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Short-term Memory and Auditory Processing Disorders: Concurrent Validity and Clinical Diagnostic Markers

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Abstract

Auditory processing disorders (APDs) are of interest to educators and clinicians, as they impact school functioning. Little work has been completed to demonstrate how children with APDs perform on clinical tests. In a series of studies, standard clinical (psychometric) tests from the Wechsler Intelligence Scale for Children, Fourth Edition (WISC-IV) were used to establish concurrent validity between tests of short-term auditory memory and two frequently used tests of auditory processing (Dichotic Digits and Frequency Patterns). The diagnostic utility of the short-term memory tests was also explored. In a matched sample, Digit Span forward predicted diagnosis of APD (sensitivity = .81, specificity = .78). Furthermore, within-subjects analyses for the clinical group found that Digit Span forward scores were significantly lower than those for the other psychometric tests (p values < .001 for Digit Span backward, Letter Span nonrhyming and rhyming scores). Although APD is a low base-rate condition, the utility of these tests as a potential screener or marker for APDs was demonstrated. The need for further studies was endorsed.

Auditory processing disorders (APDs) are deficits in the information processing of audible signals not attributed to impaired peripheral hearing sensitivity or intellectual impairment. These deficits disrupt the continuous auditory processing of acoustic, phonetic, and linguistic information and affect information processing from sound reception to discourse understanding (Jerger & Musiek, 2000). An APD may be manifest as a deficit in sound localization, discrimination, pattern recognition, temporal processing, and performance deficits when the auditory signal is degraded or embedded in competing acoustic signals. These deficits have electrophysiological as well as behavioral correlates (Bamiou, Musiek, & Luxon, 2001). Prevalence estimates of APDs put the rate of this disorder at 2%–3% of all children, with boys having the disorder twice as often as girls (Chermak & Musiek, 1997). Some of the symptoms associated with APDs include being easily distracted by loud or sudden noises, having improved behavior and performance in quieter settings, having difficulty following directions and conversations, frequently saying "huh" or "what," having difficulty listening when there is background noise, and having poor auditory attention.

The diagnosis of APDs has become a frequent occurrence in schools, although APDs are not recognized in medical diagnostic nomenclature. Current identification practice is based on audiological ("audiometric") testing. This testing is currently done only in appropriately equipped laboratories. Behavioral testing relies on psychophysical paradigms in which stimuli are presented in varying frequencies, intensities, et cetera to establish the level at which the subject can accurately respond. An issue for clinicians and psychologists is how these APDs relate to better known psychological constructs. Few studies have looked at relationships between APD test scores and scores on standard tests and psychometric tests. Furthermore, the behavioral phenotype described by audiometric tests is unique to their profession. Thus, the purpose of this study was to relate those phenotypic characteristics to constructs with which psychologists are familiar.

Watson and Miller (1993) found that performance on the auditory span tasks was modestly related to speech perception and nonsense word decoding on a staggered spondaic word test (r = .22 to .39). Participants were reading disabled and non–reading-disabled college students. Parkinson (1974) found strong relationships between dichotic listening and "digit memory" in college students, suggesting that short-term auditory memory and central auditory processes are related.

In a series of retrospective analyses, Maerlender, Wallis, & Isquith (2004) demonstrated that the Digit Span subtest of the Wechsler Intelligence Scale for Children, Third Edition (WISC-III) was strongly related to a dichotic listening test, considered the most robust measure of APD (Musiek, Gollegly, & Ross, 1985). Furthermore, the forward span element of this subtest was the most robust indicator of APD diagnosis.

Two recent studies of APD and neuropsychological tests in children with Attention-Deficit/Hyperactivity Disorder (ADHD) have found some relationships among psychometric tests. In the first, Riccio, Cohen, Garrison, and Smith (2005) studied 36 children with ADHD and administered a series of auditory and neuropsychological tests to identify relationships among audiometric tests and neuropsychological tests. Correlational analysis revealed only one significant correlation: between the right ear score of the Staggered Spondaic Word (SSW) test and a memory for sentences test (Clinical Evaluation of Language Fundamentals, 3rd ed., Sentence Repetition). They concluded that auditory

measures tap some element of auditory memory and that APD and ADHD may be overlapping but independent disorders.

In a clinical sample of children with APD matched on age and IQ score with WISC-IV clinical ADHD cases from the standardization sample, Maerlender (2006) compared the Digit Span forward (DSF) and Letter Span (rhyming and nonrhyming) scores. There were significant differences between groups on DSF and Letter Span nonrhyming scores, with DSF accounting for the most variance and providing the best discrimination between groups (Maerlender, 2006). Thus, in support of Riccio and colleagues (2005), the data provided evidence that APD was likely an independent diagnostic construct from ADHD, although significant comorbidity was also evident.

The studies reported here sought to answer the following questions: (a) Can psychometric tests be used to reliably identify children with APD? and (b) Was there convergent validity between the psychometric tests and the audiometric tests? The first question was addressed using two different comparison groups (Study 1 and Study 2). The second question was addressed in Study 1.

Study 1 Method

Participants

A total of 36 children ranging in ages from 7 to 14 participated in the psychometric portion of this study (26 boys, 10 girls). Table 1 presents age, gender, and diagnostic status. All participants were English-speaking Whites; 20 were right handed, 2 were left handed, and 2 were ambidextrous (by parental report and observation). Although socioeconomic status (SES) was not formally assessed, participants were consecutive referrals to a large, regional medical center known for assessment of APD. Thus, based on typical referral patterns, SES was estimated to be evenly distributed among the three primary levels. A total of 22 participants (61%) were given the diagnosis of APD (14 boys, 8 girls). The mean reported Verbal IQ of the APD sample was 98 (standard deviation [*SD*] = 16.5), and 106 (*SD* = 12.5) for the nondiagnosed group.

Table 1. Age, Gender, and Diagnostic Status by Gender (*N* = 36)

Age	Male	Female	APD +
7	2	0	1 M, 0 F
8	5	2	5 M, 2 F
9	3	1	3 M, 1 F
10	4	1	0 M, 1 F
11	9	2	4 M, 1 F
12	2	0	1 M, 0 F
13	1	1	0 M, 1 F
14	0	3	0 M, 2 F
Total	26	10	14 M, 8 F

Notes: APD +: positive APD diagnosis; M: male; F: female

Children who completed assessment for APD in the Audiology Department were recruited for this study. The audiological evaluation required children have completed recent intellectual and language testing; the intellectual test scores were made available for this study. Verbal IQ scores less than 70 were exclusion criteria. At the neuropsychological testing session, parents were asked to indicate what diagnoses or school identifications the child had prior to coming to the evaluation. The distribution of reported clinical comorbid conditions was not significantly different between children with APD and those without. In this sample, the rate of comorbid disorders was as follows: Anxiety = 6 APD, 3 non-APD; ADHD = 7 APD, 3 non-APD; Learning Disabled, LD—Speech = 9 APD, 4 non-APD; LD Reading = 13 APD, 6 non-APD; LD = Writing = 11 APD, 5 non-APD; Developmental Disabilities = 4 APD, 1 non-APD. Many children had more than one diagnosis, thus there are more diagnoses than participants. The APD group had a total of 22 reported comorbid conditions, whereas the non-APD sample had 14 ($X^2 = 4.2$, $p = .84$). Of those children with more than one comorbid condition, 16 had APD (44%) and only 8 did not have APD (22%). This level of comorbidity is consistent with previous research (Riccio et al., 2005).

Demographic variables by APD diagnosis were not significant for Verbal IQ (VIQ) [$F(1, 34) = 2.496$, $p = .123$, $\eta^2 = .068$] or age [$F(1, 34) = 2.30$, $p = .168$, $\eta^2 = .064$]. Of the children with APD, 64% were male; however, the result chi-square analysis of gender by APD diagnosis was nonsignificant ($X^2 = 2.079$, $p = .149$).

There was no effect of age by APD diagnosis in the sample [$F(1, 34) = 2.31$, $p = .138$]. Although the mean VIQ for the non-APD children was 8 points higher than it was for children with positive APD diagnoses (no-diagnosis mean = 106, APD diagnosis mean = 98), analysis of variance of VIQ by APD diagnosis found no significant differences [$F(1, 34) = 569.1$, $p = .123$].

Procedure

The initial clinical audiological testing was completed in the Department of Audiology by a doctoral-level audiologist with expertise in APD. The clinical protocol for assessment of APD does not require a fixed battery of specific tests. Therefore, some tests were administered infrequently, whereas some were more universally administered. By clinical protocol, diagnosis was established when two or more tests fell more than 2 *SD*s below the established mean for the age group. Patients referred to the Department of Audiology for assessment of auditory processing were contacted and asked to complete a neuropsychological battery of less than 120 minutes in length. Administration of the neuropsychological battery was in the pediatric neuropsychology laboratory at Dartmouth Hitchcock Medical Center by a trained clinician under the supervision of a board-eligible neuropsychologist (AM). This included the (then) new version of the WISC-IV Digit Span and Letter Span subtests. Human-subjects approval was obtained. Families received a $25 incentive to participate, and they were also provided results of the psychometric testing.

Measures

Cognitive Tests

The WISC-IV (Wechsler et al., 2004) subtests included Digit Span forward (DSF), Digit Span backward (DSB), Letter Span rhyming (LSR), and Letter Span nonrhyming (LSNR). Reliability and validity data are well documented.

Audiometric Tests

The auditory testing used a flexible battery of tests, determined by the evaluator, based on his perception of the clinical needs. For this reason, different tests were administered to different subjects. As noted, the criterion for identification was that the results of two tests within the battery needed to be greater than 2 *SD*s below the mean to consider the patient as positive for APD. These tests are used frequently by audiologists but have limited psychometric data available (e.g., reliability, validity).

The Dichotic Digits test (Musiek, 1983) is a dichotic listening task with two numbers presented in each ear simultaneously. The Dichotic Digits test can be both a dichotic speech and binaural integration task. This test involves some assessment of temporal sequencing and can be used with adults. Test-retest reliability was reported to be .77 (Musiek & Pinheiro, 1991); however, only four participants were assessed at ranges of 2 weeks to 1 year.

The Frequency Pattern Sequence (FPS) test (Musiek & Pinheiro, 1985) is a temporal patterning test that presents sequences of three tone bursts that are presented to one or both ears. In each of the sequences, two tone bursts are of the same frequency, whereas the third tone is of a different frequency. The child hears patterns, such as high-high-low or low-high-low, and is asked to either hum or describe the patterns heard. Reliability of this test was not available.

In the Low Pass Filtered Speech test (Willeford, 1977), consonant-vowel-consonant (CVC) monosyllabic words are passed through a filter that rejects high-pitched tones. In a general sense, this test reflects an auditory closure process in that the subject must use whatever acoustic and language cues are available to determine the word presented. Reliability data were not available.

All 36 participants received the Dichotic Digits test, 33 received the Low Pass Filtered Speech test, and 25 received the Frequency Patterns test. Each test provides a score (percent correct) for right and left ears. Each ear score was used as a variable.

Analyses

Data from test batteries were entered into SPSS (Chicago, IL). Demographic variables for age and gender were also analyzed for systematic variance. Cognitive test scores used were standardized scores reported in the manuals. Logistic regression was calculated for the four WISC-IV variables, using a forward conditional entry. As no standardized data were available for the Low Pass Filtered Speech test, those scores were age-adjusted in the correlation matrix using the standardized residual of the regression for age on the raw score.

Study 1 Results

In the logistic regression, DSF accounted for the significant amount of variance, with no other variable adding significantly to the equation (DSF $ß = -.19$, $p = .006$). Sensitivity was .90 with only 2 of 20 false negatives. Specificity was .67, with 4 of the 12 cases being incorrectly identified as having APD. Because the number was reduced by missing Letter Span data, the regression was recalculated with only DSF. The result with the increased number was again significant ($ß = -.526$, $p = .004$), with slightly reduced sensitivity (.83) and improved specificity (.86).

It was predicted that results of the auditory (audiometric) tests would be strongly related to those of the cognitive tests and thus demonstrate convergent validity. Although the original audiometric battery used several different tests, only three tests were administered to enough participants consistently to allow for analysis (Dichotic Digits: $N = 36$, Low Pass Filtered Speech: $N = 33$, Frequency Patterns, $N = 25$). DSF and DSB correlated significantly with Dichotic Digits and Frequency Patterns, whereas LSNR correlated with left-ear Dichotic Digits and both Frequency Patterns scores (see table 2). Although Frequency Patterns is reported for both ears, it is not a dichotic task, and right and left ear scores are virtually identical, as reflected in the high correlation between them. LSR correlated with left-ear Dichotic Digits only. Similarly, Frequency Patterns correlated only with Dichotic Digits (left ear, not right ear). Thus, the Dichotic Digits left-ear score was related to all four cognitive tests, whereas Frequency Patterns was related to three of the four cognitive tests. Low Pass Filtered Speech showed no relationships to any variables. The full correlation matrix appears in table 2.

Table 2. Correlations (*r*), *p* Values, and Number (*N*) for WISC-IV and APD Tests

		DSF	DSB	LSNR	LSR	DD-R	DD-L	FrqPat-R	FrqPat-L	LPFS-R	LPFS-L
DSF	*r*	1									
	p										
	N	36									
DSB	*r*	**0.51**	1								
	p	**.00**									
	N	36	36								
LSNR	*r*	**0.60**	**0.45**	1							
	p	**.00**	**.01**								
	N	32	32	32							
LSR	*r*	0.31	0.34	0.13	1						
	p	.08	.06	.49							
	N	32	32	32	32						
DD-R	*r*	**0.38**	**0.40**	0.29	0.07	1					
	p	**.02**	**.01**	.11	.71						
	N	36	36	32	32	36					
DD-L	*r*	**0.68**	**0.45**	**0.62**	**0.40**	**0.37**	1				
	p	**.00**	**.01**	**.00**	**.02**	**.03**					
	N	36	36	32	32	36	36				
FrqPat-R	*r*	**0.43**	**0.58**	**0.55**	−0.14	0.38	**0.50**	1			
	p	**.03**	**.00**	**.01**	.55	.07	**.01**				
	N	24	24	22	22	24	24	24			
FrqPat-L	*r*	**0.42**	**0.58**	**0.55**	−0.06	0.37	**0.53**	**0.98**	1		
	p	**.04**	**.00**	**.01**	.80	.07	**.01**	**.00**			
	N	24	24	22	22	24	24	24	24		
LPFS-R	*r*	0.01	−0.28	−0.11	0.02	0.15	−0.10	0.11	0.11	1	
	p	.96	.12	.55	.93	.40	.60	.64	.64		
	N	33	33	29	29	33	33	21	21	33	
LPFS-L	*r*	0.24	0.08	0.06	0.01	0.14	0.02	0.10	0.06	**0.63**	1
	p	.17	.66	.77	.97	.43	.90	.66	.78	**.00**	
	N	33	33	29	29	33	33	21	21	33	33

Notes: Numbers in bold are statistically significant. DD-R/L = Dichotic Digits right ear/left ear; FrqPat-R/L = Frequency Patterns right ear/left ear; LPFS-R/L = Low Pass Filtered Speech right ear/left ear

Study 2 Method

Procedure

The data from the 22 participants diagnosed with APD in Study 1 was used in these analyses. Those cases were matched with cases from the WISC-IV standardization sample. Matching was completed first on age, then gender, and then VIQ score. Note that, in the WISC-IV normative database, VIQ scores were calculated in the same manner as in the WISC-III, thus allowing the comparison. IQ scores for matched pairs were within 5 points of each other and within the same 10-point band. Where multiple matches were possible, the specific match was randomly chosen.

Participants

The 22 cases who received positive APD diagnoses were matched with 22 cases from the WISC-IV Integrated normative sample. The mean age of the whole sample (N = 44) was 9.86 years (SD = 2.05); there were 16 girls and 28 boys. The mean VIQ score for the APD sample was 97.77 (SD = 16.48) and for the WISC-IV sample was 97.73 (SD = 14.71).

Measures

WISC-IV DSF, DSB, Letter Span rhyming (LSR), and Letter Span nonrhyming (LSNR) scaled scores were compared between those with APD diagnoses from the previous analysis and the matched cohort from the WISC-IV normative sample.

Analyses

Means and SD values (test by group) were calculated and analyzed for group differences (table 3). The four variables were entered into logistic regression analysis (forward conditional entry). To identify cut-score for the best predictor from the logistic regression, receiver operating characteristics (ROC) were also calculated. To look at within-subject differences between scores (DSF and DSB, LSNR and LSR), separate t tests were calculated with the four tests in the clinical sample only. The normative control sample was not analyzed as score differences were not expected.

Table 3. Means, SD Values, Significance Testing, and Effect Sizes for APD and Matched Control Groups

	APD	Control		
Test	Mean (SD)	Mean (SD)	p	μ
DSF (N = 22)	6.23 (2.16)	9.86 (3.48)	< .001	0.29
DSB (N = 22)	7.82 (2.79)	10.32 (3.26)	.009	0.15
LSNR (N = 20)	7.50 (2.19)	10.14 (2.88)	.002	0.22
LSR (N = 20)	7.8 (2.67)	9.45 (2.84)	.059	0.09

Study 2 Results

Three of the four tests' scores were significantly lower in the APD group than in the normative group (table 3). LSR was lower in the APD group.

In the diagnostic utility statistics, logistic regression found that DSF was the most powerful predictor ($ß$ = −0.553, p = .002),with the other variables providing little unique variance. Sensitivity of DSF was .82, specificity was .80. When DSF was entered into the regression by itself, sensitivity was .81, and specificity was .78 ($ß$ = −.456, p = .002). Table 4 presents the final classification table.

Table 4. Classification Table for Digit Span Forward in the Matched Sample

	Predicted		
Observed	Normal	APD	Totals
Normal	18	4	22
APD	5	17	22
Totals	23	21	44

ROC analysis was significant, with 81% area under the curve accounted for by DSF. That classification table identified a cut-score of < 7.5 as providing the best combination of sensitivity (.77) and specificity (.82).

To confirm these results, another series of logistic regressions was computed to determine if any combination of these four variables was a better predictor of group membership. The 15 possible combinations of variables were each entered into separate regression equations (entry method). The two cases without Letter Span data and their matched pairs were removed, reducing the sample to $N = 40$. A slightly better classification rate was obtained with LSR, with one additional APD case correctly identified (sensitivity = .80, specificity = .85). The LSR score, however, was not significant in the equation ($ß = .154$, $p = .425$).

To understand how these four psychometric tests related to each other, paired sample *t* tests of the six combinations of psychometric tests were calculated. (It was assumed that differences within the normative database would be negligible, so only the APD group was analyzed.) Significant differences for the three scores paired with DSF were found, with lower scores for DSF than for the comparison. Thus, DSF is not only different between subjects, but is significantly lower than the other short-term memory scores when evaluated within subjects (table 5).

Table 5. Within-Subjects Comparisons of Subtests for Clinical Sample

	t	*df*	*p*
DSF			
DSB	−2.918	21	.008
LSNR	−3.007	19	.007
LSR	−4.069	19	.001
DSB			
LSNR	0.248	19	.806
LSR	−0.213	19	.834
LSNR			
LSR	−0.446	19	.661

Discussion

The analyses presented sought to document potential roles of traditional psychometric tests for understanding APDs. Specifically, tests of short term and working memory were analyzed for diagnostic utility and for convergent validity. A sample of children who were referred for APD evaluations were compared on psychometric scores by diagnosis (APD,

not APD). The participants with APD diagnoses were then compared with a matched sample of children from the WISC-IV standardization sample. Good sensitivity and specificity for DSF was demonstrated against both sets on non-APD participants. Analysis of the correlations between short-term memory tests and the audiometric tests used for diagnosing APD showed high correlations between Digit Span tests (forward and backward) and four of the six audiometric test scores. LSNR was correlated with three of the six audiometric scores.

The results demonstrating that DSF scores differentiated children with APD from those without APD were consistent with previous findings from our lab (Maerlender, 2005; Maerlender et al., 2004). Interpretation of the diagnostic utility is limited, however, by the low incidence or base rate of this disorder (2%–3%). Positive predictive power and negative predictive power were not reported due to this fact, and it should be noted that the ROC analysis might over-identify cases in the real world. Given the similar findings in both studies reported here, and the previous work, it appears that DSF and tests of auditory short-term memory may well serve as indicators of potential APD.

Span memory performance has a long tradition in experimental and clinical psychological research. Although both forward and backward span tasks are typically administered in an assessment battery, they clearly assess different cognitive functions. Physiological (Gerton, Brown, Myer-Lindenberg, et al., 2004; Larrabee & Kane, 1986), psychometric (Reynolds, 1997), and behavioral data (Hale, Hoeppner, & Fiorello, 2002) have demonstrated more executive or frontal involvement for the backward span task than for the forward task. The forward task, however, does appear to activate frontal structures somewhat, particularly Broca's area (ostensibly for articulatory rehearsal), while also activating inferior parietal structures (supramarginal gyrus; Gerton et al., 2004).

Neurologically, the left temperoparietal area is critically involved in the early stages of language processing, particularly phoneme encoding, storage, and assembly. Gerton and colleagues showed that the recruitment of left inferior parietal lobule (IPL, supramarginal gyrus) is consistent with neuroimaging studies (Awh et al., 1996; Paulesu et al., et al., 1993; Zhou et al., 2006) and lesion studies (Sakurai et al., 1998; Varney & Damasio, 1986) that demonstrate the involvement of this region in short-term phonological storage. Left IPL may therefore be an important component of the phonological loop in Baddeley's model (1992, 1996). Although there is neurological overlap of involvement between posterior and frontal systems, however, these tasks are dissociable from a psychometric point of view (Engle, Tuholski, Laughlin, & Conway, 1999; also see Maerlender et al., 2004).

It is important to note that audiometric tests primarily tap the integrity of cortical nerves (Cochlear, Auditory) and identification of basic stimulus processing up to the level of auditory cortex. Short-term memory involves "higher order" cortical processing, albeit at early stages of analysis (e.g., phoneme identification, collection, and processing). The tests used in these studies must be regarded as tests of higher cortical functioning. Our studies suggest likely "upstream" effects from "lower stream" deficits. That STM seems to be so robust in APD deserves further study.

These data, together with those from previous studies, suggest that auditory short-term memory may be a ubiquitous deficit in children with APD. The value and role of psychometric testing in APD are supported. School psychologists who see this pattern of scores

should consider referral to the speech pathologist for further screening or to an audiologist for a full evaluation. Care should be taken to consider the context of the student's presenting problem, the functional complaints, and other relevant clinical information. Clinically, weak short-term memory can impact many functions required in the school setting. Psychologists should not avoid addressing the obvious functional limitations of weak short-term memory capacity. Students may need instructions in shorter sentences, or instructions written as well as spoken. Students with weak short-term memory may appear to have working memory problems because of limited capacity, not executive processing. Information may not get encoded effectively because so much energy is being used to hold on to fragments of aural speech.

Several limitations of this study need to be noted. Certainly the sample size limits the generalizability of this study. The construct of APD as a diagnostic entity is still open to question, and this study relied on the current state of audiological knowledge. Larger groups of both diagnostic and control groups would provide more robust results. The "flexible battery" approach to the APD testing severely hindered these analyses. A consistent battery is vital to understanding how these audiometric tests perform relative to more traditional psychometric tests. The issue of comorbidity is also important, as the data obtained here provided no validation of clinical diagnoses and relied solely on parent report. Going forward, clinically sound diagnoses of comorbid conditions will better allow for the unique contribution of APD phenomena, if they exist, to stand out. Finally, these studies focused on language functioning and did not compare nonlanguage auditory functioning. In the school setting, however, APD will most likely impact the acquisition and processing of language.

As is true for any exploratory study, the findings raise more questions than provide answers. For instance, do subtypes of APD exist, and, if so, what other cognitive tests might be related? How does psychiatric comorbidity effect test score outcome? What is the relationship between auditory processing and developmental language disorders? Are audiometric tests more specific tools for understanding language disorders, and, importantly, does specific audiological treatment of APD symptoms improve language functioning? Are processes similar for nonlanguage functions? The findings of this project point to the need for further studies.

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