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The Canonical Relationship Between Sensory-Motor Functioning and Cognitive Processing in Children with Attention-Deficit/Hyperactivity Disorder

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Abstract

Children with Attention-Deficit/Hyperactivity Disorder (ADHD) typically exhibits a pattern of behavioral deficits, impairment in academic achievement, and cognitive processing, and presents with sensory-motor deficits. This study examined the relationships between sensory-motor tasks, cognitive processing, and academic achievement for a group of 67 children with ADHD. Strong canonical correlations emerged between sensory-motor functioning and academic achievement (.93) and sensory-motor functioning and cognitive processing (.98). An analysis of the redundancy coefficient showed that sensory-motor skills accounted for 65% of the variance in the achievement variables and 31% of the variance in the cognitive processing variables. The strong relationship between sensory-motor skills and higher order cognitive processes indicates that early assessment of sensory-motor skills may be useful in the identification of subsequent deficits in academic performance. Neuropsychologists should carefully consider the contribution of sensory-motor functioning to the more widely studied and assessed constructs of academic, behavioral, and emotional problems in children with ADHD.

Keywords: ADHD; Alzheimer's disease; Autism/pervasive developmental disorders; Cerebrovascular disease/accident and stroke; Dementia; Developmental and learning disabilities; Epilepsy; Executive functions; Gender effects

Introduction

Sensory-motor skills are good clinical markers of cortical and subcortical integrity. They are effective at determining the presence of impairment and in gauging lateralization (Reitan & Wolfson, 2003). Research from various fields has explored the possibility that specific patterns of sensory-motor deficits may be associated with psychiatric and neurologic conditions typically thought of as primarily cognitive in nature (e.g., Baker, Lane, Angley, & Young, 2007; Ermer & Dunn, 1998; Erlenmeyer-Kimling et al., 2000). Recent research has revealed that cortical and subcortical sensory-motor skills can predict neurologic and psychiatric impairment in the absence of cognitive processing information (Davis, Finch, Trinkle, Dean, & Woodcock, 2007). Although the current diagnostic criteria for Attention-Deficit/Hyperactivity Disorder (ADHD; for a more in-depth discussion about the characteristics of ADHD, see American Psychiatric Association, 2000; Barkley, 1998) tends to omit explicit implication of sensory-motor problems, recent research has indicated a link with deficits in fine motor skills (Martin, Piek, & Hay, 2006; Piek, Pitcher, & Hay, 1999; Pitcher, Piek, & Hay, 2003), gross motor skills (Harvey & Reid, 1997; Piek et al., 1999), balance (Iwanaga, Ozawa, Kawasaki, & Tsuchida, 2006; Piek et al., 1999), and

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motor coordination (Kadesjö & Gillberg, 1998; Karatekin, Markiewicz, & Siegel, 2003; Kroes et al., 2002; Piek et al., 1999). Developmental coordination disorder (DCD), characterized by significant deficits in motor coordination, has been found to be highly comorbid with ADHD (Carte, Nigg, & Hinshaw, 1996; Kadesjö & Gillberg, 1998, 1999; Mariani & Barkley, 1997; Piek et al., 1999; Szatmari, Offord, & Boyle, 1989; Tannock, 1998). The proposed overlap in symptomology between ADHD and DCD, as well as other findings, has lead to conflicting evidence on whether motor deficits observed in children with ADHD are predominantly due to attention and distractibility (e.g., American Psychiatric Association, 2000; Kadesjö & Gillberg, 1998; Piek et al., 1999) or comorbid motor deficits (Karatekin et al., 2003; Licari & Larkin, 2008; Piek & Dyck, 2004; Piek et al., 2004; Pitcher, Piek, & Hay, 2003).

Current models support the notion that deficits associated with ADHD may be related to impaired executive functioning (Barkley et al., 1990; Sergeant, 2000). The proposed relationship between the executive function deficits often found in ADHD and motor coordination has been supported in several studies (e.g., Livesey, Keen, Rouse, & White, 2006; Oosterlaan, Logan, & Sergeant, 1998; Pennington & Ozonoff, 1996; Jonsdottir, Bouma, Sergeant & Scherder, 2006). Problems with response inhibition are increasingly viewed as central to executive functioning difficulties in ADHD (Barkley, 1998; Pennington & Ozonoff, 1996; Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005). The inability to inhibit dominant or proponent responses leads to difficulties in maintaining adequate performance on ongoing tasks, including measures of sensory and motor functioning. Neuroimaging indicates that the ability to interrupt an about-to-be-executed response requires not only activation of regions of the basal ganglia and caudate (Casey, Tottenham, & Fossella, 2001), but also that of the right inferior frontal cortex (Aron, Fletcher, Bullmore, Sahakian, & Robbins, 2003). These regions of the brain have previously been implicated as areas of possible dysfunction in ADHD, which lend further credence to the relationship between ADHD and difficulties with response inhibition. Additionally, research has revealed that the right hemisphere, dominant for the processing of somatosensory information (Coghill, Gilron, & Iadarola, 2001), may be primarily responsible for some of the behavioral deficits expressed by children with ADHD (e.g., Castellanos et al., 1996; Mostofsky, Cooper, Kates, Denckla, & Kaufman, 2002). This anatomical correlation provides some support for the hypothesized connection between sensory skills and the dysfunction experienced by children with ADHD. However, correlations between anatomy and somatosensory processing must be made with caution, since the right hemisphere is responsible for a wide range of functions, many of which are not involved with sensory processing (Nigg, 2006).

Executive functioning is considered critical in the acquisition and efficient employment of academic skills (Murphy, 2002; Murphy, Barkley, & Bush, 2002). Deficits in working memory and inhibition, cognitive process thought to be related to ADHD (e.g., Nigg, 2006), have been implicated in severe math (Swanson & Beebe-Frankenberger, 2004) and reading disabilities (Willcutt et al., 2001). Therefore, it is of little surprise that children with ADHD have been found to have difficulties in achievement measures of reading and math (Faraone et al., 1993; Fletcher, 2005; Marshall, Hynd, Handwerk, & Hall, 1997). In addition, behavioral problems associated with ADHD may lead to poor achievement in school (Hinshaw, 1992; Marshall et al., 1997; Sealander, Eigenberger, Schwiebert, Wycoff, & Ross, 1997; Volpe et al., 2006), further predisposing children with ADHD to academic problems.

It has been proposed that the hallmark symptoms of ADHD (inattention, impulsivity, and hyperactivity) may be due to deficits in the prefrontal cortex (Arnsten & Li, 2005; Nigg, 2006; Rubia et al., 1999). This area has also been shown to have connections to areas of the brain involved in motor and sensory functions (e.g., Rubia et al., 1999; Slachevsky et al., 2003). Therefore, a link between ADHD and sensory-motor deficits is intuitively compelling; however, caution must be exercised as the prefrontal cortex is also involved with multiple functions. Although some studies indicate little evidence to link sensory difficulties with ADHD (Karatekin et al., 2003; Parush, Sohmer, Steinberg, & Kaitz, 1997; Miyahara, Piek, & Barrett, 2006; Piek & Dyck, 2004; Yochman, Ornoy, & Parush, 2006), others provide evidence for diffuse sensory deficits (e.g., Parush et al., 1997; Ermer & Dunn, 1998). For example, Parush et al. (1997) evaluated forty-nine 7- to 11-year-old children with ADHD for somatosensory problems using the Sensory Integration and Praxis Test (SIPT; Ayers, 1989). The results indicated that children with ADHD demonstrated intake tactile discrimination in the presence of diffuse sensory deficits in finger identification, graphesthesia, localization of tactile stimuli, kinesthesia, and manual form perception with and without visual feedback.

Other studies have attempted to identify which sensory patterns can differentiate children with and without ADHD. Ermer and Dunn (1998) sought to establish the possibility of differential diagnosis between children with ADHD, children with Autism or PDD, and children without disability based on how the children react to commonly encountered sensory experiences. Parents of 61 children diagnosed with ADHD reported on the frequency of their child's behavior in each of eight sensory and motor categories: auditory, visual, taste/smell, movement, body position, touch, activity level, and emotional/social. Children with ADHD demonstrated a significantly higher frequency of sensory seeking behaviors than did the PDD group or the healthy control group. The Sensory Seeking factor in the The Sensory Profile (Dunn, 1999) measures the child's sensory threshold and the level of stimulation needed for an individual to notice stimuli and respond to it. Children with higher sensory thresholds

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register sensation more slowly than do others (Dunn, 1997, 2001). These children may develop behavioral patterns to compensate for their high threshold for stimuli and engage in higher levels of activity with more risky behaviors (Dunn, 2001). The combination of strong tendencies toward inattention and distractibility and the need for frequent sensory stimulation may contribute to children with ADHD having difficulty in academic and social settings (Zeanah, 2000).

In addition to cognitive, academic, and sensory difficulties, children with ADHD have been found to have problems in motor ability, including gross and fine motor coordination and motor timing (Banaschewski, Besmens, Zieger & Rothenberger, 2001; Blondis, Snow & Accardo, 1990; Harvey & Reid, 2003; Kalff et al., 2002; Kroes et al., 2002; Mariani & Barkley, 1997; Piek et al., 2004; Piek & Dyck, 2004; Pineda, Ardila & Rosselli, 1999; Rubia, Noorloos, Smith, Gunning, & Sergeant, 2003). These findings are supported in a review of 49 studies measuring various aspects of motor performance (Harvey & Reid, 2003). They noted that while some of the evidence is conflicting, literature in the area strongly suggests that children with ADHD demonstrate definite patterns of motor skills dysfunction when compared with age-matched peers. They propose that these deficits exist in ADHD independent of overactivity.

Evidence of motor dysfunction has also been found in neuroimaging research. In a study using functional magnetic resonance imaging by Rubia and colleagues (1999), adolescent males with ADHD showed more dysfunction in the prefrontal region of the brain during motor response inhibition and motor timing. In the control groups, the area around the right mesial frontal gyrus was activated across tasks, with different parts of the anterior cingulate being activated during both the delay task and the stop task. In contrast, the hyperactive adolescents showed less brain activity in the right hemisphere mesial frontal cortex during both tasks, with diminished activity in the right inferior prefrontal cortex and left caudate nucleus during the stop task. Rubia and colleagues (1999) contend that the under-activation of these areas of the brain implicated in motor attention may be directly related to the specific deficits in higher executive functions associated with ADHD.

Despite the fact that the literature regarding ADHD is varied and often conflicting, several on cognitive, achievement, and sensory-motor functioning are clear. Overall, children with ADHD tend to have more difficulties with a variety of higher order cognitive functions, such as cognitive and behavior control, working memory, and goal-directed problem solving (Barkley, 1998; Murphy, Barkley, & Bush, 2001; Pennington & Ozonoff, 1996). Children diagnosed with ADHD tend to have more difficulty in school and struggle in social settings (American Psychiatric Association, 2000; DuPaul & Stoner, 1994; Ermer & Dunn, 1998). They exhibit fine and gross motor dysfunction, and may have poor visual-motor abilities (Hurks et al., 2005; Kalff et al., 2003, Harvey & Reid, 2003). Sensory profiles demonstrate a differential pattern of sensory processing and behavioral responses in children with ADHD, characterized by inattention, distractibility, and a high threshold for sensation (Ermer & Dunn, 1998). Despite these findings, the relationship between sensory-motor deficits and higher order cognitive processes remains unclear.

The purpose of this study was to discover the canonical correlation between sensory motor skills as measured by the *Dean-Woodcock Sensory Motor Battery* (DWSMB; Dean & Woodcock, 2003), cognitive functioning, and academic achievement in a group of children with ADHD. Although research suggests that children with ADHD are at risk for problems with cognitive processing, academic achievement, and sensory-motor skills, this study focused on exploring the quantitative strength of the relationship between these variables. The authors hypothesized that a strong relationship would emerge between these variables, especially in the connection between motor functioning and higher-order processing, in children with ADHD.

Methodology

Subjects

Participants were 67 (51 males and 16 females) children meeting the diagnostic criteria for ADHD. In general, the participants were consecutive outpatients referred to a large mid-west neurology practice who were diagnosed as having ADHD (having meet DSM-IV criteria) by both board certified neurologist and neuropsychologist independently. The participants ranged in age from 7 to 16 years (mean age = 12.03 years, standard deviation = 2.61 years). The ethnicity of the sample was: Caucasian (94.0%), African-American (3.0%), and Other (3.0%). The majority of the participants were right-handed (85.0%), 7.5% were left-handed, and the remainder (7.5%) were ambidextrous or mixed. The participants' information was selected from an archival review of data. Forty-nine of the participants had comorbid diagnoses. These included anxiety, depression, learning disabilities, and Oppositional Defiant Disorder, all common comorbid conditions with ADHD. However, none of the patients had traumatic brain injuries, seizure disorders, or an encephalopathy condition as a diagnosis.

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Instrumentation

The DWSMB consists of 8 sensory tests which measure visual, auditory, and tactile perception and discrimination, and 10 cortical and subcortical motor subtests. Although many of the subtests on the DWSMB are adaptations of traditional neurologic and neuropsychologic measures, the DWSMB has a normative sample of over 1,000 individuals ranging in age from 4 to plus 90 years, and contains standardized administration procedures. Davis, Finch, Dean, and Woodcock (2006) used exploratory factor analysis to determine that the DWSMB has adequate construct validity. Volpe, Davis, and Dean (2006) determined that the DWSMB was able to differentiate between neurologically impaired and healthy individuals at a rate of 92.8% with a sample of 250 healthy and 250 neurologically impaired individuals. Davis and colleagues (2007) used classification and regression tree analysis to determine that the DWSMB was able to predict 84.5% of a healthy group of 950 individuals and 71.4% of a group of 701 individuals with neurologic and psychiatric conditions. The reliability of the tasks of the DWSMB has also been demonstrated to be adequate (Woodward, Ridenour, Dean, & Woodcock, 2002). Overall, the early results of the DWSMB seem to indicate it is a reliable and valid instrument, although as with any new test, more information is needed. Table 1 presents the subtests from the DWSMB with a brief description of what each subtest measures. Since some of the subtests have multiple scores for a task, such as dominant/nondominant hands and lateral and bilateral stimulation, 34 W-scores were entered into the analysis. Participants were also administered 14 cognitive and 5 achievement subtests from the *Woodcock-Johnson Psycho-Educational Battery-Revised* (WJ-R, Woodcock & Johnson, 1989). The WJ-R is a widely used measure that explores several areas of cognitive processing and academic achievement. Multiple studies have determined the WJ-R to be a valid and reliable instrument of cognitive processing and academic achievement. W-scores were calculated for the participant's results of the DWSMB and the WJ-R subtests. W-scores are derived scores that can be used to determine a patient's level of difficulty with a task relative to a normative sample. W-scores have some advantages over traditional derived standard scores, which is why the authors of the DWSMB chose this metric for their test. The greater specificity of W-scores permits consideration of a smaller number of errors that could represent impairment and also provides for improved ipsative analysis. The Rasch-derived W-scale provides a common scale that represents the ability of a person measured by a test and the difficulty of the tasks included in the test. Unlike other methods, the Rasch method allows calibration of items within a test such that the difficulty between items is equal. Each test of the DWSMB was calibrated in such a fashion with age, and consequently, each test uses a W-score. Predictive statements based on the difference between a person's ability and task difficulty along this scale can be made. The difference between an individual's ability on a scale and the difficulty of a task is directly translatable into a set of probabilistic implications about the individual's expected level of success with tasks similar to those on the scale.

Table 1. DWSMB subtest descriptions

Subtest	Ability or symptom assessed
Sensory subtests	
Near-point visual acuity	Bilateral visual acuity and perception
Visual confrontation	Bilateral peripheral visual fields
Naming pictures of objects	Dysnomia, anomia, visual dysgnosia, visual agnosia, confrontational naming
Auditory acuity	Bilateral auditory acuity perception
Palm writing	Graphesthesia, bilateral tactile discrimination
Object identification	Astereognosis, bilateral tactile perceptions
Finger identification	Asomatognosia, bilateral finger agnosia, tactile perception
Simultaneous localization	Asomatognosia, broad bilateral sensory and tactile reception left-right confusion
Motor tests	
Gait and station	Ataxia, coordination, lower extremity gross motor functioning, presence of subcortical lesions, spasticity, balance, gait
Romberg	Cerebellar dysfunction, vestibular dysfunction, subcortical dysfunction
Construction (cross and clock)	Construction dyspraxia, visual motor integration, visuo-spatial awareness
Coordination (finger to nose, hand to thigh)	Bilateral coordinated motor movement at the cerebral and cerebellar levels, myoclonic jerks, upper extremity motor functioning
Mime movements	Ideomotor apraxia, receptive language
Left–right movements	Left-right confusion, perseveration
Finger tapping	Bilateral fine motor speed and control, Manual dexterity, overall functioning of the motor strip and pre-central gyrus
Expressive speech	Dysarthria, dysnomia, peripheral speech mechanisms
Grip strength	Deficits in the contralateral motor strip, overall integrity of the cerebral hemispheres, upper extremity motor strength

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Conversely, derived standard scores have a common mean such as 100 or 10 which makes them difficult to compare to W-scores; however, the mean W-score is usually around 500.

Procedure

Participants were administered the DWSMB and the WJ-R according to the procedures described in the test manuals. The examiners were advanced graduate students who had substantial training in neuropsychologic and psychologic assessment and in the administration and scoring of the DWSMB and WJ-R. The graduate students were supervised by a licensed neuropsychologist.

Data Analysis

Canonical correlation analysis was used to assess the strength and nature of the relationships between sensory-motor skills and cognitive functioning in children with ADHD. Two separate such analyses were conducted between the DWSMB and WJ-R achievement scores and the DWSMB and WJ-R cognitive processing scores. Canonical correlation is a statistical tool designed to estimate correlations between two sets of variables. The linear combinations are created through a combination of weights and the observed variables, where the weight values maximize the correlation between the two linear combinations (Tabachnick & Fidell, 2007). The equations for these linear combinations appear as follows.

$$\begin{aligned} \text{canonical variable } 1 &= a_1 * \mathrm{y}_1 + \mathrm{a}_2 * \mathrm{y}_2 + \cdots + \mathrm{a}_\mathrm{k} * \mathrm{y}_\mathrm{k} \\ \text{canonical variable } 2 &= b_1 * \mathrm{x}_1 + \mathrm{b}_2 * \mathrm{x}_2 + \cdots + \mathrm{b}_\mathrm{p} * \mathrm{x}_\mathrm{p} \end{aligned} \tag{1}$$

where y_1 is variable 1 in Set 1, a_1 weight for variable 1 in Set 1, x_1 variable 1 in Set 2 and b_1 is weight for variable 1 in Set 2.

Once the weights are determined for each variable and the canonical variable is calculated for each subject, the correlation between the two sets is calculated. This value is the canonical correlation. It should be noted that for any two sets of variables, there are p possible canonical variables, where p is the number of variables in the smaller sets. Each of these canonical variables is associated with a unique set of weights, which are determined so that the resulting sets are orthogonal with respect to any other combination of those variables. For example, when examining the canonical relationship between the sensory motor and achievement batteries, there are four canonical correlations that will be calculated, because there are five achievement variables, and achievement is the smaller set in the analysis. Each of the resulting canonical variables for achievement is independent of the other three canonical variables for achievement, as the canonical variables for the sensory motor battery are independent of one another. Furthermore, the pairs of canonical variables can be ordered with respect to their associated canonical correlations, such that the first pair will be associated with the largest correlation, the second pair with the second largest and so on. Finally, each of these correlations can be tested for statistical significance, against the null hypothesis they are 0; that is, there is no relationship between the two linear combinations of variables (Tabachnick & Fidell, 2007).

Given the presence of some missing data, multiple imputation (MI) was used (Schafer & Graham, 2002). This methodology seems to be the most effective approach for dealing with missing data (Schafer, 1997), superseding such common techniques as deletion of cases with missing information. A total of 10 imputed data sets were created, and for each of these canonical correlation was conducted.

Given that canonical correlation can be sensitive to the presence of outliers, the Mahalanobis distance was calculated for each individual in the sample. This value measures the difference between an individual data point and the centroid (multivariate center) of the data as a whole. Tabachnick and Fidell (2006) recommend that these values be compared with the χ^2 for $\alpha = 0.001$. None of the subjects were found to be outliers on any of the three sets of variables included in the study, and thus no remedial action was necessary.

Simulation research done in this area has found that when the canonical correlation is sufficiently large (defined as >0.7), a sample of 50 would yield power values of 0.8 or more (Mendoza, Markos, and Gonter, 1978). Several of the canonical correlations that were not statistically significant in our study were >0.7. Thus, given the results of Mendoza and colleagues, a sample of 67 individuals is sufficient for detecting a significant correlation.

Results

The means and standard deviations for the DWSMB, WJ-R Achievement, and WJ-R Cognitive processing variables appear in Table 2. The mean W-score from the standardization sample is provided for each subtest from the mean age of the sample

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Table 2. Means and standard deviations of DWSMB and WJ-R Achievement and cognitive variables and mean W-scores for the standardization sample at age 12 years 3 months

DWSMB	Mean	SD	Mean W-score
Near point visual acuity			
Right eye	446.99	17.71	449
Left eye	445.02	18.75	448
Visual confrontation			
Right eye	484.45	10.64	487
Left eye	486.61	10.61	489
Both eyes	487.39	9.40	490
Naming pictures of objects	412.96	13.98	510
Auditory acuity			
Left ear	485.69	8.33	488
Right ear	481.43	4.24	482
Both ears	490.88	7.00	493
Palm writing			
Dominant hand	494.72	12.38	500
Nondominant hand	494.67	11.79	502
Object identification			
Right hand	488.88	9.06	494
Left hand	495.75	9.95	500
Finger identification			
Right hand	487.88	6.47	491
Left hand	489.06	6.86	491
Simultaneous localization			
Right hand	510.70	1.72	511
Left hand	510.87	1.10	511
Both hands	514.70	1.72	515
Hands and cheeks	485.05	3.91	530
Gait and station	484.99	7.16	487
Romberg	494.55	20.03	505
Cross construction	486.46	15.03	500
Clock construction	487.60	13.23	497
Coordination finger to nose			
Left	489.13	13.24	494
Right	491.85	13.04	496
Coordination hand to thigh			
Right	478.43	14.87	483
Left	477.03	15.61	481
Mime movements	498.81	6.01	500
Left–right movements	496.87	11.12	500
Finger tapping			
Dominant hand	501.37	4.83	501
Nondominant hand	501.31	6.44	500
Expressive speech	491.69	10.09	498
Grip strength			
Dominant hand	522.52	10.93	522
Nondominant hand	520.67	11.80	520
WJ-R cognitive			
Memory for names	499.67	11.86	502
Memory for sentences	500.40	18.53	505
Visual matching	499.90	17.24	512
Incomplete words	497.05	8.49	503
Visual closure	504.06	10.00	504
Picture vocabulary	507.54	15.58	511
Analysis–synthesis	502.34	16.54	507
Visual–auditory learning	501.96	9.24	500
Memory for words	495.97	19.98	505
Cross out	504.32	12.64	508
Sound blending	499.74	14.64	505
Picture recognition	505.29	10.41	505

(*continued on next page*)

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Table 2. Continued

DWSMB	Mean	SD	Mean W-score
Oral vocabulary	507.99	19.94	510
Concept formation	499.82	22.93	509
WJ-R achievement			
Letter–word identification	504.40	27.17	512
Passage comprehension	504.25	22.35	508
Calculation	502.70	27.11	518
Applied problems	503.80	18.34	511
Dictation	492.48	19.93	510

(12.3 years). Although this provides an estimate of where impairment existed, it is important to note that these are not the average of the scores from the standardization sample for each participant.

Canonical Correlation Between Sensory-Motor and Achievement

One canonical correlation (0.93) relating the DWSMB and WJ-R Achievement scores was found to be statistically significant ($p = 0.0002$). The first canonical variable represents a strong relationship between sensory-motor skills and academic achievement in this sample of children with ADHD ($Rc^2 = .86$). In order to gain an understanding of the nature of how these two sets of variables were related, structure coefficients linking each observed measure with its canonical variable were examined. On the basis of guidelines for interpretation found in the literature (e.g., Tabachnick & Fidell, 2001), structure coefficients >0.3 are considered evidence of an "important" relationship between the observed and canonical variables. These results appear in Tables 3 and 4.

The first canonical variables for each set were largely a reflection of general achievement and complex motor tasks of the DWSMB, respectively. Thirteen subtests from the DWSMB had structure coefficients above .30, 10 of which were complex motor tasks. The remaining 3 were complex sensory tasks (finger identification and object identification). It is noteworthy that no subcortical motor or simple sensory tasks contributed to the canonical variable with achievement. All five WJ-R Achievement variables substantially contributed to the canonical variable. Passage comprehension had the highest structure coefficient (.99), which may reflect the multidimensional nature of this achievement task.

In order to gain a greater understanding of the predictive value of the DWSMB with respect to the WJ-R achievement measures, a redundancy coefficient for the latter was calculated. This value can be interpreted as the proportion of variation in the set of achievement variables that is accounted for by the DWSMB canonical variable, which in this case is 0.65. In other words, 65% of the variation in the achievement variables can be explained by the DWSMB canonical variable.

Canonical Correlation Between Sensory-Motor and Cognitive Processing

The second canonical correlation analysis yielded one statistically significant correlation between the sensory motor measures and the measures of cognitive processing, with a value of 0.98 ($Rc^2 = .96$). These canonical variables represented an extremely strong relationship between sensory-motor skills and cognitive processing in children with ADHD. The structure coefficients for the DWSMB variables for this analysis appear in Table 3.

There were 17 structure coefficients above .30 for the canonical variable of the DWSMB. These structure coefficients represented a more diverse group than the DWSMB canonical variable with achievement, and included eight complex motor tasks, seven complex sensory tasks, and two subcortical motor tasks (Gait and Station, Romberg). Similar to the canonical variable with achievement, this canonical variable was devoid of simple sensory task structure coefficients above .30. In regards to the cognitive processing canonical variable, all 14 subtests contributed to the canonical variable. The structure coefficients for the canonical variable associated with cognitive processing appears in Table 4.

As with the achievement variables, a redundancy analysis was conducted for the cognitive processing variables as a function of the first DWSMB canonical variable. The result was 0.31, indicating that 31% of the variation in the set of cognitive processing variables was accounted for by the DWSMB. This value is slightly less than half as large as that for the achievement measure, suggesting that the DWSMB provides more predictive information for that achievement than for cognitive processing.

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Table 3. Structure coefficients for DWSMB measures with WJ-R Achievement and cognitive measures

DWSMB measure	Achievement	Cognitive
Near point visual acuity		
Right eye	−0.05	0.16
Left eye	0.06	0.09
Visual confrontation		
Right eye	0.03	0.02
Left eye	0.11	−0.14
Both eyes	−0.06	−0.05
Naming pictures of objects	0.11	0.09
Auditory acuity		
Left ear	0.11	0.02
Right ear	0.09	0.00
Both ears	0.09	0.04
Palm writing		
Dominant hand	0.42	0.60
Nondominant hand	0.42	0.64
Object identification		
Right hand	0.46	0.49
Left hand	0.22	0.42
Finger identification		
Right hand	0.47	0.35
Left hand	0.44	0.37
Simultaneous localization		
Right hand	−0.19	0.20
Left hand	0.00	0.00
Both hands	0.22	0.18
Hands and cheeks	0.18	0.34
Gait and station	0.22	0.39
Romberg	0.23	0.42
Cross construction	0.39	0.61
Clock construction	0.45	0.38
Coordination finger to nose		
Left	−0.06	0.06
Right	0.08	0.16
Coordination hand to thigh		
Right	0.29	0.37
Left	0.34	0.19
Mime movements	0.18	0.18
Left right movements	0.17	0.07
Finger tapping		
Dominant	0.47	0.35
Nondominant	0.35	0.46
Expressive speech	0.34	0.66
Grip strength		
Dominant	0.43	0.52
Nondominant	0.45	0.53

Discussion

This study examined the relationship between sensory-motor skills and the higher order cognitive processes as measured by academic ability and cognitive processing in children with ADHD. Neuropsychologists typically assess cognitive processing and achievement in children referred for ADHD, although broad-based standardized and norm-referenced sensory-motor assessment is much less common. This represents a significant oversight because even a single error on a sensory or motor task may be pathognomic of dysfunction and predict a profound impact on a child's ability to function academically and cognitively. Because children with ADHD are already at risk for academic, social, and emotional problems due to their behavior problems and cognitive processing weaknesses, associated sensory-motor deficits represent another domain in which assessment for intervention should take place. It has been well documented that many children with ADHD suffer from sensory-motor deficits; this study was unique in that it revealed a strong canonical correlation between sensory-motor skills and

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Table 4. Structure coefficients for WJ-R Achievement and cognitive measures with DWSMB measures

WJ-R Achievement measure	Canonical 1
Letter–word identification	0.78
Passage comprehension	0.99
Calculation	0.60
Applied problems	0.66
Dictation	0.75
WJ-R cognitive measure	Canonical 1
Memory for names	0.32
Memory for sentences	0.80
Visual matching	0.47
Incomplete words	0.40
Visual closure	0.58
Picture vocabulary	0.77
Analysis–synthesis	0.50
Visual–auditory learning	0.44
Memory for words	0.45
Cross out	0.72
Sound blending	0.43
Picture recognition	0.53
Oral vocabulary	0.71
Concept formation	0.61

both cognitive processing and academic achievement. The strength of the relationship suggests a strong functional relationship between the better investigated higher order processing domains and sensory and motor functions.

A canonical correlation of .93 emerged between sensory-motor skills and academic achievement in this sample of children with ADHD, and the canonical variable accounted for 86% of the shared variance between these two data sets. In order to gain a greater understanding of the predictive value of the DWSMB with respect to the WJ-R achievement measures, a redundancy coefficient for the latter was calculated. This value can be interpreted as the proportion of variation in the set of achievement variables that is accounted for by the DWSMB canonical variable, which in this case is 0.65. In other words, 65% of the variation in the achievement variables can be explained by the DWSMB canonical variable.

In general, motor tasks had higher structure coefficients than did sensory tasks, which was expected based upon the preponderance of literature which links motor deficits to ADHD. There are two broad areas of explanation for this relationship between motor and academic functioning. The first is that children with ADHD have areas of neurologic impairment which are associated with motor skills. For example, recent research is exploring the link between ADHD and the basal ganglia and dopaminergic system, which are associated with motor planning and motor memory (e.g., Mehler-Wex, Riederer, & Gerlach, 2006). An alternative explanation is that motor problems can substantially contribute to the lack of academic knowledge exhibited by children with ADHD, as the ability to learn new information and express acquired information is affected by motor skills (i.e., turning book pages, writing, using manipulatives to reinforce verbal learning). Interestingly, basic sensory registers such as visual acuity, auditory acuity, and tactile recognition demonstrated low structure coefficients for the canonical variable with achievement. Although children with ADHD may present with hearing or vision problems despite vision and auditory exams in the normal range, these observed deficits are likely a reflection of inattention and impulsivity, and perturbations in these basic sensory registers do not substantially contribute to academic achievement for this group of children.

Complex sensory skills such as graphesthesia (Palm Writing) emerged with high structure coefficients relative to the other DWSMB subtests. These tasks are broad measures of tactile discrimination and may be reflective of clumsiness and problems with dexterity, as well as predictive of neurologic deficit (Dean & Woodcock, 2003; Lezak, 1995). Impairment in tactile discrimination may not be readily observable in school age children with ADHD, but they likely show a profound impact on children's use of motor manipulatives, tasks which are commonly used to reinforce abstract verbal concepts. For example, patients with difficulty in tactile discrimination, perception and/or manual dexterity may not benefit from manipulatives used to reinforce calculation concepts in young children. The high structure coefficients in this study reveal that children with ADHD may present with deficits in these complex sensory tasks, and that these deficits have a strong relationship with academic achievement. Parents, neuropsychologists, and educators should be aware of this relationship, assess for these deficits early in a child's academic career, and implement appropriate interventions and accommodations. Finger identification was another complex sensory task with a relatively high structure coefficient, and finger agnosia has long been linked to reading difficulties (e.g., Satz, Taylor, Friel, and Fletcher, 1978) and Gerstmann's syndrome, which is associated with finger agnosia, left–right confusion, and dyscalculia.

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Bilateral measures of grip strength and dominant hand finger tapping also emerged with high structure coefficients for the relationship between sensory-motor skills and academic achievement. Grip strength is a measure of the integrity of the contralateral motor strip, and grip strength deficits have been associated with white matter hyperintensities and neurologic impairment (e.g., Haaland, Temkin, Randahl, & Dikmen, 1994; Sachdev, Wen, Christensen, & Jorm, 2006). Finger tapping is a task which is sensitive to fine motor problems, neurologic impairment, and lateralized brain impairment (e.g., Reitan & Wolfson, 1996; Russell, Neuringer, & Goldstein, 1970). More recent research has used finger tapping to conclude that children and adolescents with ADHD have trouble with motor timing and rhythm, (Ben-Pazi, Gross-Tsur, Bergman, & Shaley, 2003; Toplak & Tannock, 2005) which may a reflection of the motor impulsivity displayed by children in ADHD. All of the WJ-R academic tasks contributed to the canonical variable with sensory-motor skills. Passage comprehension (.99) had the highest loading, which likely reflects the complex nature of the task. Passage comprehension measured the participant's ability to use semantic and contextual clues to comprehend read material. From a hierarchical perspective, the sensory-motor impairments discussed earlier could easily inhibit the acquisition of the more basic tasks that underlie passage comprehension for children with ADHD.

A canonical correlation of .98 emerged between the sets of sensory-motor skills and cognitive processing data, and accounted for 96% of the shared variance. According to the redundancy coefficient, the DWSMB predicted 31% of the variance in the cognitive processing variables. Although still a large number, it was less than 65% for achievement and is reflected in the disparate pattern of high and low loadings of the cognitive processing variables. A wider range of sensory-motor constructs contributed to the canonical variable compared with the relationship between sensory-motor and achievement; the canonical variable was noteworthy for the absence of highly loading basic sensory register structure coefficients. Obviously, while impairment in simple visual, auditory, or tactile perception will interfere with cognitive processing and academic achievement, it is likely that these children with ADHD did not have the level of impairment in these skills which would be pathognomic of dysfunction. Some of the sensory-motor tasks that had substantial contributions to the relationship with academic ability also had a strong relationship with cognitive processing, including palm writing, finger identification, grip strength, and finger tapping.

One of the sensory-motor tasks with the highest structure coefficient was cross construction. This finding was not unexpected; construction tasks are often used as indicators or screeners of gross neurologic disturbance because they require a multitude of higher order cognitive processes, such as visual-spatial ability, visual-motor integration, motor coordination, planning, and other executive functions (Lezak, Howieson, & Loring, 2004), deficits which are commonly expressed by children with ADHD. Of particular interest, especially when compared with the canonical relationship between sensory-motor and achievement, was the high loadings of subcortical motor constructs in the sensory-motor and cognitive processing canonical variable. In addition to assessing gait and lower extremity motor coordination, Gait and Station and the Romberg tests are measures of cerebellar functioning. The relationship between these measures and cognitive processing may be related to recent research that has explored the contribution of the cerebellum to executive functioning, reading, language, knowledge of sequence, and motor learning (e.g., Brookes & Stirling, 2005; Nicolson, Fawcett, and Dean, 2001; Schmahmann, 2004). Interestingly, some recent research has implicated the cerebellum and the frontal–striatal–cerebellar circuitry in the neurologic etiology of ADHD (e.g., Ashtari et al., 2005; Biederman & Faraone, 2006; Carmona et al., 2005). The cerebellum is believed to involve not only motor control and timing, but also temporal information in cognition and executive functioning (Diamond, 2000). This certainly suggests that children with ADHD will struggle with cerebellar-based motor tasks and is further evidence that motor difficulties are a part of the syndrome of deficits in ADHD.

Although all of the cognitive processing measures had structure coefficients above .30, there were some tasks that contributed more substantially to the canonical variable with sensory-motor skills. Multiple processing domains were well represented, including crystallized intelligence (oral vocabulary, picture vocabulary), short-term memory (memory for sentences, memory for words), visual processing (cross out, visual closure), and fluid intelligence (concept formation, analysis-synthesis). The cognitive construct that contributed the least to the canonical variable was long-term memory (memory for names, visual-auditory learning). It seems the motor impulsivity and inhibition problems that interfere with measures of sensory-motor functioning also affect cognitive skills such as short-term memory and the acquisition of knowledge (crystallized intelligence), and have less effect on long-term storage and retrieval.

Conclusion

The extremely high canonical correlations found between sensory-motor skills and the higher order processes of cognitive processing and academic achievement strongly support the hypothesis that sensory-motor skills are an integral component of the more commonly measured academic and intellectual deficits in children with ADHD. A redundancy coefficient indicated that the DWSMB accounted for 65% of the variance in the achievement variables and 31% of the variance in the set of cognitive processing variables. These numbers were remarkably high given the simple nature of sensory and motor tasks.

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Interestingly, the sensory-motor tasks appear to be better predictors of academic achievement than cognitive processing, although the shared variance was largely equivalent. Although the authors hypothesized that there would be a significant canonical correlation, the high canonical correlations of .93 and .98 underscore the importance of assessing sensory-motor skills in children with ADHD. Furthermore, while it is often not feasible to measure academic deficits until the child has been in school for several years, the DWSMB can be administered to children as young as age 4 and assessment of motor and sensory problems can begin during infancy. With the high canonical correlations and redundancy coefficients that emerged in this study, it is likely that longitudinal assessment would discover that pre-academic assessment of sensory-motor skills would predict later academic problems, which would enable early intervention. This would be especially helpful in children with ADHD, because it is difficult to diagnose children with ADHD younger than 4 or 5 years old due to the variations in the symptomatic behavior, and young children are often not required to demonstrate sustained attention (American Psychiatric Association, 2000).

There were several limitations with this study. This study did not examine the differential relationship between the types of ADHD subtypes; future research should address this, especially as children with ADHD-Primarily Hyperactive-Impulsivity Type may have increased sensory-motor difficulty. This study did not consider the relationship between sensory-motor functioning and specific ADHD symptomology such as the relationship between sensory-motor impairment and deficits in sustained attention, hyperactivity, and impulsivity. It is certainly possible that one of these behavioral problems may be accounting for a significant portion of the variance in the results. Another limitation is the lack of a control group, which suggests that future studies should examine these canonical relationships in other populations, especially in those in whom sensory-motor deficits have not been investigated. The effects of medication on the canonical relation were not accounted for in this study, which is also an area for future investigation. Additional research should investigate the longitudinal and predictive relationship between early-diagnosed sensory-motor deficits and later academic and cognitive processing problems in children with ADHD and other groups. However, it is important to note that not all children with ADHD demonstrate sensory and motor impairment and future empirical research is necessary in order to gauge the efficacy of this approach.

Conflict of Interest

The Dean-Woodcock Sensory Motor Battery was co-authored by Drs. Raymond S. Dean and Richard E. Woodcock who have an interest in this test. It is published by the Riverside Publishing Company.

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