ARCHIVAL REPORT

Brain Organization Underlying Superior Mathematical Abilities in Children with Autism

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Background: Autism spectrum disorder (ASD) is a neurodevelopmental disorder characterized by social and communication deficits. While such deficits have been the focus of most research, recent evidence suggests that individuals with ASD may exhibit cognitive strengths in domains such as mathematics.

Methods: Cognitive assessments and functional brain imaging were used to investigate mathematical abilities in 18 children with ASD and 18 age-, gender-, and IQ-matched typically developing (TD) children. Multivariate classification and regression analyses were used to investigate whether brain activity patterns during numerical problem solving were significantly different between the groups and predictive of individual mathematical abilities.

Results: Children with ASD showed better numerical problem solving abilities and relied on sophisticated decomposition strategies for single-digit addition problems more frequently than TD peers. Although children with ASD engaged similar brain areas as TD children, they showed different multivariate activation patterns related to arithmetic problem complexity in ventral temporal-occipital cortex, posterior parietal cortex, and medial temporal lobe. Furthermore, multivariate activation patterns in ventral temporal-occipital cortical areas typically associated with face processing predicted individual numerical problem solving abilities in children with ASD but not in TD children.

Conclusions: Our study suggests that superior mathematical information processing in children with ASD is characterized by a unique pattern of brain organization and that cortical regions typically involved in perceptual expertise may be utilized in novel ways in ASD. Our findings of enhanced cognitive and neural resources for mathematics have critical implications for educational, professional, and social outcomes for individuals with this lifelong disorder.

Key Words: Autism, brain organization, cognitive strengths, mathematical abilities, multivariate pattern analysis, support vector machine

Autism spectrum disorder (ASD), a neurodevelopmental disorder with an estimated prevalence rate greater than 1% (1), is characterized by a complex phenotype that includes social, communicative, and sensorimotor processing deficits (2). Despite the clinical focus on cognitive deficits, it has been noted that the "altered developmental trajectory that defines ASD can also lead to remarkable cognitive strengths" (3) and that children with ASD might present "islets of ability" in various domains (4). One domain in which individuals with ASD often demonstrate exceptional abilities is mathematics. Evidence for greater proficiency in mathematics in ASD has been mostly anecdotal (5) and descriptive (6). It has been shown that scientists score higher than nonscientists on self-administered questionnaires for "autism associated traits" (6) and there is a "three- to seven-fold increase for autism spectrum condition among mathematicians" (7). Furthermore, a recent study in 14- to 16-year-olds with ASD demonstrated a larger discrepancy between IQ and mathematical abilities compared with other abilities such as reading (8).

A seminal theoretical account proposes that systematic, logical, and analogical thinking are enhanced in individuals with ASD (3), suggesting that "hyper-systemizing" may be an adaptive mechanism to reduce environmental variance into a series of regular sets with repeatable rules. Mathematics represents the most concrete instantiation of such abilities, as it is built upon systematic axiomatic procedures. Mathematical skills are essential for educational and professional success and are also crucial in everyday life (9). Thus, mathematics represents an ideal domain to experimentally measure potential cognitive strengths in ASD.

Here, we provide the first simultaneous cognitive and neural characterization of mathematical abilities in children with ASD compared with typically developing (TD) children. We predicted that compared with TD children, children with ASD would show better mathematical abilities, as measured by standardized neuropsychological assessments. We further hypothesized that compared with TD children, children with ASD would show different patterns of brain responses during arithmetic problem solving, with greater reliance on posterior brain areas (10,11). Finally, we hypothesized that neural processes subserving mathematical skills in children with ASD might rely on cortical areas typically devoted to other cognitive abilities.

Methods and Materials

Participants

We studied eighteen 7- to 12-year-old children with ASD (14 male subjects; mean age = 9.60; SD = 1.64) and eighteen TD children (14 male subjects; mean age = 9.59, SD = 1.53). All children in the ASD group were verbal and within an IQ range

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Table 1. Demographic, IQ, and Diagnostic Measures

Measure	ASD ($n = 18$)	TD ($n = 18$)	t Test	p Value
Male to Female Ratio	14:4	14:4		
Age (Years)	9.60, SD = 1.64	9.59, SD = 1.53	.016	.988
IQ–WASI Scale				
Full IQ	113.27, SD = 15.25	113.27, SD = 15.50	−.022	.983
Verbal IQ	112.00, SD = 19.32	112.72, SD = 16.64	−.139	.891
Performance IQ	112.05, SD = 17.88	111.22, SD = 16.65	.145	.886
ADI-R				
Social	19.00, SD = 6.66			
Communication	15.33, SD = 6.03			
Repetitive behavior	5.94, SD = 2.80			
ADOS[a]				
Social	8.24, SD = 1.86			
Communication	3.41, SD = 1.46			
Algorithm	11.65, SD = 3.10			

Demographic and mean IQ scores are shown for the ASD and TD groups. Mean ADI-R and ADOS scores are shown for the ASD group only. Note: $df = 1{,}34$ for all analyses.

ADI-R, Autism Diagnostic Interview-Revised; ADOS, Autism Diagnostic Observation Schedule; ASD, autism spectrum disorder; TD, typically developing; WASI, Wechsler Abbreviated Scale of Intelligence.

[a]Missing score from one participant.

considered to be high-functioning. Children with ASD received a diagnosis based on scores from the Autism Diagnostic Interview-Revised (12,13) and/or the Autism Diagnostic Observation Schedule (14) (Table 1). Children with ASD were screened through a parental phone interview and excluded if they had other known genetic, psychiatric, or neurological disorders (e.g., fragile X syndrome or Tourette syndrome). Table S1 in Supplement 1 contains additional clinical information on the ASD sample. The TD cohort was selected from a larger sample of children, based on matching of the following parameters: age, full-scale IQ, and gender (Table 1).

Parental consent and child assent forms were obtained for each child. All protocols were approved by the human participants Institutional Review Board at the Stanford University School of Medicine. All participants were volunteers and were treated in accordance with the American Psychological Association's Ethical Principles of Psychologists and Code of Conduct.

Neuropsychological and Strategy Assessments

Prior to the functional magnetic resonance imaging (fMRI) scan, each child participated in a neuropsychological assessment session consisting of the Wechsler Abbreviated Scale of Intelligence (15), the Wechsler Individual Achievement Test-Second Edition (WIAT-II) for mathematics (16), and the Working Memory Test Battery for Children (17). On the day of the fMRI scan, children performed a strategy assessment task, outside the scanner, consisting of single-digit addition problems (e.g., 5 + 6 = ?) (18–21). The problems were presented one at a time on a computer screen. There were 18 problems that used random pairs of integers from 2 to 9 and sums ranging from 6 to 17. Children were given explicit examples of strategy use: "just knew it" (i.e., retrieval), "counted on my fingers", "counted in my head" (i.e., counting), and "broke down the problem, such as 9 + 5 = 9 + (1 + 4) = (9 + 1) + 4 = 10 + 4 = 14" (i.e., decomposition). Subsequently, children were instructed to say the answer out loud as soon as they had it in their head. The experimenter then probed the child on which strategy was used during problem solving. Responses were categorized as retrieval, counting, and decomposition. Trials where the experimenter noted overt signs of counting even when the child reported retrieval were classified as counting and not retrieval or decomposition. Six children (three in each group) did not complete the strategy assessment due to time constraints. For each remaining child, we computed the proportion of correctly answered problems solved by retrieval, counting, or decomposition strategies.

Functional Brain Imaging

Experimental Design. The fMRI experiment consisted of two arithmetic conditions, 1) complex addition and 2) simple addition, and two nonarithmetic conditions, 1) number identification and 2) passive fixation/rest. In the complex addition task, participants were presented with an equation involving two addends and asked to indicate, via a button box, whether the answer shown was correct or incorrect (e.g., 3 + 4 = 8). One operand ranged from 2 to 9 and the other operand ranged from 2 to 5 (tie problems, such as 5 + 5 = 10, were excluded), and answers were correct in 50% of the trials. Incorrect answers deviated by ±1 or ±2 from the correct sum. The simple addition task was identical except that one of the addends was always 1 (e.g., 3 + 1 = 4). In the number identification task, arithmetic symbols were replaced by alternative keyboard symbols (e.g., 4 o 5 @ 7) and participants were asked to assess if the number 5 was among the presented digits. Finally, in the passive fixation task, the symbol * appeared at the center of the screen and participants were asked to focus their attention to it. To aid children's performance, specific task instructions appeared below each problem. During the complex and simple addition tasks, the word "Solve" was presented below the problem. In the number identification task, the word "Find" appeared on the screen, and during the passive fixation/rest trials, the word "Look" appeared on the screen.

Stimuli were presented in a block fMRI design to optimize signal detection. In each task, stimuli were displayed for 5 seconds with an intertrial interval of 500 milliseconds. There were 18 trials of each task condition, broken up into four blocks of 4 or 5 trials; thus, each block lasted either 22 or 27.5 seconds. The order of the blocks was randomized across participants with the following constraints: in every set of four blocks, all conditions were presented and the complex and simple addition task blocks were always separated by either a number identification or a passive fixation/rest block. All orders of arithmetic and nonarithmetic task