting the existence of some common process, such as attention, underlying the three subcomponents of EFs (Miyake et al., 2000).

On a neuroanatomical level, the executive system is associated with circuits in the prefrontal cortex, which is highly interconnected to areas of the brain associated with motivation, arousal, perceptual processes, and motor responses, and which likely provides regulatory control over perceptual coding and attentional functions (Welsh & Pennington, 1988). The prefrontal system develops over a longer period of time compared to other areas of the brain, with maturation continuing well into the 20s (Steinberg, 2010).

Converging evidence indicates that the brain of an adolescent differs morphologically and functionally from the brain of a child or an adult, according a recent collection of papers published in *Brain and Cognition* (Luciana, 2010). During adolescence, there are significant changes in grey and white matter in the prefrontal cortex, heightened brain plasticity, increases in structural and functional connectivity linking different brain regions, and changes in subcortical process, such as an increase in dopaminergic activity associated with reward-seeking (Steinberg, 2010; for more information on brain changes during adolescence, see "Executive Functions and Communication in Adolescents" by Lyn S. Turkstra and Lindsey J. Byom). Other evidence from fMRI studies suggests that the neural networks that share processing with the prefrontal cortex become more distributed and strengthened during adolescence, but have not yet reached the efficiency and flexibility of adulthood, perhaps limiting the flexible use of cognitive control during adolescence (Luna, Padmanabhan, & O'Hearn, 2010).

Memory Capacity and Processing Speed

The ability to process enormous amounts of novel auditory input in developing speech-language skills after cochlear implantation relies heavily on domain-general EOI areas such as working memory capacity and processing speed. Because even mild hearing loss interferes with critical early spoken-language experiences, it is possible that the development of core EOI skills may be at risk in children who are deaf. To explore this possibility, our center examined the relationship between working memory capacity and verbal rehearsal speed and speech and language development in children with CIs (Pisoni et al., in review).

Working memory capacity, which reflects the ability of an individual to recall recently presented information, was measured with a digit-span task that requires recall of a series of orally presented digits. Performance on the digit-span test requires rapid phonological coding and verbal-sequential short-term phonological memory. Verbal rehearsal speed was measured by calculating the duration of children's repetitions of sentences on the McGarr sentence repetition task (McGarr, 1983). Children completed assessments when they were 8 to 9 years old and again eight years later in adolescence.

Study results showed that although almost all children improved in working memory capacity and verbal rehearsal speed after eight years of implant use, children with CIs were delayed in both areas compared to typically hearing, same-age peers. Furthermore, working memory capacity and verbal rehearsal speed at age 8 predicted performance on measures of speech perception, production, language, vocabulary, and reading at age 16. These new developmental findings support the hypothesis that performance on traditional speech and language measures and the development of speech and language skills are highly dependent on core domain-general neurocognitive processes that allow phonological representations of speech to be perceived efficiently, encoded, maintained, and processed. These processes may be at risk in some children who use CIs.

Parent Report of Executive Function

To investigate further the executive skills of children with CIs, we used the Behavior Rating Inventory of Executive Function (BRIEF®; Gioia, Isquith, Guy, & Kenworthy, 2000), an 86-item questionnaire completed by parents and teachers of children ages 5–8 years to assess behavioral regulation and problem-solving skills in everyday life across eight EF domains. The BRIEF provides a Global Executive Composite (GEC) comprising two summary indexes—the Behavioral Regulation Index (BRI; inhibitory control, shifting behavior, and emotional control) and the Metacognitive Index (MI; initiating tasks and ideas, working memory, planning and organizing, organization of materials, and monitoring). The BRIEF provides normative benchmarks from a group of typically hearing children (average t-score for BRIEF subscales and composites is 50, with a standard deviation of 10), which we used for comparison to identify strengths, weaknesses, and milestones in our sample of adolescents who use CIs. Higher scores correspond to greater executive difficulties; scores greater than 60 are elevated and scores greater than 65 are clinically significant.

Parents of 54 adolescent CI users 16 to 18 years of age, who used their CI for at least eight years, completed the BRIEF. We compared the mean scores of our sample on each of the eight BRIEF subscales and composites to the normative mean of 50. Means on the GEC, BRI, MI, and five of the eight BRIEF subscales (inhibiting, shifting, initiating, planning/organizing, and monitoring) in our sample were significantly greater than the normative mean, suggesting more difficulties in this sample of adolescent CI users.

Although the sample average score did not fall in the clinically significant range on any of the eight domains or indexes of the BRIEF, a higher-than-average proportion of individual adolescents fell in elevated ranges.

Figure 1 [PDF] provides a boxplot of the distribution of scores on each BRIEF domain. Fifty percent of the scores fall in the shaded box, with the black horizontal line representing the median score on the BRIEF. The dashed line represents the mean or average expected score. We are especially concerned with the group of children who have scores in the clinically significant range (65 or higher) that fall above the blue horizontal line in Figure 1 [PDF]. In addition, we are interested in children with extreme scores represented by the circles. In a normal distribution, we would expect about 7% of children to have scores higher than 65; however, in this sample there is a larger percentage (9% to 24%) of children in the clinically significant range for most EF domains.

Evidence from both performance measures of executive processes and behavioral reports of executive control in everyday life suggest that children with CIs may be at risk for executive difficulties that may account for variation in their performance on speech, language, cognitive, and academic outcome measures.

Why would a period of auditory deprivation and delayed language affect areas such as working memory, speed of processing, learning, cognitive control, and self-regulation that appear, on the surface, unrelated to deafness? If we view the brain as a functionally integrated system that is shaped by experience and in which no part acts independently, then a period of degraded access to sound may affect subsequent neural organization and plasticity of multiple brain systems responsible for efficient processing, executive control, attention, learning, and working memory. All of these processes are required to learn to perceive and use language efficiently for those with and without typical hearing throughout the lifespan. Adolescence in particular is a period of development characterized not only by social, emotional, cognitive, and self-regulatory development and corresponding changes in societal expectations in these areas, but also by changes in brain structure and function (Ciccia, Meulenbroek, & Turkstra, 2009). As a consequence, adolescence may be a very important time for additional assessment and focused intervention and treatment.

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These new research findings suggest that neurocognitive processes such as executive functions, cognitive control, working memory, processing speed, and working memory capacity may be at risk in some children with CIs. Deficits in these areas early in childhood predict speech perception, vocabulary, language, and reading in adolescence. Early identification of possible deficits in core EOI processes through a comprehensive neurocognitive assessment may better allow clinicians, educators, and parents to provide the appropriate support and intervention necessary for children with hearing loss to achieve their maximum potential.

Biographies

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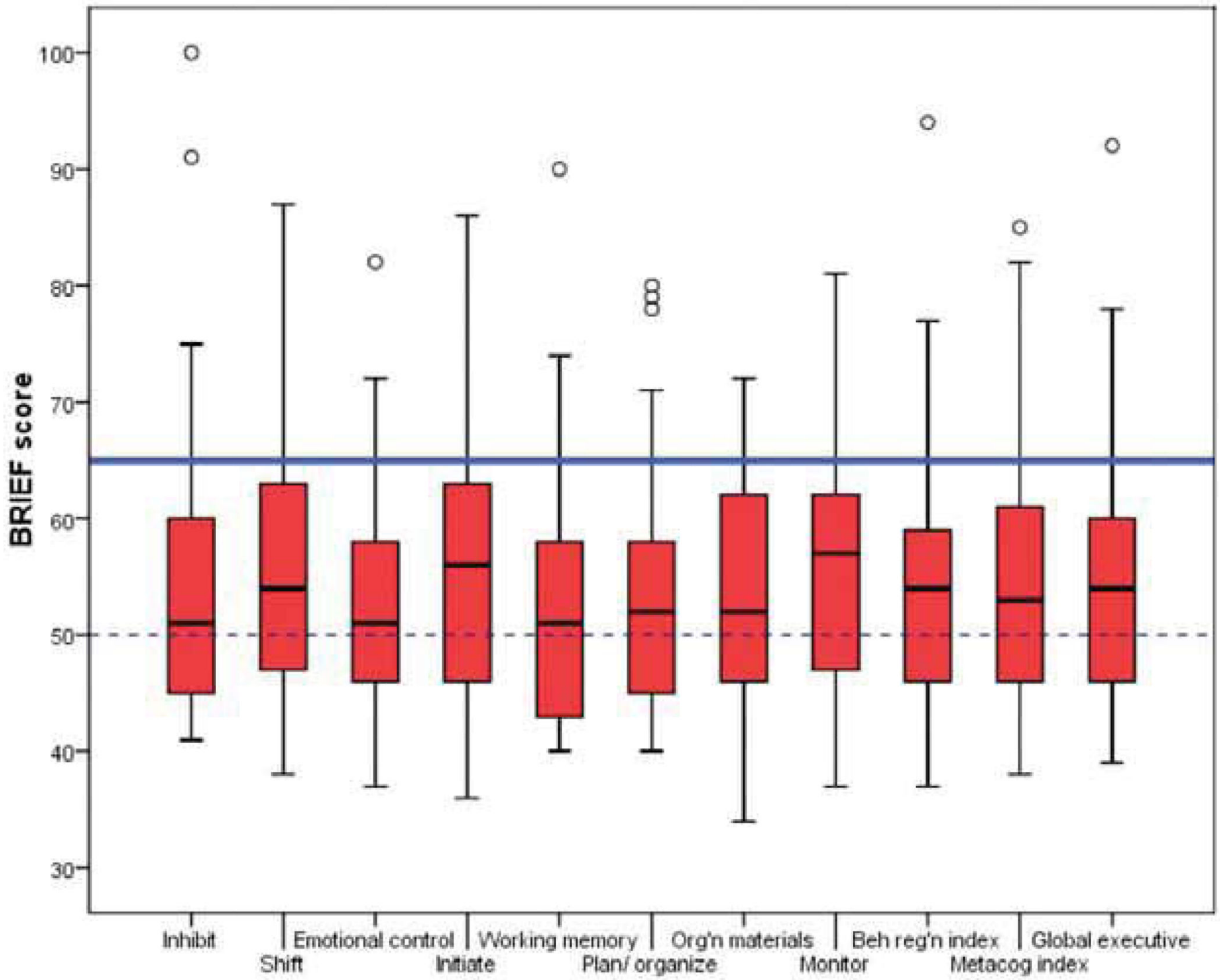

Figure 1.
Distribution of scores in BRIEF. This box plot is a summary of the distribution of children's t-scores on the eight domains and three indexes of the BRIEF. The top of each red box represents the 75th percentile, the bottom of the box represents the 25th percentile, and the line in the middle of the box is the median. The whiskers represent the highest and lowest BRIEF t-scores that are not extreme scores; extreme scores are represented by the circles. The dashed line represents the average expected score (t-score = 50) and the solid line represents the clinically significant range (t-score = 65 or higher).