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NEUROPSYCHOLOGIC FUNCTIONING IN CHILDREN WITH AUTISM: FURTHER EVIDENCE FOR DISORDERED COMPLEX INFORMATION-PROCESSING

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Abstract

A wide range of abilities was assessed in 56 high-functioning children with autism and 56 age- and IQ-matched controls. Stepwise discriminant analyses produced good group discrimination for sensory-perceptual, motor, complex language, and complex memory domains but lower agreement for the reasoning domain than previously obtained for adults. Group discrimination did not occur for attention, simple language, simple memory, and visuospatial domains. Findings provide additional support for a complex information-processing model for autism, previously based on adult data, demonstrating a pattern across domains of selective impairments on measures with high demands for integration of information and sparing when demands were low. Children as compared to adults with autism exhibited more prominent sensory-perceptual symptoms and less pronounced reasoning deficits reflecting brain maturation.

Autism is a behaviorally defined syndrome that is based on a triad of signs and symptoms involving social, language-communication-imaginative play, and restricted and repetitive behavior and interests. Over the past two decades, there has been a growing appreciation that other areas or domains of cognitive and neurologic functioning beyond this diagnostic triad are integrally involved in this syndrome (Baron-Cohen, Leslie, & Frith, 1985; Behrmann et al., 2006; Klin, Sparrow, de Bildt, Cicchetti, Cohen, & Volkmar, 1999; Minshew & Goldstein, 2001; Ozonoff et al., 2004). For example, studies of motor abilities have documented a range of problems with motor praxis, motor planning, and imitation that now appear to be an integral element of this syndrome (see review in: Dawson & Watling, 2000; Rogers, Hepburn, Stackhouse, & Wehner, 2003). The view of autism as an amnesic disorder of memory has been refuted (Bowler, Matthews, & Gardiner, 1997; Minshew & Goldstein, 1993; Renner, Klinger, & Klinger, 2000); however, an entire area of research describing the unique features of memory dysfunction in autism has evolved (Bennetto, Pennington, & Rogers, 1996; Minshew & Goldstein, 2001; Mottron, Morasse, & Belleville, 2001; O'Shea, Fein, Cillessen, Klin, & Schultz, 2005). Only a few studies, primarily survey-based, have been published about the sensory issues in autism, but these suggest that disturbances in this area are also elements (Baranek, Foster, & Berkson, 1997; Kientz & Dunn, 1997; Meyer & Minshew, 2005; Rogers, Hepburn, & Wehner, 2003; Rogers & Ozonoff, 2005). Neurologic studies of the postural

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control system (reviewed in: Minshew, Sung, Jones, & Furman, 2004) and the oculomotor system (Goldberg, Lasker, Zee, Garth, Tien, & Landa, 2002; Takarae, Minshew, Luna, & Sweeney, 2004) have demonstrated involvement of neural systems outside those previously thought to be involved on the basis of traditional behavioral observations. Models of autism must expand conceptually to consider broader cognitive, neurologic, and brain involvement in autism.

We previously proposed a model that has the capacity to accommodate impairments in autism beyond the diagnostic triad as well as to incorporate the emerging results of functional magnetic resonance imaging (fMRI) studies. According to this model, autism is a selective impairment in the neural processing of complex information across domains and sensory modalities, with intact or enhanced simple abilities in the same domains as impairments (Minshew & Goldstein, 1998; Minshew, Johnson, & Luna, 2001; Minshew, Sweeney, & Luna, 2002). In this model, complexity is a proxy for the level of demand placed on the brain's processing capacity by tasks or situations. Cognitive or neurologic function is compromised when the processing demands placed on the brain's systems exceed their capacity. A breakdown in processing occurs in autism when the information to be handled is inherently complex or becomes complex due to its amount or time constraints. Therefore, individuals with autism exhibit impaired performance on complex or higher order tasks that are well within the capability of individuals of their general ability level, e.g., they have selective impairments in higher order processing not explained by their general ability level. At the same time, individuals with autism can perform simpler skills in the same domains as impairments as well as or even better than peers. Hence, the concept of complexity has more to do with the effect on the brain's mechanisms during processing of information than it does with the type of information (i.e., social or language) per se.

A major consideration in the choice of the term for this model for autism was the need for it to apply to the motor, sensory, postural control, and oculomotor systems, as well as to cognition and language. We also wanted terminology that was resonant with that of neurophysiological, functional imaging, structural imaging and neuropathological studies. If findings from the investigation of autism are to be integrated across methodologies, a model and terminology is needed that facilitates this integration. Information-processing is a term highly familiar to neuroscientists, neurophysiologists, neurologists, and cognitive psychologists. The term "complex" is not optimal because of its imprecision at capturing the dynamic nature of the impairment, but it is useful for describing the shared characteristic of the impairments across domains. Another possible choice such as "higher order abilities" does not reference the key link to neural processing and the dynamics of the task demands and situations imposed on the brain. Terms such as "integration" or "computation" do not have the meaning that "information-processing" does across the range of scientific disciplines engaged in the study and treatment of autism. Regardless of the term chosen for the model, the emphasis should be on the concepts that it represents.

The complex information-processing model of autism was originally based on a neuropsychological profile study of 33 individually matched pairs of typical controls and high-functioning adolescents and adults with autism (Minshew, Goldstein, & Siegel, 1997). This study was designed to objectively investigate hypotheses as to whether various sensory perceptual, attention, memory, or language impairments were present individually as single primary deficits or whether there was evidence that many symptoms co-occurred in the same individuals with autism. If the latter were true, the key questions from a neurologic perspective were, first, what feature or characteristic did the *impairments* have in common and, second, what feature did the *intact abilities* have in common.

The neuropsychological battery used in the original profile study was designed to include measures of multiple aspects of attention (encoding, sustained attention, selective attention, attention to extrapersonal space, focused attention, and intramodal shifting of attention), elementary sensory and higher cortical sensory perception, elementary motor and motor praxis abilities, multiple aspects of auditory and visual memory, oral and written language functions ranging from phonetics to text comprehension, problem solving, and the rule-learning, concept formation, and flexibility aspects of abstraction. These measures were selected to test the hypothesized core neuropsychological deficits of eight different primacy arguments that had been proposed up to that point, as well as our own hypothesis that autism was a disorder of higher order abilities dependent on neocortical systems (see Minshew et al., 1997 for a complete listing of these). The division of abilities into subdomains was possible when there were a large number of measures available to assess performance within a domain. When these divisions were made, they respected known conventions in the respective disciplines. When the number of measures was small, measures were retained in a single domain and performance within the domain was evaluated to determine if there was a dissociation between simple and complex abilities. In the sensory perceptual domain, elementary or simple sensory perceptual abilities corresponded to the sensory abilities supported by the spinothalamic tracts and posterior columns, whereas higher cortical or complex sensory perception referred to cortically mediated perception. This distinction between elementary and higher cortical sensory perceptual abilities is conventional to behavioral neurology, reflecting the complexity of abilities and their different localizations in the nervous system. A similar distinction was made between elementary motor movements and motor praxis. The specific hypothesis was that if neocortical systems were involved, there would be motor praxis problems. With regard to memory, a distinction was made between memory tasks that involved organizing strategies, either their use or detection, (16 word list on the California Verbal Learning Test or the Rey Osterreith Complex Figure) and memory tasks that relied solely on basic associative processes (paired-associate word learning or three-word short-term memory). In the case of language, a division was made between formal language (decoding of words and nonwords, spelling, vocabulary, fluency) and interpretative language abilities, which are considered emergent skills (language abilities not reducible to the component elements of words and rules of grammar). Within the category of reasoning, conventional neuropsychological distinctions were made, separating attribute identification, rule-learning and concept formation, with flexibility being a reflection of the completeness of concept apprehension. Hence, the selection and characterization of measures as tests of simple (basic or elementary) or complex (higher order) abilities was based on neuropsychological or neurological considerations.

The resulting neuropsychological profile of the adult autism group was characterized by poorer performance than the age-and IQ-matched control group on higher order or skilled motor, interpretive language, memory for complex material (requiring an organizing strategy or the detection of inherent organization in the material to support recall), and concept formation tasks (Minshew et al., 1997). Within the sensory perceptual domain, differing performance was seen between tests of elementary and higher cortical sensory perception tests, though the mixed performance resulted in lack of significance for the domain as a whole. Because the autism group was matched to the control group on Full Scale, Verbal, and Performance IQ and age, the individuals with autism performed poorer in these areas than would be predicted by their age and overall cognitive ability. Their poorer performance could not be attributed simply to task difficulty, as task difficulty is typically a function of IQ and there were no IQ discrepancies between the two groups nor were all the tests on which they did poorly dependent on IQ. For example, motor and sensory tasks have low correlations with IQ. The pattern of performance was also not readily explained by lack of effort, as some tasks that they did poorly on, such as Verbal Absurdities or Picture Absurdities, required minimal effort and others that they did well on, such as the Continuous Performance Test or the cancellation tasks, required considerable effort. Scores on tasks within the simple language domain also discriminated

between the two groups; however, the discrimination occurred because the adults with autism performed *better* than the controls on measures of phonetic analysis and spelling.

The one exception to the pattern of differing performance within domains on simple and complex tasks was that individuals with autism and normal controls did equally well on both simple and complex visuospatial tasks. It should be noted that many aspects of visuospatial processing such as mental rotation, second order motion, and complex constructional tasks were not assessed. Importantly, the traditional complex visuospatial stimulus in neuropsychologic assessment is face recognition and this was not studied until later. Many studies have since reported impairments of this ability in autism (de Gelder, Vroomen, & van der Heide, 1991; Gepner, de Gelder, & de Schonen, 1996; Joseph & Tanaka, 2003; Klin et al., 1999; McPartland, Dawson, Webb, Panagiotides, & Carver, 2004; Schultz, et al., 2000). In addition, other complex visuospatial tasks have been reported to be impaired in individuals with autism (Bertone, Mottron, Jelenic, & Faubert, 2003, 2005; Shah & Frith, 1983; Spencer, O'Brien, Riggs, Braddick, Atkinson, & Wattam-Bell, 2000).

The results of the neuropsychologic profile study with adults (Minshew et al. 1997) provided substantive evidence that autism is not the result of a single primary deficit; rather, it has a simultaneous impact on many domains. The common denominator of the impairments in autism across domains and modalities appeared to be the high processing demands; the common denominator of the intact abilities appeared to be involvement of low-level cognitive or neurologic processes. Symptoms were most prominent in those domains that placed the highest demands on higher order processing and integration of information—the social, communication, and reasoning areas. However, signs and symptoms were also present on higher order tasks in other domains—the sensory, motor, and memory domains—and these should be considered integral parts of the disorder of autism.

Because autism is a developmental disorder, any proposed model must explain not only the manifestation of the disorder in the adult population but also what occurs during the developmental process. It was not known whether the neuropsychological profile described by Minshew et al. (1997) in adults with autism is characteristic of autism throughout development or whether it is the result of a developmental process.

Numerous research studies in children with autism have focused on a single cognitive domain that has been proposed as the primary, or core, deficit in autism. Such views are based on the hypothesis that very early biological damage in a module of the developing brain causes a disruption in the neurodevelopmental process (Leslie, 1991). According to this temporal primacy hypothesis, a single deficit appears during childhood before all other deficits and is instrumental in generating the additional deficits that emerge as the child matures (Bruinsma, Koegel, & Koegel, 2004; Zwaigenbaum, Bryson, Rogers, Roberts, Brian, & Szatmari, 2005). For example, an early lack of motivation to socialize in children with autism could hypothetically lead to deficits in social orienting, joint attention, emotion perception, affective sharing, and imitation (Dawson et al., 2004)[1]. Earlier primary deficit models included sensory imperception (Ornitz, 1983), inattention to extrapersonal space (Dawson & Lewy, 1989), difficulty with shifting attention (Courchesne et al., 1994), and memory dysfunction (Bachevalier, 1991, 1994; Bauman & Kemper, 1994; Boucher, 1981). These deficits were hypothesized to compromise the capacity to develop language, memory, conceptual reasoning, and other related higher order skills.

[1]These gaze abnormalities are sometimes assumed to be abnormalities in elementary attention. However, they are complex behavior and likely to represent a composite of functions. In neurology, the social use of gaze is a right frontal hemisphere function and it is likely that these early gaze abnormalities in autism will be understood as the result of interactions between neural systems.

Other models of the neurobehavioral basis of autism have proposed primary deficits in cognitive processes or modules that are associated with a particular cortical region or regions. This approach assumes that autism is the result of a deficit within a particular neural system. Candidate systems that have been extensively studied are the executive function or dorsolateral prefrontal cortex network and the theory of mind or medial frontal network. The executive function model of autism was predicated on the observation that individuals with autism have difficulty with several cognitive skills that are thought to be mediated by the prefrontal cortex such as response inhibition, working memory, cognitive flexibility, planning, and fluency (Geurts, Verté, Oosterlaan, Roeyers, & Sergeant, 2004; Hill, 2004; Pennington & Ozonoff, 1996; Edgin & Pennington, 2005). The theory of mind model of autism originated from behavioral studies that demonstrated that individuals with autism had difficulty inferring what other people were thinking (Baron-Cohen et al., 1985). Neuroimaging work with theory of mind tasks has identified a "mentalizing" network (medial prefrontal cortex, superior temporal sulcus at the temporo-parietal junction and temporal poles) that is less activated in individuals with autism (Castelli, Frith, Happé, & Frith, 2002). Thus, these models propose that autism is related to disturbances in a single neural system.

The Minshew et al. (1997) study was completed with older adolescents and adults with autism, therefore, an earlier occurring deficit in a single modality or domain that influenced the development of the other domains could not be excluded. If the complex information-processing model of autism is viable, this pattern of impairments should be seen at earlier points of development. Therefore, it is necessary to evaluate individuals with autism at the youngest age at which a comprehensive neuropsychologic battery can be administered. Although not as definitive as a longitudinal study of children followed to adulthood, a child study that parallels the previous adult study could characterize the neuropsychologic profile at an earlier stage of development.

Although neuropsychological measures are not as ideal as experimental measures carefully constructed to control for levels of processing, they provide a reasonable first approach for the systematic measurement across a *large* number of domains in a *single* sample. The aim of the present study was to test our proposed model by assessing children with autism, compared to age-and IQ-matched controls, using age-appropriate measures that correspond to those from the previously reported Minshew et al. (1997) study of adults with autism.

METHOD

Participants

The autism group was composed of 56 children with autism (46 males and 10 females) and 56 controls (39 males and 17 females). The groups ranged in age from 8 to 15 years. Demographic and psychometric data are presented in Table 1. As was the case for the adult study, we restricted the sample to individuals with high-functioning autism, (e.g., those with IQs of 80 or above) and age 8 and older to assure that the participants could fully cooperate for psychological testing and were unlikely to have the numerous additional disorders associated with low-functioning autism. Another consideration in setting the lower limit of the IQ score at 80 was to ensure that typically developing control participants could be identified for the study. The lower age limit of 8 years was also chosen, first, to ensure that participants with autism were sufficiently verbal and had enough capacity to complete a thorough battery and, second, so that relatively uniform measures could be used across this sample.

All participants in the affected group met the cutoffs for autism on the Autism Diagnostic Observation Schedule (ADOS: Lord et al., 1989; Lord et al., 2000) for the Reciprocal Social Interaction, Communication, and Total algorithm scores. In addition, all participants with autism met cutoffs for autism on the Autism Diagnostic Interview-Revised (ADI-R; Le Couteur

et al., 1989; Lord, Rutter, & Le Couteur, 1994) for Reciprocal Social Interaction, Communication, and Restricted, Repetitive, and Stereotyped Behaviors and had abnormal development before 3 years of age. The ADI-R assesses developmental history and reported current functioning based on an interview with a caregiver. The diagnosis of autism established on the basis of the ADI-R and ADOS was verified by expert opinion [NJM] or [DLW] based on accepted clinical descriptions of high-functioning individuals with autism (Minshew, 1996; Minshew & Payton, 1988; Rapin, 1991; Rutter & Schopler, 1987). A subject with ADI-R and ADOS scores above the cutoffs for autism could be ruled out on the basis of expert opinion, but expert opinion could not override ADI-R or ADOS scores that fell below the cutoff. All participants with autism communicated in complete spoken sentences and did not have behavioral problems that prevented them from completing testing. The participants with autism did not have any associated or causative genetic, neurologic, or infectious conditions, were in good medical health and had no history of seizures, birth injury, or head trauma. The participants with autism were community volunteers recruited through advertisements in newsletters, postings on autism-related websites, and presentations for parents and professionals (NJM and DLW). The sample was based upon consecutive admission of all referrals meeting the inclusion criteria.

Controls were community volunteers recruited through advertisements in neighborhoods with the same socioeconomic level as the families of origin of the participants with autism. They were prescreened by completing a questionnaire on demographic information and family and personal history of medical, neurological, and psychiatric disorders. Inclusion criteria included good physical health, no regular medication use, and good peer relationships based on parent or self-report and staff observations during eligibility testing. Exclusion criteria included a personal history of neuropsychiatric disorders, learning disability or brain insults prior to or after birth, and a family history in first-degree relatives of developmental cognitive disorders, mood, and anxiety disorders, and autism in first-, second-, and third-degree relatives.

The University of Pittsburgh Medical Center Institutional Review Board approved the study. Procedures were fully explained to all participants and to their parents or guardians. Written informed consent was obtained from their parents or guardians and written assent was obtained from the children. All participants were recruited through the Subject Core of the University of Pittsburgh Collaborative Program of Excellence in Autism funded by the National Institute of Child Health and Human Development.

Test Battery

The tests and variables used are presented in Table 2 with means and standard deviations of the obtained scores. Tests were chosen from available measures for child cognitive and neuropsychological assessment to represent the same domains and modalities evaluated in the adult study and the same range of abilities within domains. The assignment of a test to a domain was made on the same basis as it was for adults, and was consistent with the generally accepted classification system used in neuropsychological assessment (Lezak, 1995). In some cases, the same test used in the adult study could be used because a child version of the test was available. In other cases, we had to choose tests that were roughly equivalent. For example, the Wide Range Assessment of Memory and Learning (WRAML; Sheslow & Adams, 1990) was used as the major memory test to replace the two memory measures used in the adult study—the Wechsler Memory Scale-Revised (Wechsler, 1987) and the California Verbal Learning Test (Delis, Kramer, Kaplan, & Ober, 1987). Child versions of these instruments were not available at the time the current study was initiated. We retained the three-word short-term memory procedure (described in Ryan, Butters, Montgomery, Adinolfi, & Didario, 1980) and the first trial (with 6 choice points) of a stylus maze-learning task in the simple memory domain. The latter is an unpublished, experimental task used in our previous research with the adult sample.

We also retained the Nonverbal Selective Reminding Test (NVSRT; Fletcher, 1985) in the complex memory domain. We replaced the Wechsler Adult Intelligence Scale-Revised (Wechsler, 1981) subtests with the equivalent Wechsler Intelligence Scale for Children-III (WISC-III; Wechsler, 1991) subtests in the appropriate domains. The 20 Questions task (Olver & Hornsby, 1966) and Stanford-Binet Intelligence Scale (4th Ed.) Picture Absurdities test (S-B IV; Thorndike, Hagen, & Sattler, 1986) used in the adult study as measures of reasoning were also used in this study. The Problem Situations and Plan of Search Tests from the S-B IV (Thorndike et al., 1986) were included as additional measures of reasoning and problem-solving ability. The sensory perception domain measures were the same as the ones used in the adult study—the Luria-Nebraska Tactile Scale (Golden, Purisch, & Hammeke, 1986) and the finger agnosia and fingertip number writing tasks from the Halstead-Reitan Neuropsychological Test Battery (Reitan & Wolfson, 1993). The attention domain included the Digit Span subtest from the WISC-III (see Lezak, 1995, p. 360) and two measures that had been used with the adults—the Continuous Performance Test (CPT; Conners, 1995) and the Number Cancellation task (Mesulam, 1985). In the motor domain, we retained two of the adult measures—finger tapping (Reitan & Wolfson, 1993) and the grooved pegboard (Matthews & Klove, 1964)—and added two new measures—the WISC-III Coding subtest (a measure of psychomotor processing speed) and a measure of grip strength in the dominant hand. The simple language domain included measures from the Wide Range Achievement Test 3 (Wilkinson, 1993), the Woodcock Reading Mastery Tests-Revised (WRMT-R; Woodcock, 1987), a verbal fluency measure (Spreen & Strauss, 1998), and the WISC-III Vocabulary subtest. Two subtests from the Test of Language Competence-Expanded (TLC-E; Wiig & Secord, 1989), the Passage Comprehension subtest from the WRMT-R, Verbal Absurdities from the S-B IV, and an Oral Directions subtest from the Detroit Test of Learning Aptitude (DTLA-2; Hammill, 1985) comprised the complex language domain.

We did not obtain full samples for some of the measures; sample sizes for each measure are indicated in Table 2. Missing data occurred largely because the participant could not cooperate for the test. Because the group sizes were still substantial for these tests, and the subsamples were still age- and IQ-matched, we did not exclude them from the multivariate analyses. Two tests from the adult study—the Wisconsin Card Sorting Test (Heaton, 1981) and the Halstead Category Test (Reitan & Wolfson, 1993)—were administered at the beginning of the study; however, results in both the autism and control groups indicated performance was not valid below age 15. These two tests were discontinued and were, therefore, not included in the child battery.

Trained neuropsychology technicians, under the supervision of a clinical neuropsychologist, administered the test battery over several test sessions. Length of test sessions and breaks were tailored to each participant's needs so that test performance was representative of participant ability. It typically took 2 to 3 days (5 to 6 sessions) to complete the testing.

Data Analysis

The statistical method used to analyze the pattern of deficits was Wilks' stepwise discriminant analysis, as was the case in the adult study. We employed Shutty's (1991) recommendation that preliminary direct method analyses should be performed prior to using stepwise procedures. In the stepwise method, the most discriminating variable, typically the one that produces the highest F-ratio, is entered first, followed by other variables that combine with the first variable in a way that increases discriminatory accuracy. Variables are entered or removed until a preestablished tolerance test is failed indicating that additional entry of available variables would make no further contribution to discriminative accuracy. For this study, the F to enter was 1.0, and the F to remove was .95. This method generates a final classification matrix that provides the percentage of correct classifications (autism or control) and the

percentages of true and false positives and negatives. The statistical significance of the classification matrices was evaluated with kappa, a coefficient of agreement for nominal scales. Relatively high kappas indicate that the variables chosen to represent a domain discriminated well between the participants with autism and the controls, whereas low kappas indicate the reverse. According to the Landis and Koch criteria (1977), a kappa of .40 or greater indicates fair to good agreement beyond chance. Examination of variables entered and not entered provided an indication of the nature of the variables within each domain that discriminated best between the participants with autism and the controls.

Before analyzing the data, we considered using logistic regression as it has been suggested that this may provide more accurate solutions. However, based on a paper by Press and Wilson (1978) that indicated that in most cases logistic regression and discriminant analysis yield similar solutions and to remain consistent with the adult study, we used discriminant analysis for the final analyses. Preliminary logistic regression analyses with the present data did, in fact, yield similar solutions.

RESULTS

The results of the stepwise discriminant function analyses are presented in Tables 3 and 4. Table 3 presents data concerning entry of variables and general classificatory accuracy. Table 4 contains the classification matrices for the various domains that provide information concerning percentages of true and false positives and negatives. Percentages were used because of variations in sample sizes across domains.

Using the Landis and Koch criteria, fair to good agreement beyond chance that the domains discriminated between the autism and control groups (a kappa of .40 or higher) was obtained for the sensory perceptual, motor, complex language, and complex memory domains. All of the complex language measures passed the tolerance test for the children, reflecting the central role of problems with interpretative language in autism. The kappa of .35 obtained for the reasoning domain approached the discriminatory level. The attention, simple language, simple memory, and visuospatial domains were not found to discriminate between the autism and control groups beyond chance levels. Within domains without prior determined simple and complex subdomains, the tests that failed to pass the tolerance test generally represented lower level skills within that domain. For example, within the sensory perceptual domain, the position sense and sharp-dull discrimination scores failed the tolerance tests; the measures that passed all reflected higher cortical tactile functions, such as form recognition. Within the motor domain, the Coding subtest from the WISC-III, a measure of psychomotor or processing speed that requires integrative functioning, passed the tolerance test.

Comparison to Adult Results

A comparison of the results from the current study of children with our previous study of older adolescents and adults with autism can be made by examining the kappa scores from that study, which, for ease of comparison, are provided in Table 3 for each of the domains. The kappa scores show that the neuropsychological profile for the children with autism was quite similar to that of the adults with a few notable exceptions. As in the adult study, tests of attention, simple memory, and visuospatial abilities failed to discriminate between the autism and control groups and tests of motor, complex memory, and complex language did discriminate between the two groups. Unlike the adults, in the sensory perceptual domain, the child group showed a significant impairment. There was no superior performance for the simple language domain in the children. The children with autism performed slightly better than the controls on the measure of spelling (but this did not meet statistical significance), but performance on the other measures in this domain was comparable to that of the controls. In the adult study, the kappa

for the reasoning domain was well within the fair to good range; this domain yielded a kappa just below the range of fair discrimination in the current child study.

DISCUSSION

The present study of 56 children with high-functioning autism and 56 matched typical controls replicates and expands the findings of our previous study of neuropsychologic functioning in adults with autism. Moreover, the child data provide evidence that the neuropsychologic profile observed in adults is present earlier in life. These data fail to support the hypothesis of a single primary cognitive deficit as a cause of the multiple deficit pattern observed in either the children or the adults.

The children with autism exhibited involvement of multiple domains and a differential pattern of impairment between simple and complex skills within the affected domains of sensory perception, motor, language, and memory. The children with autism had difficulty on tasks that placed the highest demands on integration of information, e.g., memory for large amounts of material or complex material and comprehension of text. At the same time, the children with autism did not differ significantly from age- and IQ-matched controls on elementary or basic cognitive skills within these same domains, e.g., associative learning, vocabulary, and spelling.[2] The children in the autism group also did not differ from the controls on attention and visuospatial domains. Lower agreement occurred for the reasoning domain than previously obtained for the adults.

Thus, at the earliest age that a comprehensive battery of this type could be administered, the cognitive profile in autism was consistent with a reduction or constraint in information-processing that differentially impacted the major domains and abilities within those domains. The most affected domains were those that placed the highest demands on information-processing resources. Within affected domains, the skills affected were likewise those that placed the most demands on integration of information.

Some notable differences between the results of the adult and the child studies were obtained. Although caution must be exercised in drawing longitudinal conclusions from cross-sectional data, it does appear that there is a more pronounced impairment in sensory perceptual abilities in childhood in autism. In addition, it appears that these impairments become attenuated, at least to the point that the measures employed failed to yield significant domain differences, in later adolescence and adulthood. The lack of significance in the adult group for this domain may reflect developmental amelioration over time in the sensory symptoms, e.g., improved integration within the sensory system at the cortical level as occurs to some extent with other abilities during the second decade. An actual greater sensory disturbance in children would be consistent with the findings reported in the small sensory literature of the prominence of sensory symptoms in children, the frequent use of sensory interventions in children for calming, and the comparable mixed-sensory-perceptual findings in the adult neuropsychological profile study of Rumsey and Hamburger (1988). Studies of sensory gating or other cortical sensory mechanism as a function of age may shed light on the changes in the sensory profile with maturity in autism.

In the adult study, the simple language domain had a significant kappa, reflecting better performance of the autism group than individually matched controls. This was not seen in the present study of children. The reason for this difference in simple language performance

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[2]Basic skills, in addition to attentional and visual skills, are the basis for performance on IQ tests. This pattern of results may explain why IQ scores can be in the normal range in verbal children with autism despite striking impairments in high-order skills and adaptive behavior.

between the adults and the children is not clear; it may represent a decrease in performance in adulthood for both groups with the adult autism group maintaining more of their spelling and phonetic analysis abilities than the adult controls. The major point of the simple language domain finding, in both the adult and child studies, is that those individuals with autism who become verbal do not demonstrate deficits in basic or formal language skills and cannot be differentiated from IQ-matched controls on this basis. Formal language skills are the basis upon which others automatically estimate an individual's ability level. In the case of individuals with autism, their formal language skills are misleading predictors of their higher order or complex language abilities. Consequently, they are at high risk that those speaking to them are overestimating what they comprehend.

Another difference in the results of the children and the adults was in the reasoning domain with adults having a kappa score in the good range of agreement and children having a kappa below the fair range (.35). The variability in the children's scores was apparently too great to carry the domain to the high level of discriminatory accuracy found in the adults. Part of the reason for this lack of discrimination in the children may be the lack of equivalency in measures for this domain across the two studies. Whereas both studies used the S-B IV Picture Absurdities and the 20 Questions task, the other two measures in this domain differed between the studies. In addition, the Wisconsin Card Sorting test had to be dropped from the child test battery due to the inability on the part of many participants to complete this test. As a result, the reasoning measures used in the child study may have been less able to detect a possible difference in reasoning and problem solving. Alternately, neither the children with autism nor the typically developing controls may have reached the level of development that allowed the manifestation of the reasoning impairments in autism. Other research has shown that the key features of the abstraction-executive function impairment in autism relate to inflexibility (Hill, 2004; Kleinhans, Akshoomoff, & Delis, 2005; Ozonoff, Strayer, McMahon, & Filloux, 1994) and self-initiated concept formation (Minshew, Meyer, & Goldstein, 2002). Typical children do not attain these abilities until the frontal lobes mature in the second decade of life. Comparative studies of children and adolescents with autism have shown that reasoning and strategy deficits emerge during the adolescent years as typical children develop these skills and the children with autism do not (Minshew, Meyer, & Goldstein, 2002).

One obvious question that could be raised about this profile and its interpretation is why the tests were not rank-ordered by complexity, independent of domains. From a purely cognitive perspective, it might be assumed that any simple language task is more complex than any motor task; however, this rank ordering might not be valid from a neural perspective. The organization of abilities and tests into domains used in this study reflects the basic neurobiologic principle that different cognitive and neurologic functions are subserved by separate neural systems in the brain. These biologically based boundaries were respected. A limitation of this study is that there are domains affected by autism that were not assessed with this battery. The most obvious are the social domain and the nonverbal language (communication with gaze or eyes, face expression, prosody, and body language) domain. Whereas these domains were not assessed within the neuropsychologic battery, they were clearly affected in the children with autism in the present study, as evidenced by their scores above cutoffs in these domains on the ADOS and ADI-R.

Another limitation of this study is that, due to the demands of the neuropsychological measures, it was confined to children 8 years of age or older. It is possible that a study of children with autism younger than 8 years would reveal involvement of a single domain rather than multiple domains. However, research to date has not provided support for this hypothesis. Even at first diagnosis, which is about 18 months, there is involvement of multiple domains. Studies have reported evidence of motor and sensory processing impairments in infants later diagnosed with autism (Baranek, 1999; Teitelbaum, Benton, Shah, Prince, Kelly, & Teitelbaum, 2004). Thus,

at an early age there is evidence of impairments outside of the traditional diagnostic triad for autism. Another theoretical consideration against a single primary deficit model is that it is not easy to explain sensory, motor, and memory impairments as the outcome of early joint attention, gaze, or social impairments.

Both the adult and child studies were completed with individuals with IQs in the normal range. It has not been empirically shown that lower functioning individuals with autism evidence a pattern of intact simple and impaired complex information-processing. However, elements of this pattern were confirmed by the studies of Fein and colleagues (1996). Theoretical application of the model to the lower functioning group with autism predicts that, as autism severity increases, total information-processing capacity would be reduced, but there would be a disproportionate reduction in higher order skills and disproportionate preservation of lower order skills relative to the overall loss in information-processing capacity. This would lead to mental retardation but of a type that retains the features of autism. From a neurobiologic perspective, as the severity of autism increases, there would be a progressive shrinkage of higher order circuitry and increased reliance on lower order circuitry until all connectivity between primary sensory motor cortices and association cortex was lost. Thus, whereas the model has been formulated with high-functioning individuals with autism, it could be extended to explain the symptoms in lower functioning individuals with autism including the unexplainable high rate of co-occurrence of mental retardation with autism.

Emerging results from functional neuroimaging studies with individuals with autism also provide supportive evidence for the complex information-processing model. This model predicted that neural underconnectivity would be the analogue of deficits and that intact connectivity or overconnectivity would be the analogue of intact or enhanced abilities. Evidence of this type is being provided by functional magnetic resonance imaging studies of language comprehension (Just, Cherkassky, Keller, & Minshew, 2004) and problem solving (Just, Cherkassky, Keller, Kana, & Minshew, 2006). The proposed “underconnectivity theory” of autism is the biological extension of the complex information-processing model (Just et al., 2004). Another fMRI study has shown that individuals with autism compensate for deficient higher order cognitive abilities and circuitry by using basic cognitive processes and posterior brain regions (Koshino, Carpenter, Minshew, Cherkassky, Keller, & Just, 2005). An additional fMRI study, which has been particularly enlightening with regards to this profile, investigated visual perception by the cortex and concluded that differences in sensory perception were “likely related to higher level cognitive areas, and were the result of top down processes” (Hadjikhani et al., 2004). These neuroimaging studies have provided further validation of the findings of the neuropsychologic profile.

The above described fMRI studies have provided evidence of functional underconnectivity in higher order circuitry and intact lower order circuitry, analogous to the cognitive pattern observed in the present study. Structural morphometry of the brain in autism has yielded evidence of enlarged brain volume beginning postnatally and likely preceding the onset of the symptoms of autism (Courchesne et al., 2001; Hazlett et al., 2005; Sparks et al., 2002). This early overgrowth is thought to disrupt the normal histologic processes associated with brain development and the emerging connectivity of cortical gray and white matter. Therefore, although fMRI studies are demonstrating functional underconnectivity, the volumetric analogue of this brain disturbance is an increase in volume. In an extension of this work, Akshoomoff et al. (2005) reported that variability in cerebral and cerebellar size is correlated with functioning level in children with autism. More correlations between fMRI and brain structure and between brain structure/function and behavioral indices of autism can be expected to occur.

It is important to recognize that in the interval between the publication of the adult profile study and the present study there has been considerable research in autism that has documented the domain specific impairments observed in both studies. The unique contribution of the child profile study at this juncture is that the assessments of multiple domains were completed in the same participant sample with the key questions of, first, what critical feature the impairments share across domains and, second, what critical feature the intact abilities share. The answers appear to be 1) that the acquisition of information is intact; 2) that there is an overall constraint or reduction in the capacity to process information; 3) that this constraint disproportionately impacts higher order information-processing or the capacity to process information or material when the demands of the task or situation are high; and, 4) that this processing constraint occurs at a lower level than would be expected based on the individual's age and IQ.

We have now provided evidence from a total of 89 individuals with autism and 89 matched controls ages 8 to 40 years that documents a disproportionate impact of deficits on higher order abilities and intact basic abilities in these same domains. Because the individuals with autism ranged in IQ from 80 to 125 and were below the age of 40, they could be matched to typically developing healthy control individuals, ensuring that the findings were related to autism and not to mental retardation in the autism group. These data provide substantive support for the proposed complex information-processing model of autism.

The complex information-processing model not only broadens the conceptualization of autism beyond the diagnostic triad, it is also a working concept that facilitates the integration of findings across cognitive and neurobiologic methodologies. Such connections are essential in the search for the neural basis and developmental neurobiologic mechanism of autism. The answers in this realm are likely to be a long way off, but the present findings suggest that answers lie in the mechanisms associated with the underdevelopment of higher order abilities across domains rather than in a single neural system or single brain region.

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Table 1

Demographic Data for Autism and Control Groups.

	Autism Group *n*=56		Control Group *n*=56		
	M	***SD***	***M***	***SD***	***p***
Age	11.36	2.18	11.82	2.20	.26
Years of Education	5.57	2.34	5.96	2.11	.38
Verbal IQ	105.52	16.12	107.86	8.21	.34
Performance IQ	102.07	14.63	105.98	8.40	.09
Full Scale IQ	104.13	15.09	107.50	8.21	.14
Male: Female	46:10		39:17		

Table 2

Psychometric Data Used for Discriminant Analysis.

Tests entered into prediction equations [autism, control]	Autism Group *M*	Autism Group *SD*	Control Group *M*	Control Group *SD*
Attention Domain				
WISC-III Digit Span (scaled score) [55, 55]	10.05	3.09	10.73	2.84
Continuous Performance Test (mean reaction time correct responses) [32, 35]	381.34	125.53	375.55	122.13
Number Cancellation (omissions) [39, 34]	12.92	9.62	16.21	13.44
Sensory perceptual Domain				
LN[1] Simple Touch (raw score) [54, 56]	.41	.86	.21	.56
LN Stereognosis (raw score) [41, 55]	.51	.90	.18	.55
LN Sharp-Dull Discrimination (raw score) [53, 56]	1.08	1.28	.77	.99
LN Position Sense (raw score) [54, 56]	.11	.60	0.00	.00
Reitan-Klove—Finger Agnosia (raw errors) [32, 51]	.75	1.19	.65	1.66
Halstead-Reitan: Fingertip Number Writing (errors) [51, 56]	12.73	9.21	5.79	6.28
Motor Domain				
Finger Tapping—dominant hand [52, 56]	39.15	10.21	43.68	7.04
Grooved Pegboard—dominant hand (time in seconds) [56, 56]	84.96	20.23	76.93	13.63
WISC-III Coding Scaled Score [56, 56]	8.38	3.53	10.66	2.86
Grip Strength—dominant hand (kilograms) [56, 56]	16.35	7.80	22.26	7.65
Simple Language Domain				
WISC-III Vocabulary (scaled score) [56, 56]	11.14	3.18	11.27	1.96
WRAT Reading (standard score) [54, 55]	108.07	14.57	106.84	11.02
Verbal Fluency Test—FAS (number of words) [44, 36]	25.27	10.22	27.06	10.66
Woodcock Reading Mastery—Word Attack (standard score) [52, 40]	108.23	13.97	108.45	9.11
WRAT Spelling (standard score) [54, 55]	111.57[2]	16.27	106.60	10.67
Complex Language Domain				
TLC Figurative Language (scaled score) [47, 40]	7.38	3.16	9.93	2.64
TLC Making Inferences (scaled score) [45, 41]	8.44	3.06	9.59	2.97
Woodcock Reading Mastery—Passage Comprehension (standard score) [53, 40]	101.45	11.65	105.30	7.74
S-B IV Verbal Absurdities (raw score) [56, 56]	8.25	3.85	11.95	2.67
Detroit Oral Directions (scaled score) [42, 36]	9.60	2.84	10.67	1.69
Simple Memory Domain				
3 Word Short Term Memory (number of correct sequences) [43, 36]	3.37	2.55	3.50	2.74
Maze Learning Trial 1 Errors [32, 36]	3.88	1.52	3.67	1.51
WRAML Verbal Learning (scaled score) [55, 55]	9.96	3.52	11.62	2.65
WRAML Sound Symbol (scaled score) [46, 43]	11.28	3.20	10.95	2.85
WRAML Visual Learning (scaled score) [46, 43]	10.98	3.09	11.16	2.52
Complex Memory Domain				
WRAML Verbal Learning—Delayed (scaled score) [53, 56]	9.19	3.64	10.38	2.73
WRAML Visual Learning—Delayed (scaled score) [46, 43]	9.35	3.19	9.47	3.03
WRAML Picture Memory (scaled score) [47, 43]	8.79	3.05	10.26	2.74
WRAML Design Memory (scaled score) [47, 43]	8.53	3.19	10.60	2.51
Nonverbal Selective Reminding—Consistent Long-Term Retrieval [28, 31]	29.25	17.49	36.68	15.78
WRAML Finger Windows (scaled score) [46, 44]	8.98	2.58	11.23	3.21
Reasoning Domain				
20 Questions (% constraint seeking) [55, 56]	45.27	21.49	57.54	13.58
S-B IV Picture Absurdities (raw score) [43, 37]	25.00	3.38	26.30	2.80
S-B IV Problem Situation 1 & 2 [54, 56]	1.98	1.12	2.68	.86
S-B IV Plan of Search [45, 56]	.36	.484	.66	.478
Visual-Spatial Domain				
WISC-III Block Design (scaled score) [56, 56]	11.75	3.62	11.27	2.92
WISC-III Object Assembly (scaled score) [56, 56]	10.43	3.25	10.07	1.87
WISC-III Picture Completions (scaled score) [56, 56]	10.80	3.08	11.14	2.35

[1] LN = Luria-Nebraska Battery.

[2] Autism group had a mean score higher than control group.

Table 3

Discriminant Analysis Results by Domain for Child & Adult Profile Studies.

Domain	Tests Failing Tolerance Test	Tests Passing Tolerance Test (in order of entry)	% Correct Classification for Children	Child *k*	Adult[1] *k*
Attention	WISC-III Digit Span, Continuous Performance Test	Number Cancellation	53.4	.06	.33
Sensory perceptual	LN Position Sense; LN Sharp-Dull	HR Fingertip # Writing; LN Stereognosis; LN Simple Touch; RK Finger Agnosia	73.8	**.44**[2]	.29
Motor	Finger Tapping; Grooved Pegboard	Grip Strength; WISC-III Coding;	73.2	**.46**	**.52**
Simple Language	WISC-III Vocabulary WRAT Reading; Verbal Fluency Test;	WRAT Spelling; WRMT-R Word Attack	55.6	.12	**.42**
Complex Language	None	Verbal Absurdities; TLC Figurative Language; TLC Inferences; Detroit Oral Directions; WRMT-R Passage Comprehension	73.2	**.47**	**.45**
Simple Memory	3 Word Short Term Memory; Maze Learning, Trial 1; WRAML Verbal Learning; WRAML Sound Symbol	WRAML Visual Learning	51.7	.04	.30
Complex Memory	WRAML Verbal Learning-Delayed	WRAML Picture Memory; WRAML Finger Windows; NVSRT—Consistent Long Term Retrieval; WRAML Visual Learning—Delayed; WRAML Design Memory;	72.4	**.45**	**.55**
Reasoning	Picture Absurdities	Plan of Search; Twenty Questions Problem Situations	67.3	.35	**.52**
Visual-Spatial		WISC-III Picture Completion, Block Design, Object Assembly[3]	53.6	.07	.12

[1]Adult kappas are provided to allow comparison of results within each domain (although tests included within a domain may have differed by age group).

[2]Bolded kappas indicate discrimination between the control and autism group for that age group.

[3]The direct entry method was used for this domain allowing for the production of a classification table and computation of kappa.

Table 4

Percentages of Correct Classifications by Discriminant Function Analyses for the Cognitive Domains.

		Predicted Group	
Domain	**Actual Group**	**Autism**	**Control**
Attention	*Autism*	61.5	38.5
	Control	55.9	44.1
Sensory perceptual	*Autism*	66.7	33.3
	Control	22.0	78.0
Motor	*Autism*	69.6	30.4
	Control	23.2	76.8
Simple Language	*Autism*	52.0	48.0
	Control	40.0	60.0
Complex Language	*Autism*	71.1	28.9
	Control	24.2	75.8
Simple Memory	*Autism*	45.7	54.3
	Control	41.9	58.1
Complex Memory	*Autism*	45.7	54.3
	Control	41.9	58.1
Reasoning	*Autism*	68.9	31.1
	Control	33.9	66.1
Visual-Spatial	*Autism*	50.0	50.0
	Control	42.9	57.1