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The Relationship between Central Auditory Processing, Language, and Cognition in Children Being Evaluated for Central Auditory Processing Disorder

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Abstract

Background: Pediatric central auditory processing disorder (CAPD) is frequently comorbid with other childhood disorders. However, few studies have examined the relationship between commonly used CAPD, language, and cognition tests within the same sample.

Purpose: The present study examined the relationship between diagnostic CAPD tests and "gold standard" measures of language and cognitive ability, the Clinical Evaluation of Language Fundamentals (CELF) and the Wechsler Intelligence Scale for Children (WISC).

Research Design: A retrospective study.

Study Sample: Twenty-seven patients referred for CAPD testing who scored average or better on the CELF and low average or better on the WISC were initially included. Seven children who scored below the CELF and/or WISC inclusion criteria were then added to the dataset for a second analysis, yielding a sample size of 34.

Data Collection and Analysis: Participants were administered a CAPD battery that included at least the following three CAPD tests: Frequency Patterns (FP), Dichotic Digits (DD), and Competing Sentences (CS). In addition, they were administered the CELF and WISC. Relationships between scores on CAPD, language (CELF), and cognition (WISC) tests were examined using correlation analysis.

Results: DD and FP showed significant correlations with Full Scale Intelligence Quotient, and the DD left ear and the DD interaural difference measures both showed significant correlations with working memory. However, ~80% or more of the variance in these CAPD tests was unexplained by language and

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cognition measures. Language and cognition measures were more strongly correlated with each other than were the CAPD tests with any CELF or WISC scale. Additional correlations with the CAPD tests were revealed when patients who scored in the mild–moderate deficit range on the CELF and/or in the borderline low intellectual functioning range on the WISC were included in the analysis.

Conclusions: While both the DD and FP tests showed significant correlations with one or more cognition measures, the majority of the variance in these CAPD measures went unexplained by cognition. Unlike DD and FP, the CS test was not correlated with cognition. Additionally, language measures were not significantly correlated with any of the CAPD tests. Our findings emphasize that the outcomes and interpretation of results vary as a function of the subject inclusion criteria that are applied for the CELF and WISC. Including participants with poorer cognition and/or language scores increased the number of significant correlations observed. For this reason, it is important that studies investigating the relationship between CAPD and other domains or disorders report the specific inclusion criteria used for all tests.

Key Words: central auditory processing disorder, dichotic listening, neuroaudiology, temporal processing

Abbreviations: ADHD = attention-deficit/hyperactivity disorder; CANS = central auditory nervous system; CAPD = central auditory processing disorder; CELF = Clinical Evaluation of Language Fundamentals; CS = Competing Sentences Test; CSIA = CS interaural asymmetry; CSL = CS left; CSR = CS right; DD = Dichotic Digits Test; DDIA = DD interaural asymmetry; DDL = DD left; DDR = DD right; FP = Frequency Patterns Test; FSIQ = Full Scale Intelligence Quotient; PRI = Perceptual Reasoning Index; PSI = Processing Speed Index; PTA = pure-tone average; SD = standard deviation; UCONN = University of Connecticut; VCI = Verbal Comprehension Index; WISC = Wechsler Intelligence Scale for Children; WMI = Working Memory Index

INTRODUCTION

Central auditory processing disorder (CAPD) refers to hearing difficulties that arise due to dysfunction of the central auditory nervous system (CANS) (AAA, 2010). CAPD affects one or more of the following auditory skills: sound localization and lateralization, auditory discrimination, various temporal aspects of audition (e.g., temporal resolution, temporal masking, temporal integration, and temporal ordering), and perception of competing sentences or degraded acoustic signals (ASHA, 2005). Symptoms often exhibited by individuals with CAPD include difficulties with hearing in the presence of background noise; understanding rapid speech or degraded speech; following verbal directions; learning from or retaining information provided orally; musical abilities, including difficulty recognizing sound patterns or rhythms; as well as receptive and/or expressive language, with a possible discrepancy between the two skill sets (AAA, 2010).

Although pediatric CAPD involves dysfunction primarily affecting the CANS, it is also a condition that commonly coexists with other childhood disorders (AAA, 2010). This frequent comorbidity occurs in part because the central nervous system is nonmodular and dysfunction in one region can affect processing in other regions (Musiek et al, 2005). Common comorbid conditions include language, learning, cognitive, and attention deficits. Sharma et al (2009) observed that only 4% of children being evaluated for CAPD were diagnosed with this disorder alone. A much larger percentage of their sample, ~60%, was diagnosed with CAPD and a comorbid language disorder. It has also been demonstrated that performance on some types of CAPD tests is significantly correlated with performance on measures of cognition/intelligence (e.g., intelligence quotient), attention, and/or memory in children (Sharma et al, 2009; Rosen et al, 2010).

The high comorbidity between CAPD and other childhood disorders has raised the concern that poor central auditory test performance in children is a result of a language or cognitive deficit (Moore et al, 2010; Kamhi, 2011). Some have suggested that one way in which these disorders can be differentiated is through the application of intratest measures (Bellis et al, 2011). An intratest measure is a computation performed on two slightly different administrations of a central auditory test to the same individual. Examination of the difference between ears on dichotic tests is an example of an intratest measure. The reasoning behind calculation of this intratest measure is that nonauditory issues, such as a language delay or cognitive deficit, should affect both ears equally, yielding at most a small interear difference. Children with CAPD tend to show poorer left-ear than right-ear performance (Musiek and Weihing, 2011 for a review); therefore, the magnitude of their intratest measure tends to be much larger. Bellis et al (2011) examined performance differences in participants with CAPD, attention-deficit/hyperactivity disorder (ADHD), and typically developing children on an intratest measure. While ear-specific test performance was negatively impacted by ADHD, the ear-difference intratest measure discriminated children with CAPD from those with ADHD. Specifically, children with CAPD showed significantly larger interear differences than children with ADHD or typically developing peers (Bellis et al, 2011), demonstrating the utility of intratest comparison measures to improve differential diagnosis of CAPD.

While existing research has examined the relationship between pediatric central auditory test performance and at least one other condition, these studies have infrequently examined the relationship between central auditory processing, language, and cognitive ability within the same sample. Additionally, none of these studies have examined to what degree of intratest performance on CAPD is related to these comorbid conditions. The present retrospective study examined pediatric performance on tests commonly used to diagnose CAPD (i.e., Dichotic Digits [DD; Musiek, 1983], Competing Sentences [CS; Willeford and Burleigh, 1994], and Frequency Patterns [FP; Musiek and Pinheiro, 1987]), a measure of language ability (i.e., Clinical Evaluation of Language Fundamentals [CELF; Semel et al, 2003]), and a test of cognition (i.e., Wechsler Intelligence Scale for Children [WISC; Wechsler, 2003]) to identify relationships across these three areas.

Specifically, the present study addressed the following questions using traditional CAPD test scoring methods as well as intratest measures:

1) To what degree were CAPD tests scores correlated with language and cognition measures?
2) How do the interrelationships between CAPD test scores and language and cognition measures change when considering patients with reduced language and cognition scores?
3) What is the relationship between measures of language and cognition?

METHODS

Participants

A total of 27 participants were included in this retrospective study. Participants ranged from 7 yr 11 mo to 16 yr, with a mean age of 11 yr (standard deviation [SD] = 2.1). All participants were seen at the University of Connecticut (UCONN) Speech and Hearing Clinic for CAPD evaluation. A total of 44% of the sample were diagnosed with CAPD per the ASHA (2005) or AAA (2010) criteria. This sample reflects consecutive patients seen at the clinic who met the inclusion criteria detailed below. It is the policy of the UCONN clinic that children with an attention disorder take their prescribed medication on the day of the CAPD evaluation.

Inclusion Criteria

Inclusion criteria for the participants enrolled in this study were (a) hearing sensitivity of no poorer than 20 dB HL for the tested octave frequencies (500, 1000, 2000, and 4000 Hz); (b) no air-bone gaps >10 dB HL bilaterally; (c) interaural asymmetry not >10 dB HL for the pure-tone average (PTA) of 500, 1000, and 2000 Hz; (d) normal middle-ear status (Jerger type A tympanograms); (e) completion of the three central auditory processing tests specified in the testing section below; (f) completion of the CELF-4; and (g) completion of the WISC-III or WISC-IV. An audiologist experienced in CAPD testing and differential diagnosis (author LG) carried out the CAPD assessments reported in the current study. Licensed professionals in the local area administered the language and cognition tests as part of their clinical evaluations.

Initial CELF/WISC inclusion criteria for the study were a Core Language score of ≥85 on the CELF and a Full Scale Intelligence Quotient (FSIQ) score of ≥80 on the WISC. These criteria identified the 27 participants for our first analysis series. There were an additional seven participants who obtained scores on the three central auditory processing tests described, as well as on the CELF and WISC, but who fell below the inclusion criteria for one or both of the latter two measures. In a second analysis series, we included these seven participants to yield a sample size of N = 34. The purpose of this second analysis was to examine the impact of including children with poorer language and/or cognition scores on CAPD × WISC/CELF correlations. This reflects a situation that might occur if (a) broader inclusion criteria were used for language and cognitive tests, and/or (b) inclusion criteria for these tests were not specified in a study and the language and/or cognitive status of participants was unknown. This second series is described separately in the Results section below.

Central Auditory Processing Test Battery

The central auditory processing test battery administered to all participants included DD (Musiek, 1983), CS (Willeford and Burleigh, 1994), and FP (Musiek and Pinheiro, 1987). Unless otherwise specified, all CAPD tests were presented at 50 dB SL re: PTA. The DD test is a dichotic processing measure of binaural integration. This test presents two different digit pairs simultaneously to each ear. Participants are instructed to repeat all four digits in any order (i.e., free report). There are a total of 20 digit pairs presented to each ear, and each digit is worth 2.5%. The CS is a dichotic processing measure of binaural separation, with two different sentences simultaneously presented to each ear. Participants are instructed to attend to one ear and repeat what is heard, while ignoring the sentence presented to the contralateral ear. The presentation levels are 35 and 50 dB SL re: PTA, for the signal to be repeated and the signal to be ignored, respectively. A total of 20 sentences are presented, 10 to each ear. Participants receive 10% if they repeat the entire sentence correctly, 7.5% if one or two key words are incorrect, 5% if half of the sentence is incorrect, 2.5% if only one or two key words are repeated correctly, and 0% if no portion of the sentence can be recited correctly. Additionally, a score of 0% is given if a participant recites the sentence from the unattended ear. This method was used previously in Musiek et al (2011) and Weihing et al (2015).

The FP test is a measure of temporal processing skills (specifically temporal ordering). The FP was presented either monaurally to each ear separately or binaurally. Binaural presentation of this test is frequently performed because ear differences are uncommon (Musiek and Pinheiro, 1987). If the test was administered monaurally, scores from each ear were then averaged to obtain an average FP score. The FP test presents three different tones, which are either low (880 Hz) or high (1122 Hz) in frequency. On any given trial, the participant labels verbally the frequency order of the three tones (e.g., high-low-high). Trials are counted as incorrect if the sequence repeated back does not match the presentation pattern, including reversal of the pattern (e.g., high-low-low for low-high-high). For monaural administration, a total of 30 patterns are presented separately to each ear; however, if all trials but one are correct during the first 15 trials, the test is terminated. For sound-field administration, a total of 45 patterns are presented to an individual; however, if all trials but two are correct or incorrect during the first 20 trials, then the test is terminated. In the case of early termination, performance is scored based on the initial 15 or 20 trials. All participants had FP labeling scores used in the present analysis that represented the percentage of patterns correctly labeled verbally. These percent correct scores on the labeling task were considered reflective of participants' temporal processing skills.

Clinically patients may be asked to hum the patterns on the FP test if their labeling scores are below normal limits. Humming is a less difficult auditory processing task, and these scores can sometimes reveal relevant information about auditory processing abilities. Humming data were available for only a few participants in this study (19%); therefore, these data were not included in the current analysis. There were no instances in which participants had humming scores but not labeling scores.

Procedures and Scoring of Auditory Test Battery

All hearing tests were administered using a GSI 61 two-channel audiometer (Grason Stadler, Eden Prairie, MN) in an IAC sound-treated booth (IAC Acoustics, North Aurora, IL) using TDH-39 headphones (Telephonics, Farmingdale, NY) or ER-3A insert earphones (Etymotic Research, Elk Grove Village, IL), except for the FP test when it was conducted in the sound field. The modified Hughson-Westlake procedure was used to determine audiometric pure-tone thresholds. A GSI Tympstar was used to perform tympanometry. The presentation order of the central auditory tests varied by patient, and some participants were administered additional auditory processing tests not included for analysis in the present study. For the battery examined in the present study (DD, CS, and FP), participants were considered to have failed a test if they scored below Dartmouth Hitchcock Medical Center normative values (i.e., means minus 2 SDs) for one or both ears. These norms were applied previously in Musiek et al (2011) and Weihing et al (2015). Ear-specific scores were obtained for DD (left [DDL] and right [DDR]) and CS (left [CSL] and right [CSR]). Participants were considered to have failed these tests if they scored below normal cutoff values in one or both ears. One participant was only several weeks from 8 yr of age, therefore the 8-yr-old normative values were used for this case. Participants scoring below normal cutoffs on at least two of the three central auditory tests, or below three SDs on at least one test, were diagnosed with CAPD (ASHA, 2005; AAA, 2010). Descriptive statistics for the CAPD tests in the present sample are included in Table 1.

The ear-difference intratest measure was calculated for DD and CS. This was computed as the absolute value of the right- minus left-ear percent correct, referred to as DD interaural asymmetry (DDIA) and CS interaural asymmetry (CSIA). As mentioned previously, it was expected that children with CAPD would show larger scores on this intratest measure because the right ear tends to outperform the left ear in many cases of pediatric CAPD (Bellis et al, 2011).

Language Assessment

Language was assessed using the CELF-4 (Semel et al, 2003). This is a normative assessment, which provides a comprehensive, broad-based evaluation of the language ability of children ages 5–21 yr. Receptive and expressive language modalities are assessed

Table 1. CAPD Test Descriptive Statistics (N = 27)

	CSL	CSR	CSIA	DDL	DDR	DDIA	FP
Mean	90.65	96.22	7.06	88.57	95.00	8.72	73.24
SD	11.35	5.33	7.99	11.45	4.99	10.23	22.07
Range	53–100	83–100	0–30	53–100	85–100	0–45	15–100

individually. Results from the CELF-4 can be used to (a) identify the presence of a language disorder, (b) describe the nature of the disorder, (c) evaluate the underlying clinical behaviors, and (d) evaluate contextual language and communication skills (Pearson Education Inc., 2008). The CELF-4 is commonly used to evaluate language disorders in populations with comorbid disabilities (Bailey and Gross, 2010). This was the standard language assessment that was used clinically at UCONN at the time the participants in this study were evaluated.

The primary score obtained from administration of the CELF-4 is the Core Language score. The Core Language score is based on performance on a set of subtests including Concepts and Following Directions (i.e., pointing to objects in response to verbal instructions), Word Structure (i.e., completing a sentence using a specific format), Recalling or Imitating Sentences, and Formulating Sentences (using a picture to create the sentence for a specific word or phrase). Receptive and Expressive Language scores also were available for most participants and were also used to evaluate correlations with various auditory and cognitive assessments. The Receptive Language scores reflect listening and auditory comprehension in general. The subtests used to evaluate this construct vary depending on age, and include Concepts and Following Directions, Word Class (i.e., describing a relationship between a set of two words), Sentence Structure, Understanding Spoken Paragraphs, and Semantic Relationships (Pearson Education Inc., 2008). The Expressive Language scores reflect one's ability to use language to communicate with others. This construct's subtests also vary depending on age and include Formulating Sentences, Recalling Sentences, and Expressive Vocabulary (Pearson Education Inc., 2008). For the present study, individuals were defined as having a language deficit if their Core Language score was <85, as a score of 85 is the cutoff for 1 SD below the mean of normal performance scores (the range for typical performance on the CELF is 85–115 on the composite score chart) (Pearson Education Inc., 2008). Descriptive statistics for the CELF in the present sample are included in Table 2.

Cognitive Assessment

The WISC third and fourth editions (WISC-III and WISC-IV; Wechsler, 2003) comprised the cognitive assessment. The WISC measures the intellectual ability of children, ages 6 to 16 yr, 11 mo. The WISC FSIQ score denotes general intellectual ability and is based on subtests that provide information about specific cognitive domain functional abilities, as well as verbal and nonverbal intelligence. The indices that make up the WISC-IV include Verbal Comprehension, Working Memory, Perceptual Reasoning, and Processing Speed (Sandhu, 2002). Two patients were administered the WISC-III (Wechsler, 1991), which offers FSIQ scores but does not include the same index scores. For those patients, FSIQ scores were used only in analyses. The WISC is a commonly used cognitive assessment when evaluating populations with comorbid disabilities (Bailey and Gross, 2010) that was standardized on a large group of individuals (N = 2,200) (Bailey and Gross, 2010). This was the standard cognitive assessment used clinically at the time the participants of this study completed their evaluations.

Table 2. CELF and WISC Descriptive Statistics (N = 27)

	CELF Core Language	WISC FSIQ
Mean	99.26	98.78
SD	9.11	9.34
Range	85–121	82–120

The WISC-IV Verbal Comprehension Index (VCI) is a measure of a child's ability to formulate verbal concepts. This index is derived from a child's ability to listen to a question and use learned information to reason though and construct a verbal response. The Working Memory Index (WMI) is a measure of one's ability to store and process new as well as previously obtained information, which aids in processes such as reasoning, comprehension, learning, and memory updating. WMI tests require children to remember new information using their short-term memory, and then take that novel information and manipulate it to produce a desired result or demonstrate various reasoning/language processes (Sandhu, 2002). The Perceptual Reasoning Index (PRI) uses visual-motor integration and spatial processing to determine perceptual and fluid reasoning abilities. These subtests present problems that require use of these various reasoning and processing strategies to devise a solution to the problem (Sandhu, 2002). The Processing Speed Index (PSI) measures the speed at which individuals are able to process information. These subtests require focused attention and present different constraints, so children must persevere to complete the tasks that require visual perception and organization and proficient hand–eye coordination (Sandhu, 2002). For the present study, individuals were defined as having a cognitive deficit if their FSIQ was <80, as the current Wechsler FSIQ classification of 80–114 is considered performance in low average to high average ranges (mean FSIQ = 100, SD = 15; Sattler, 2008). Descriptive statistics for WISC scores obtained in the present sample are included in Table 2.

Statistics Overview

The analyses below addressed the main questions of the present study. In a first correlation series, the relationship was examined between the CAPD tests (CSL, CSR, CSIA, DDL, DDR, DDIA, FP) and the CELF and WISC. The CELF scales included Core Language, Receptive Language, and Expressive Language. The WISC scales included FSIQ, VCI, PRI, WMI, and PSI. This analysis was performed to determine the degree of association between the CAPD tests and these other measures. Any significant correlations were also expressed as a percentage of shared variance between the two measures to describe the magnitude of the effect. Since the CAPD data contained maturation variance, significant correlations also were examined while partialing out the effect of chronological age to determine whether the relationship might reflect the influence of normal maturational processes. If significance remained after adjusting for chronological age, we interpreted this to mean that the observed associations were more likely related to some factor that is not part of the normal maturational process.

Correlations between CAPD tests and CELF and WISC measures were then reexamined in a second series that included participants who scored in the mild–moderate deficit range on the CELF and/or in the borderline FSIQ range on the WISC. This was done to simulate scenarios that might occur if broader study inclusion criteria allowed for participants to score within the disordered range on the CELF and WISC measures, or the language and/or cognitive status of the participants were unspecified in a study sample. All the correlations in the first series were repeated in the second series. This included computing a separate set of correlations that adjusted for chronological age.

Finally, correlations between language and cognition scores were examined. Few studies have examined the relationship between central auditory processing, language ability, and cognitive ability within the same pediatric sample. Since the present dataset included data on all three groups of tests, we considered the magnitude of the CAPD × language/cognition correlations within the context of how much performance on other tests of childhood disorders tends to overlap.

RESULTS

To What Degree Were CAPD Tests Scores Correlated with Language and Cognition Measures?

We examined individual correlations between CAPD test scores and the composite and subscale scores for the CELF and WISC. Not all participants had results available for all subscales. Results for this analysis are shown in Table 3. CELF scores were not correlated with any of the CAPD measures. WISC FSIQ was significantly correlated with DDL and FP. The WISC WMI subscale was significantly correlated with DDL and DDIA. The degree of shared variance for significant correlations is shown in Figure 1. As can be seen in this figure, the majority of the variance in CAPD test scores (~80%) was unexplained by the cognition score.

To determine whether the observed correlations between DD and FP and the WISC were related to normal maturational trends reflected in the CAPD test scores, we computed these significant correlations a second time after adjusting for chronological age. If significance remained after controlling for chronological age, we reasoned that the observed associations were more likely related to some factor that is not part of the normal maturational process. In this analysis, all four correlations remained significant, suggesting that normal maturation could not account for the observed trends [DDL × FSIQ: $r_{(24)} = 0.458$, $p > 0.02$; DDL × WMI: $r_{(18)} = 0.471$, $p < 0.04$; DDIA × WMI: $r_{(18)} = -0.485$, $p < 0.03$; FP × FSIQ: $r_{(24)} = 0.447$, $p < 0.03$].

How Do the Interrelationships between CAPD Test Scores and Language and Cognition Measures Change When Including Patients with Reduced Language and Cognition Scores?

In our initial records review, seven patients were identified who scored in the mild–moderate range on the CELF and/or in the borderline range on the WISC. In the present study, this included children who scored between 70 and 84 on the CELF and/or between 70 and 79 on the WISC. In a subsequent correlation series, we considered the impact of including these participants. This simulates scenarios that might occur if broader study inclusion criteria allowed for participants to score within the disordered range on the CELF and WISC measures, or the language and/or cognitive status of the participants were unspecified in a study sample. For this analysis, this increased the possible maximum sample size for an analysis from 27 participants to 34.

Table 4 presents the correlations obtained in this second series. Most of the correlations reported in the first correlation series remained significant in this second series. Many additional correlations were found in the second series that were not present in the first. Specifically, significant correlations were now noted between CELF and all three CAPD tests, and a correlation emerged between the CS and WISC. These findings suggest that including participants who score very poorly on the CELF and WISC increases the likelihood of those measures being correlated with CAPD test scores.

To address whether the increase in the number of significant correlations in this second series was the result of the increased sample size, we reevaluated all the correlations in Table 4 using degrees of freedom that were similar to those correlations reported in Table 3. We used the average sample size in Table 3 (N = 24) for this approach. For df = 22, the critical r value required to achieve significance for an alpha level of 0.05 is 0.404. There were initially ten significant correlations in the second series (Table 4) that were not noted in the first series (Table 3). Of these ten correlations,

Table 3. Correlations between CAPD Tests and Language and Cognition Scores

	CELF			WISC				
	Core	Receptive	Expressive	FSIQ	VCI	PRI	WMI	PSI
CSL	−0.179 (27)	−0.140 (23)	0.231 (26)	0.158 (27)	0.326 (25)	0.010 (25)	−0.234 (21)	−0.298 (21)
CSR	0.165 (27)	−0.128 (23)	0.272 (26)	0.122 (27)	0.051 (25)	0.000 (25)	−0.030 (21)	−0.252 (21)
CSIA	0.232 (27)	0.081 (23)	−0.163 (26)	−0.073 (27)	−0.154 (25)	−0.085 (25)	0.276 (21)	0.233 (21)
DDL	0.247 (27)	−0.073 (23)	0.088 (26)	**0.450*** (27)	0.285 (25)	0.086 (25)	**0.423*** (21)	−0.071 (21)
DDR	0.134 (27)	−0.263 (23)	0.317 (26)	0.139 (27)	−0.137 (25)	−0.032 (25)	0.104 (21)	−0.221 (21)
DDIA	−0.254 (27)	−0.014 (23)	−0.029 (26)	−0.360 (27)	−0.142 (25)	−0.149 (25)	**−0.475*** (21)	0.156 (21)
FP	0.235 (27)	0.015 (23)	0.177 (26)	**0.437*** (27)	0.279 (25)	0.236 (25)	0.384 (21)	−0.405 (21)

Notes: Values in boldface are significant at $^{*}p < 0.05$ and $^{**}p < 0.01$ (While ** = $p < 0.01$, no correlations in this table were significant for this criterion.). N values are given in parentheses.

six remained significant with the more conservative degrees of freedom. This suggests that the increase in the number of significant correlations in the second series cannot be readily explained by the slightly larger sample size.

Finally, as with the first correlation series, we addressed whether significant correlations remained after adjusting for chronological age. When chronological age was adjusted, all the correlations observed between the CAPD tests and the WISC remained significant [CSR × FSIQ: $r_{(31)} = 0.452$, $p < 0.009$; CSR × PRI: $r_{(29)} = 0.359$, $p < 0.05$; DDL × FSIQ: $r_{(31)} = 0.355$, $p < 0.05$; DDL × WMI: $r_{(25)} = 0.401$, $p < 0.04$; DDR × FSIQ: $r_{(31)} = 0.377$, $p < 0.04$; FP × FSIQ: $r_{(31)} = 0.500$, $p < 0.004$; FP × PRI: $r_{(29)} = 0.418$, $p < 0.02$; FP × WMI: $r_{(25)} = 0.496$, $p < 0.009$]. For language, most correlations remained significant after adjusting for chronological age [CSL × Core Language: $r_{(31)} = 0.375$, $p < 0.04$; CSIA × Core Language: $r_{(31)} = -0.438$, $p < 0.02$; CSIA × Receptive Language: $r_{(27)} = -0.375$, $p < 0.05$; FP × Core Language: $r_{(31)} = 0.488$, $p < 0.005$]. However, there were two correlations that were only marginally significant after adjusting for chronological age [DDL × Core Language: $r_{(31)} = 0.336$, $p = 0.056$; FP × Receptive Language: $r_{(27)} = 0.343$, $p = 0.068$].

What is the Relationship between Measures of Language and Cognition?

The correlations between CELF and WISC scores were also examined in the present sample. Significant correlations were observed between Core Language and FSIQ [$r_{(28)} = 0.381$, $p < 0.05$], between Core Language and WMI [$r_{(21)} = 0.594$, $p < 0.005$], and between Expressive Language and WMI [$r_{(21)} = 0.572$, $p < 0.009$]. The percentage of variance in language scores that was explained by cognition measures is shown in Figure 2. Notably the relationship between CELF Core Language and WISC WMI showed the greatest degree of shared variance of any of the comparisons made in the present study (35%). This indicates that about one-third of the variance in language scores is accounted for by the working memory ability of patients.

DISCUSSION

General Findings

The primary findings of the present study were that the "gold standard" measures of language and cognition (CELF and WISC, respectively) predicted only a

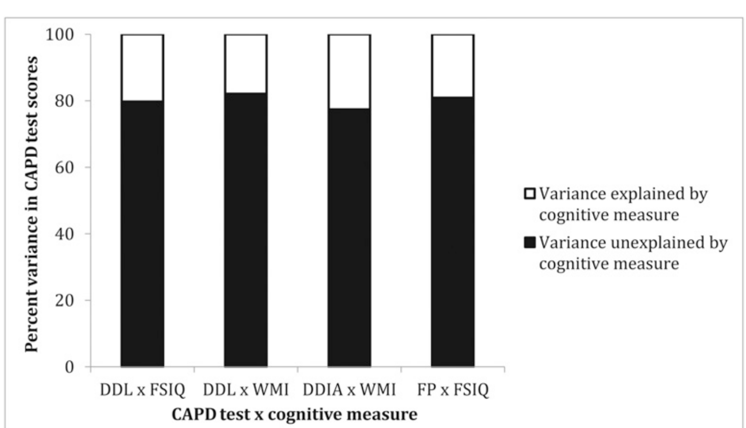

Figure 1. Pearson r^2 effect sizes (expressed as a percentage) between CAPD test scores and WISC measures that were significantly correlated. Variance explained is represented by the white portion of each bar.

Table 4. Correlations between CAPD Tests and Language and Cognition Scores When Also Include Participants Who Scored in the Borderline Range on the WISC and/or in the Mild–Moderate Range on the CELF

	CELF			WISC				
	Core	Receptive	Expressive	FSIQ	VCI	PRI	WMI	PSI
CSL	**0.441**** (34)	0.334 (30)	0.332 (33)	0.299 (34)	0.292 (32)	0.158 (32)	0.263 (28)	−0.098 (28)
CSR	0.247 (34)	0.162 (30)	0.177 (33)	**0.456**** (34)	0.296 (32)	0.372* (32)	0.175 (28)	0.246 (28)
CSIA	**−0.493**** (34)	**0.396*** (30)	−0.314 (33)	−0.290 (34)	−0.205 (32)	−0.214 (32)	−0.283 (28)	0.054 (28)
DDL	**0.398*** (34)	0.062 (30)	0.181 (33)	**0.359*** (34)	0.158 (32)	0.136 (32)	**0.381*** (28)	−0.041 (28)
DDR	0.331 (34)	0.160 (30)	0.334 (33)	**0.383*** (34)	0.046 (32)	0.257 (32)	0.296 (28)	0.085 (28)
DDIA	−0.265 (34)	0.076 (30)	−0.075 (33)	−0.173 (34)	−0.031 (32)	−0.043 (32)	−0.315 (28)	0.238 (28)
FP	**0.541**** (34)	**0.367*** (30)	0.289 (33)	**0.488**** (34)	0.217 (32)	**0.421*** (32)	**0.465*** (28)	−0.167 (28)

Notes: Values in boldface are significant at *$p < 0.05$ and **$p < 0.01$. N values are given in parentheses.

minority of the variance in CAPD test scores among children who showed average or better language skills and low average or better FSIQ. This indicates that the majority of variance in these CAPD measures was not accounted for by these particular measures of language and cognition. Further, where the overlap between CAPD test scores and these other measures was greatest, it appeared to be cognition, and not language, that was explaining this small amount of variance in the CAPD scores.

The primary correlation series performed in the present study indicated that FSIQ was significantly correlated with DDL and FP, and that WMI was significantly correlated with DDL and DDIA. While the vast majority of variance in the CAPD measures remained unexplained even after accounting for these cognition measures, we consider some of the possible explanations for these trends. For the dichotic tests, the observation that DDL and DDIA were correlated with cognition while CS was not suggests that the DD × Cognition relationship reflects something unique to the stimuli or response mode of the DD measure and not something specific to all dichotic tests. One possibility is that the number of disparate auditory elements (i.e., four numbers) needing to be remembered and recalled on any given trial places increased demands on working memory. The finding that the WMI subscale was correlated only with the left ear suggests that participants may be repeating back their dominant dichotic processing ear first (i.e., right ear), after which they have difficulty recalling the left ear. CS may not have shown this relationship because the sentence stimulus contains word elements that are related by the sentence context, and this may benefit recall. For the FP and FSIQ relationship, it is possible that the memory requirements (i.e., remembering three tone frequencies) and abstract nature of the labeling response mode places increased demands on patients. Those who obtain cognition scores in the low average range may encounter greater difficulties performing the task successfully.

Impact of Adding Patients with Language and/or Cognitive Deficits

The present study reevaluated correlations between CAPD tests and these other measures after children with language and/or cognitive deficits were added into

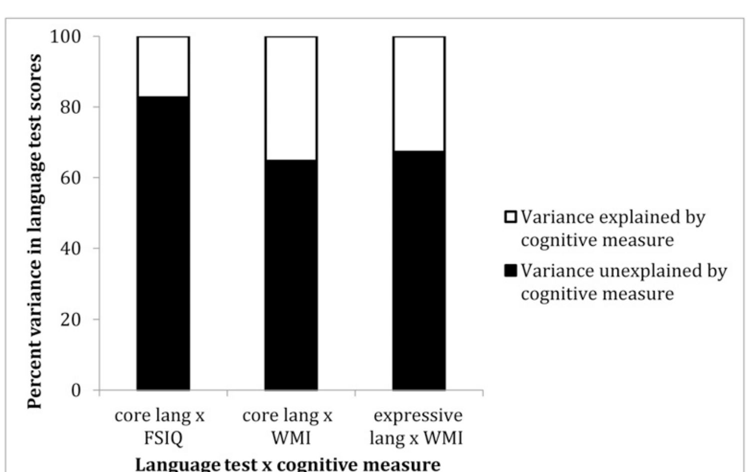

Figure 2. Pearson r^2 effect sizes (expressed as a percentage) between CELF test scores and WISC measures that were significantly correlated. Variance explained is represented by the white portion of each bar. Lang = language.

the analysis. This included participants who showed a mild–moderate deficit on the CELF and/or who scored in the borderline low intellectual functioning range on the WISC FSIQ. The purpose of this analysis was to investigate the impact of adding participants with clearly compromised language or cognitive functions.

Results indicated a much larger degree of association between CAPD scores and language and cognition scores when these children with language and/or cognitive deficits were included. Specifically, all three CAPD tests showed one or more significant correlations with the CELF and its subscales in this second correlation series. Further, the CS was correlated with FSIQ in this second series. These findings indicate that the pattern of correlations will vary as a function of the inclusion criteria used for language and cognitive tests. Not specifying clearly what inclusion criteria were used for a particular research study would be expected to make it more difficult to know how best to interpret the findings.

There are several possible explanations for why CAPD tests were more closely associated with the CELF in this second correlation analysis. One possibility, which attributes a causal role to central auditory processing, is that children with CAPD have a listening (auditory processing) disadvantage, and it is this auditory processing issue that hinders normal development of language skills. A second possibility, which attributes a causal role to language ability, is that poorer language skills make it more challenging for children to complete speech-based auditory processing tests and/or understand the spoken instructions. Finally, it is possible that there is a more global developmental issue that is not auditory specific but that includes the auditory system, and this developmental issue also affects language development. As an example, Musiek et al (1984) speculated that, in some children, a delay in myelin development negatively affects the CANS and contributes to dichotic listening issues. This delay would not be expected to be localized to the auditory system and could affect the central nervous system more globally.

Relationship between Language and Cognition Measures

Although it was not a primary purpose of this study, we also investigated the relationship between the language and cognition measures in the present sample. It was noted that language scores showed some relationship to FSIQ and working memory. Interestingly, the relationships between Core Language and WMI and between Expressive Language and WMI surpassed the effect sizes seen for the majority of CAPD correlations. For comparison, the largest proportion of shared variance for the CAPD measures was 23% (DDIA $\times$ WMI, derived from Table 3), whereas the largest value for the language and cognition correlations was 35% (Core Language $\times$ WMI). This trend of significant correlations between language and cognition measures is supported by previous reports that have shown that children who do poorly on language tests also tend to present with poorer working memory (Pearson Education Inc., 2005 for a summary).

Therefore, language and cognition measures were more highly related to each other than they were to the CAPD tests in the present study. If the metric of CAPD as an independent clinical entity is gauged by the degree to which CAPD test scores disassociate from these other childhood tests, then it should be noted that common clinical measures of language and cognition are much more strongly associated with each other than they are with CAPD tests. Thus, relative to these three groups of tests, the CAPD measures appear to be the most independent.

Comparison to Previous Studies

The correlations observed in the present study also have been reported in other studies. Keith et al. (1989) administered a dichotic word subtest of the SCAN to children with Verbal IQ scores ≥90. Similar to the present study, they did not note any correlations between the CELF and the dichotic measures. They noted some association between vocabulary and dichotic word processing when using an open set of stimuli, although this may not be relevant to the present findings, which were obtained from a dichotic test with a small closed set (DD) as well as from a dichotic sentence test in which word recognition likely benefited from sentence context (CS). Also consistent with the present findings are those of Lum and Zarafa (2010), who reported a relationship between dichotic ability and language function in patients with reduced performance on language measures.

It has been observed that IQ and working memory are correlated with dichotic digits performance (Maerlender et al, 2004; Wilson et al, 2011; Gyldenkrne et al, 2014; Tomlin et al, 2015), though several studies have not reported this finding (e.g., Sharma et al, 2009; Weihing et al, 2015). It also generally has been reported that left-ear dichotic digit scores tend to show more significant correlations with IQ and working memory than right-ear dichotic digit scores (Wilson et al, 2011; Gyldenkrne et al, 2014). Several studies also have examined competing sentences performance, noting some relationship between IQ and/or working memory and these measures (Wilson et al, 2011; Ahmmed et al, 2014), though again some studies have not reported significance (Riccio et al, 2005; Weihing et al, 2015). It should be pointed out that most of the previous studies examining these correlations using competing sentences computed a total score that merged performance at each ear (e.g., SCAN), making their trends difficult to compare to the present study, in which ear-specific scores were used. Finally, FP performance also has been examined in previous research, corroborating that performance often is significantly correlated with IQ and/or working memory (Sharma et al, 2009; Wilson et al, 2011; Gyldenkrne et al, 2014; Tomlin et al, 2015; Weihing et al, 2015).

A recently published study from our laboratory examined the relationship between cognition and CAPD tests (Weihing et al, 2015). One key difference between the present study and Weihing et al (2015) is that the present study found a significant correlation between cognition and DD test scores that was not observed in our earlier study. Relative to the present study, Weihing et al (2015) showed a greater percentage of DDL scores closely approaching or within the normal range. This truncated range limited the linearity that could be established between this CAPD measure and cognition. Conversely, in the present study, a greater percentage of participants showed lower DDL performance, and there was a greater tendency toward linearity in the DDL $\times$ FSIQ relationships. Therefore, it is possible that the reduced percentage of participants who scored poorly on DDL in the Weihing et al (2015) study led to their finding of fewer significant relationships.

Clinical and Research Implications

Our findings reinforce that clinical testing for language and cognitive function by cognizant professionals should be an important component of the CAPD preevaluation process, as recommended by current consensus documents and clinical practice guidelines (ASHA, 2005; AAA, 2010). Administration of the DD and/or FP test may be contraindicated if participants score in the low average range on the WISC. However, since the majority of the variance on both (DD and FP) of these CAPD measures remains unexplained by cognition, this decision should be made on a case-by-case basis. All CAPD tests were relatively uninfluenced by language, when considering children who score average or better on the CELF. While there is some degree of association between language scores and the CAPD tests when including children with mild-to-moderate language deficits, the majority of the variance in the CAPD measures is still unexplained by the CELF.

There likely is some value in calculating interaural asymmetry to reduce the effects of language and cognition on dichotic test performance, particularly when participants perform low bilaterally on a dichotic test. For the DD test, however, there also appears to be complex relationships between cognition and the left-ear dichotic score, suggesting that a simple difference calculation of the performance at each ear may not completely eliminate the effects of these other variables. It is possible that new paradigms for applying differential diagnosis to the DD test, such as the Dichotic Digits difference Test (Cameron et al, 2016), might yield better discrimination of CAPD from other disorders when compared to interaural asymmetry measures.

Given the potential bidirectional influence across central auditory processing, cognition, and language, it is critical that future research carefully specify participant inclusion criteria. As the present study demonstrated, relationships vary considerably as a function of performance cutoffs; therefore, outcomes and interpretation of results will vary as a function of subject inclusion criteria. Failure to specify inclusion criteria limits the degree to which findings can be generalized across studies and to clinical situations that do not impose these criteria.

Limitations

There are several limitations of the present study. First, the sample of participants examined was relatively small, with the sample size limited by the inclusion criteria imposed during the retrospective chart review (i.e., CS, DD, FP, CELF, and WISC scores must have been documented in each participant's record). This was addressed to some extent in the present study by not applying a Bonferroni correction and reporting effect sizes. However, future studies should seek to replicate these findings in a larger sample. Second, as half the sample was not diagnosed with CAPD, the correlations may generalize best to children being evaluated for the disorder, rather than to children specifically diagnosed with CAPD. The number of participants diagnosed with CAPD as well as the number not presenting with CAPD were each too small to consider correlations by group.

Finally, attention deficits may also influence performance on certain CAPD tests (Gyldenkrne et al, 2014), as well as on language and working memory cognition test performance (McInnes et al, 2003). This interaction was not assessed in the present study. It should be noted, however, that the pattern of correlations between the DD and the WISC subscales was different than what is typically observed between the WISC and measures of attention. In the present study, DD was correlated with WMI in children being evaluated for CAPD but for whom attention issues were not the focus of concern. In contrast, prior studies have demonstrated that children diagnosed with ADHD present poor performance on both WMI and PSI (Mayes and Calhoun, 2006). PSI was not correlated with DD in the present study, and children who met criteria for CAPD demonstrated PSI performance that was not significantly different from those with normal auditory processing [PSI CAPD mean = 93.92 versus Normal Processing mean = 92.92; $t_{(24)} = 0.269$, $p = 0.790$]. Although both WMI and PSI involve frontal-executive function, WMI uses verbal presentation of stimuli while PSI employs visual stimuli. Taken together, these differences might inform differential diagnosis and clarify the independence seen between types of central auditory processing tests (e.g., DD, Gaps-In-Noise, Masking Level Difference) and attention deficits (Gyldenkrne et al, 2014). In other words, more global (supramodal) attention deficits seen in ADHD may be distinguished from CAPD, in part, by examining performance on visual frontal-executive tasks such as the PSI.

CONCLUSIONS

The findings of the present study established that the majority of the variance in CAPD test scores was unexplained by the "gold standard" language (CELF) and cognition (WISC) measures. Language and cognitive measures were more closely associated with each other than they were with CAPD tests. Including participants who scored in the mild–moderate deficit range on the CELF and/or in the borderline FSIQ range on the WISC, as might happen with broadened inclusion criteria or unspecified participant inclusion criteria, increased the number of significant correlations between CAPD tests and the language and cognitive measures. For this reason, it is important that future studies specify inclusion criteria for language and cognition measures when examining the relationship between CAPD and other domains or disorders in children.

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