Neuropsychology
2008, Vol. 22, No. 5, 563–570

0894-4105/08/$12.00 DOI: 10.1037/0894-4105.22.5.563

Intact Implicit Learning of Spatial Context and Temporal Sequences in Childhood Autism Spectrum Disorder

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Autism spectrum disorder (ASD) is defined by atypicalities in domains that are posited to rely on implicit learning processes such as social communication, language, and motor behavior. The authors examined 2 forms of implicit learning in 14 children with high-functioning ASD (10 of whom were diagnosed with Asperger's syndrome) and 14 control children, learning of spatial context known to be mediated by the medial temporal lobes (using the contextual cueing task) and of sequences known to be mediated by frontal–striatal and frontal–cerebellar circuits (using the alternating serial reaction time task). Both forms of learning were unimpaired in ASD. Spatial contextual implicit learning was spared in ASD despite slower visual search of spatial displays. The present findings provide evidence for the integrity of learning processes dependent on integration of spatial and sequential contextual information in high-functioning children with ASD.

Keywords: frontostriatal circuits, medial temporal lobes, spatial attention, sequence learning, developmental disorders

The ability to learn environmental regularities (e.g., where or when events may occur) implicitly, without intention or conscious awareness, is posited to support linguistic and motor skill acquisition (Perruchet & Pacton, 2006) and social intuition (Lieberman, 2000). Impairments in these domains characterize children with autism spectrum disorder (ASD) in whom difficulties with social communication accompany repetitive behaviors and restricted interests. Implicit learning of contextual information guides perception of social cues and predicts actions and, therefore, may mediate atypical cognition in ASD. However, investigation of the integrity of learning processes has not figured centrally in models of cognitive dysfunction in ASD. In the present study, we examined implicit contextual learning in two domains: In the spatial domain, repeated experience with invariant spatial relationships provides predictive cues that guide visual attention during visual search tasks (e.g., contextual cueing [CC] task; Chun, 2000). In the perceptual–motor domain, repeated experience with invariant sequential structure of stimuli forms the basis for predicting subsequent responses to contiguous (e.g., serial reaction time [SRT] task; Nissen & Bullemer, 1987) or noncontiguous (e.g., alternating SRT [ASRT] task; Howard & Howard, 1997) stimuli. Learning is implicit because participants cannot recollect or recognize the learned spatial context or sequential information. Knowledge of these two forms of implicit learning in ASD is necessary for constraining knowledge about the status of cognition in the disorder.

Examining two forms of implicit learning in ASD provides the opportunity to probe the functional integrity of learning mechanisms shown to be dissociable in adults. Whether functional specialization of memory systems is complete by late childhood is not fully known. Nevertheless, forms of learning that have been dissociated in adults provide a heuristic for systematic examination of memory systems in childhood (see also Berl, Vaidya, & Gaillard, 2006). Spatial contextual learning is hypothesized to involve the medial temporal lobes (i.e., the hippocampus and entorhinal, perirhinal, and parahippocampal cortices) because learning was reduced in patients with extensive medial temporal lobe lesions (Chun & Phelps, 1999). Although hippocampal lesions did not disrupt learning on the CC task (Manns & Squire, 2001) hippocampal involvement was observed using functional brain imaging during CC performance in healthy adults (Greene, Gross, Elsinger, & Rao, 2007). Furthermore, activations also involve lateral–frontal and temporal cortices projecting to the medial temporal lobe. Thus, although the role of the hippocampus remains to

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Funding support came from Georgetown University, National Alliance for Autism Research, National Institute of Mental Health Grants MH 065395, NIA R37AG15450, and the Frederick and Elizabeth Singer Foundation. We thank Jennifer Foss-Feig and Margaret Benner for assistance with data collection, and Sunbin Song and Marvin Chun for providing the ASRT and CC tasks, respectively. Lisa Gilotty is now with the National Institute of Mental Health, the National Institutes of Health.

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be elucidated, other medial temporal lobe regions and their cortical projections appear to be important for spatial contextual learning.

In contrast to spatial contextual learning, sequence learning is hypothesized to involve striatal circuitry because it is impaired in people with Huntington's and Parkinson's disease (Willingham, 1997), which are characterized by degeneration of basal ganglia structures. Functional brain imaging studies also show involvement of the cerebellum and regions projecting to the striatum such as prefrontal and motor cortices in adults on the ASRT and SRT tasks (Fletcher et al., 2005; Rauch, Whalen, et al., 1997; Willingham, Salidis, & Gabrieli, 2002) and in children on the SRT task (Thomas et al., 2004). Double dissociations in elderly participants further suggest that implicit spatial contextual and sequence learning are separable. Specifically, Negash et al. (2007) reported reduced CC but not ASRT learning in individuals with mild cognitive impairment, a condition characterized by medial–temporal lobe pathology, compared with age-matched controls. In contrast, reduced ASRT but not CC learning was reported in healthy aging (Howard, Howard, Dennis, Yankovich, & Vaidya, 2004), a period characterized by reductions in striatal, cerebellar, and prefrontal volumes with relative sparing of the medial–temporal lobes (Raz et al., 2005). Thus, brain imaging and neuropsychological findings suggest that medial temporal and frontostriatal–cerebellar circuits mediate learning of spatial context and sequential structure, respectively.

Cognitive strengths and weaknesses observed in ASD lead to distinct hypotheses about the status of implicit learning. A strength observed in ASD is a tendency toward superior processing of local information. Relative to controls, participants with ASD are faster at detecting targets embedded in complex visual figures (Jolliffe & Baron-Cohen, 1997) and give fewer context-appropriate pronunciations of homographs (Happé, 1997). The source of this bias, whether due to impaired (Happé, 1999) or unaffected (Mottron, Burack, Iarocci, Belleville, & Enns, 2003; Plaisted, Saksida, Alcantara, & Weisblatt, 2003) global information processing, remains unresolved. Nevertheless, those findings suggest that contextual information weakly modulates visual–perceptual and linguistic processing in ASD. Such a bias could reduce contextual encoding, thereby reducing learning dependent on invariant contextual information in ASD, regardless of stimulus domain. Thus, this view hypothesizes reduced learning on both sequence learning and contextual cueing tasks. Consistent with this prediction, sequence learning on the SRT task was reduced in children with ASD (Mostofsky, Goldberg, Landa, & Denckla, 2000). Alternatively, intact learning on both sequence learning and contextual cueing tasks may be hypothesized in light of one of the core symptoms of ASD, the need for sameness and regularity. The preference for repetition in ASD may promote acquisition of invariant contextual information, leading to spared or superior learning of spatial and sequential relationships. Thus, there are reasonable arguments to hypothesize both impaired and intact contextual learning in ASD. The present study tested these hypotheses by examining both learning of spatial context and sequential information in the same children with ASD and matched controls.

We examined implicit learning of spatial context using the CC task and of sequences using the ASRT task in children with ASD and age-, sex-, and IQ-matched controls. On the CC task, participants search for a target among distractors whose spatial configuration repeats on some trials and is novel on others. Context-dependent learning is indexed by faster responding on trials with repeated than novel distractor configurations. On the ASRT task, participants respond to the location of a visual stimulus by pressing a corresponding key. Unbeknownst to participants, the stimulus location varies in a fixed sequence involving alternate trials (i.e., item n predicts item $n + 2$ on these trials); randomly determined stimulus locations alternate with sequence trials. Context-dependent learning is indexed by faster responding on sequential than on random trials. The ASRT rather than SRT task was used for two reasons. First, the ASRT task is more resistant to the development of conscious awareness of underlying sequential structure and use of explicit memory strategies during performance. Therefore, differences in explicit memory abilities are less likely to influence sequence learning. Second, the ASRT task is more sensitive to ongoing learning because performance on sequential and random trials is assessed continuously during learning rather than after learning has occurred. Thus, factors affecting expression of learning, such as fatigue, are minimized for ASRT than they are for SRT learning.

Method

Participants

Fourteen children with ASD (13 boys) ages 8 to 14 years with IQ within the normal range were recruited from Children's National Medical Center (see Table 1). Ten children with ASD had a diagnosis of Asperger's syndrome; of the 4 remaining children with ASD, 2 had a diagnosis of high-functioning autism and 2 had a diagnosis of pervasive developmental disorder—not otherwise specified. Fourteen control children (13 boys) ages 7 to 14 years with IQ within the normal range were recruited from the Washington, DC, area through advertisements. The groups matched for sex, age (ASD: $M = 11.57$ years, $SD = 1.65$; controls: $M = 11.00$ years, $SD = 1.80$; $p = .39$), and IQ (ASD: $M = 110.43$, $SD = 12.59$; controls: $M = 116.29$, $SD = 13.79$; $p = .25$). All parents or guardians provided informed consent; children provided informed assent and were paid for participation.

Children were diagnosed with ASD by clinicians using criteria in the *Diagnostic and Statistical Manual of Mental Disorders* (4th ed., text revision; *DSM–IV–TR*; American Psychiatric Association, 2000); diagnosis was confirmed by expert opinion of clinicians specializing in ASD (LK, LG; see Table 1). The Childhood Asperger Syndrome Test (CAST) (Scott, Baron-Cohen, Bolton, & Brayne, 2002) was used to objectively screen for ASD symptoms (cutoff = 15); all participants with ASD were above the ASD cutoff (see Table 1). In addition, a portion of children with ASD who had clinical evaluations at Children's National Medical Center received the Autism Diagnostic Interview—Revised (ADI–R) and the Autism Diagnostic Observation Schedule (ADOS; Lord et al., 2000; Lord, Rutter, & Le Couteur, 1994). Seven children received both ADI–R and ADOS, 3 children ADOS only, 1 child ADI–R only, and 3 children neither ADI–R nor ADOS. All ADOS Social Domain summary scores ($M = 8.60$, range = 4–13, cutoff = 4) and all but one of the ADOS Communication Domain summary scores ($M = 3.60$, range = 1–8, cutoff = 2) were above the ASD cutoff. Restricted and Repetitive Behavioral Domain summary scores were consistent with Lord et al.'s (2000) scores ($M = 3.00$, range = 2–4, no cutoff). ADI scores were above the

Table 1
Demographics of Participants With Autism Spectrum Disorder

ID	Age (years)	FSIQ	Sex	Diagnosis	CAST	CC learning	ASRT learning
S1	14	123	F	ASP	19	No	Yes
S2	10	124	M	ASP	16	Yes	Yes
S3	13	121	M	ASP	15	Yes	Yes
S4	11	101	M	ASP	20	Yes	Yes
S5	13	107	M	HFA	24	No	Yes
S6	11	121	M	ASP	21	Yes	Yes
S7	11	110	M	ASP	19	Yes	Yes
S8	8	109	M	PDD	20	Yes	No
S9	10	117	M	HFA	16	Yes	Yes
S10	11	88	M	ASP	27	Yes	Yes
S11	12	121	M	ASP	16	Yes	Yes
S12	12	85	M	PDD	14	Yes	Yes
S13	12	103	M	ASP	22	Yes	Yes
S14	14	116	M	ASP	27	Yes	Yes

Note. FSIQ = Full-scale IQ determined by Wechsler Intelligence Scale for Children (3rd ed.) or Wechsler Abbreviated Scale of Intelligence; CAST = Childhood Asperger Syndrome Rating Scale Score (autism spectrum disorder [ASD] diagnosis suggested by scores higher than 15). M = male; F = female. Diagnosis: ASP = Asperger syndrome; HFA = high-functioning autism; PDD = pervasive developmental disorder—not otherwise specified. All children with a diagnosis of ASP had normal onset of language and normal adaptive functioning. Contextual cueing (CC) learning = faster reaction times to repeated than to novel configurations in the last epoch. Alternating serial reaction time (ASRT) learning = faster reaction times to pattern than to random trials in the last epoch. S3's CAST score was 1 point below cutoff, but this participant met criteria for ASD on the Autism Diagnostic Interview—Revised or the Autism Diagnostic Observation Schedule.

autism cutoff (Reciprocal Social Interaction: $M = 21.12$, range = 18–25, cutoff = 10; Communication: $M = 19.25$, range = 14–24, cutoff = 8; Restricted and Repetitive Behaviors: $M = 8.62$, range = 5–12, cutoff = 3). Exclusion criteria included other neurological disorders (e.g., epilepsy), IQ < 85, or use of antipsychotic medications. Medications could not be withdrawn in 10 children with ASD who participated on antidepressants (9), stimulants (3), nonstimulants (i.e., Strattera; 1), or valproic acid (1); 4 children were unmedicated.

Control children were screened for ASD using the CAST (Scott et al., 2002) and psychiatric conditions (e.g., attention problems) using the Child Behavior Checklist (Achenbach, 1991). Children completed the subtests of the Woodcock–Johnson III Diagnostic Reading Battery to screen for reading disorder. No control participants had any neurological or psychiatric conditions, including ASD. Unpaired *t* tests confirmed that symptoms on the CAST were higher in ASD than those in control participants (ASD: $M = 19.71$, $SD = 4.20$; controls: $M = 5.00$, $SD = 3.19$), $t(26) = 10.45$, $p < .0001$.

CC Task

Design and stimulus materials. A $2 \times 2 \times 6$ mixed design was used with group (ASD vs. control) as a between-subjects factor and configuration (repeated vs. novel) and epoch (1–6) as within-subject factors.

Each trial consisted of a 12-element stimulus array of a single target and 11 distractors presented in white on a gray background (Figure 1, upper portion). The target was a horizontal *T* rotated left or right by 90°, to which subjects responded by pressing a keyboard key (*Z* for left, "/" for right). The distractors were *L*s randomly rotated by 0°, 90°, 180°, or 270°. Arrays were generated by randomly placing the 12 items into cells of an invisible grid (6 rows $\times$ 8 columns). Target location was balanced for distance from the screen's center and screen half (left/right); no targets appeared in the four center or corner cells. Every element was randomly repositioned by ± 2 pixels along each axis to avoid colinearity. Each block consisted of 24 trials: 12 unique configurations of distractors (novel) and 12 configurations of distractors that repeated across the experiment (repeated). Target location, but not orientation (left/right), was fixed for each repeated configuration.

Procedure. Stimuli were presented via Matlab with instructions to locate the *T* as quickly and accurately as possible. Following 24 practice trials, participants completed 30 blocks of 24 trials each. Trials were randomized within blocks. Blocks were grouped into 6 epochs of 5 blocks (e.g., Blocks 1–5 made up Epoch 1). On each trial, a fixation dot appeared for 1 s, followed by a stimulus, which remained until a response was made. If no response was made within 6 s, the trial timed out following an error tone. Feedback tones were high pitched for correct responses and low pitched for errors. Following the task, 24 configurations (12 novel, 12 repeated) were presented for recognition memory; participants pressed a key for familiar configurations.

ASRT Task

Design and stimulus materials. A $2 \times 2 \times 5$ mixed design was used with group (ASD vs. control) as a between-subjects factor and trial type (pattern vs. random) and epoch (1–5) as within-subject factors.

Each trial began with three empty circles displayed horizontally across a screen (Figure 1, lower portion), mapped to a keyboard key (*M* and the adjoining symbol keys $<$ and $>$). On each trial, one circle filled in and remained filled until participants pressed the correct key. The circles remained empty for 120 ms between trials. One of two patterns was randomly assigned to each participant (either A-r-B-r-C or A-r-C-r-B-r, where A, B, and C denote the left, central, and right

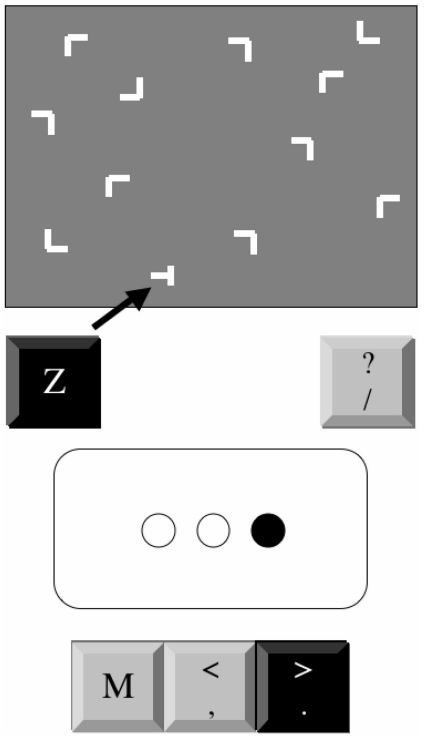

Figure 1. Schematics of computer displays for the contextual cueing (CC; upper portion) and alternating serial reaction time (ASRT; lower portion) tasks. The arrow in CC task display indicates the target's location. For both tasks, the black keys indicate the correct response.

positions and r denotes a random element, constrained so that all locations appeared with equal frequency). The three-position long pattern repeated throughout the experiment.

Procedure. Stimuli were presented via E-Prime with instructions to press the key that matched the filled-in circle's location (*M* and the adjoining symbol keys < and > on a keyboard). Participants completed 20 blocks of 60 trials each. Blocks were grouped into 5 epochs of 4 blocks (e.g., Blocks 1–4 made up Epoch 1). Each block began with 8 practice trials and ended with feedback encouraging speed and accuracy. Conscious awareness for learned sequences is commonly tested subjectively with questions such as "Did you notice any regularity in the way the stimulus moved?" We did not include such a test because metacognitive immaturity in childhood often results in unreliable introspective reports (Kuhn, 2000).

General Procedure

Participants performed the CC and ASRT tasks within a single session in counterbalanced order. Both tasks were self-paced. Participants took short breaks between blocks, approximately every 60 s on the CC task and every 90 s on the ASRT task. Including breaks, total time on the CC task ranged from 30 to 45 min and total time on the ASRT task ranged from 20 to 25 min. For both tasks, children were instructed to rest their hands over the relevant response keys during the experiment. The experimenter confirmed that this was done throughout the task.

Results

Trials with reaction times (RTs) that were 3 or more standard deviations from the mean were excluded. The percentage of excluded trials did not differ between groups (CC–ASD: $M = 1.00\%$, $SD = 0.73$, control: $M = 0.81\%$, $SD = 0.54$, $p = .45$, $d = 0.30$; ASRT–ASD: $M = 1.15\%$, $SD = 0.49$, control: $M = 1.27\%$, $SD = 0.63$; $p = .56$, $d = 0.21$). Based on past research using the CC task (Chun & Jiang, 1998), trials without a response within 6 s were excluded (total trials: ASD = 11; controls = 5). Cohen's *d* and η_p^2 effect sizes are reported for *t* tests and analyses of variance (ANOVAs), respectively.

CC Task

Percentage of correct responses (accuracy) and mean RTs for correct trials were computed for each participant and were analyzed in Group (ASD vs. control) × Configuration (repeated vs. novel) × Epoch (1–6) repeated measures ANOVAs (see Figure 2). Analysis of accuracy revealed no significant main effects or interactions, except a trend for higher accuracy for repeated than novel configurations (main effect of configuration), $F(1, 26) = 3.89$, $p = .06$, $\eta_p^2 = .13$ (other ps $> .26$, $\eta_p^2 < .05$). Overall accuracy was high (ASD: $M = 97.58\%$, $SD = 1.88$; control: $M = 97.03\%$, $SD = 2.31$).

Analysis of RTs revealed that responses were slower in ASD than in control children (main effect of group), $F(1, 26) = 5.20$, $p < .03$, $\eta_p^2 = .17$. Participants exhibited learning of visual search skill because responses were faster with practice (main effect of epoch), $F(5, 130) = 43.57$, $p < .0001$, $\eta_p^2 = .63$. Although overall responses were faster to repeated than to novel configurations (main effect of configuration), $F(1, 26) = 17.95$, $p < .0001$, $\eta_p^2 = .41$, children exhibited context-dependent learning because the benefits of repetition increased with practice (Configuration × Epoch interaction), $F(5, 130) = 3.25$, $p = .008$, $\eta_p^2 = .11$. Magnitude of learning did not differ between groups (Group × Epoch × Configuration interaction, $p = .95$, $\eta_p^2 = .01$). No other interactions reached significance (all ps $> .14$, $\eta_p^2 < .06$).

In light of slower visual search in ASD relative to control children, we determined whether differences in magnitude of learning were apparent on a measure that equated speed by expressing learning as a proportion of one's baseline speed (i.e.,

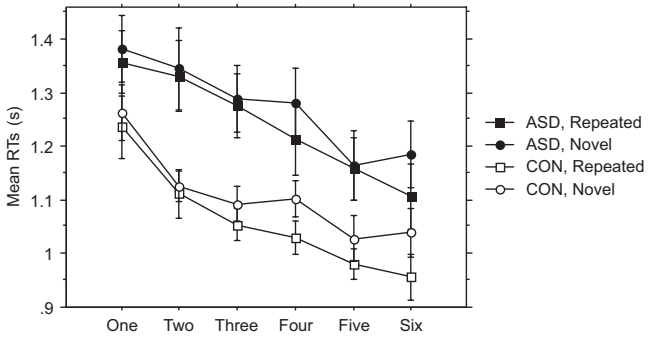

Figure 2. Mean response time (in seconds) on the contextual cueing (CC) task as a function of epoch and type of configuration for autism spectrum disorder (ASD) and control groups.

novel – repeated/novel, calculated per epoch). Proportional learning scores computed for each participant were analyzed in a Group × Epoch ANOVA. The main effect of group and the Group × Epoch interaction were not significant ($ps > .43$, $\eta_p^2 < .02$), indicating that measures of proportional learning did not differ between ASD and control children. Thus, the absence of group differences in learning was not an artifact of speed differences because group differences were not observed after equating for response speed.

For the recognition memory test, d' scores [z (%hits) – z (%false alarms)] were computed for each participant. One-sample t tests indicated that d'scores did not differ from chance in ASD ($M = 0.75$, $SD = 1.50$, $p = .11$) and control ($M = 0.28$, $SD = 1.41$, $p = .54$) children. Furthermore, an unpaired t test indicated that d'scores did not differ between groups ($p = .44$, $d = 0.32$). Thus, participants were unable to consciously recognize the repeated configurations.

ASRT Task

Percentage of correct responses (accuracy) and mean RTs for correct trials were computed for each participant and were analyzed in Group (ASD vs. control) × Trial Type (pattern vs. random) × Epoch (1–5) repeated measures ANOVAs (see Figure 3). Accuracy did not differ between ASD ($M = 92.25\%$, $SD = 3.48$) and control ($M = 93.37\%$, $SD = 3.08$) participants (main effect of group, $p = .38$, $\eta_p^2 = .03$). Participants were more accurate on pattern than random trials (main effect of trial type), $F(1, 26) = 36.40$, $p < .0001$, $\eta_p^2 = .58$, and accuracy increased with practice (main effect of epoch), $F(4, 104) = 2.42$, $p < .05$, $\eta_p^2 = .09$. No interactions reached significance (all $ps > .17$, $\eta_p^2 < .06$).

Overall RTs did not differ between groups (main effect of group, $p = .90$, $\eta_p^2 = .001$). Participants exhibited perceptual–motor skill learning because responses were faster with practice (main effect of epoch), $F(4, 104) = 6.59$, $p < .0001$, $\eta_p^2 = .20$. Although overall responses were faster to pattern than random trials (main effect of trial type), $F(1, 26) = 32.13$, $p < .0001$, $\eta_p^2 = .55$, children exhibited sequence learning because the benefits of repetition increased with practice (Trial Type × Epoch interaction), $F(4, 104) = 3.72$, $p = .007$, $\eta_p^2 = .13$. Group differences in learning were suggested by a Group × Epoch × Trial Type interaction, $F(4, 104) = 2.53$, $p < .05$, $\eta_p^2 = .09$. No other interactions reached significance (all $ps > .26$, $\eta_p^2 < .05$). We examined the three-way interaction for effects of group (with Epoch × Trial Type ANOVAs for each group) and epoch (with Group × Trial Type ANOVAs for each epoch). Each group exhibited sequence learning because the Epoch × Trial Type interaction reached significance: ASD, $F(4, 52) = 2.60$, $p < .05$, $\eta_p^2 = .17$; control, $F(4, 52) = 3.60$, $p = .01$, $\eta_p^2 = .22$. Sequence learning marginally differed between groups in Epoch 5 (Group × Trial Type interaction), $F(1, 26) = 3.84$, $p = .06$, $\eta_p^2 = .13$, but not in Epochs 1–4 (all $ps > .11$, $\eta_p^2 < .10$). Planned comparisons indicated that the difference between pattern and random trials was larger in ASD than control participants in Epoch 5, $t(26) = 1.96$, $p = .06$, $d = 0.74$ (other epochs $ps > .11$, $d < 0.63$). Thus, ASD but not control children continued to show learning into the last epoch.

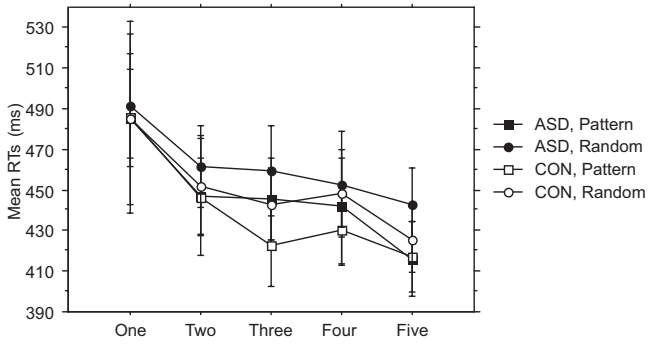

Figure 3. Mean response time (in milliseconds) on the alternating serial reaction time (ASRT) task as a function of epoch and type of trial for autism spectrum disorder (ASD) and control groups.

It is possible that group differences in magnitude of learning emerged because the ASD group's response speed appeared to improve to a greater extent than did controls' response speed. We therefore determined whether differences in magnitude of learning were apparent on a measure that equated speed by expressing learning as a proportion of one's baseline speed (i.e., random – pattern/random, calculated per epoch). Proportional learning scores computed for each participant were analyzed in a Group × Epoch ANOVA. Overall measures of proportional learning did not differ between ASD and control children (main effect of group), $p = .41$, $\eta_p^2 = .03$. Group differences in learning were suggested by a significant Group × Epoch interaction, $F(4, 104) = 2.47$, $p < .05$, $\eta_p^2 = .09$. We examined this interaction to determine whether each group demonstrated learning (with one-way ANOVAs for each group) and whether magnitude of learning differed between the two groups (with unpaired t tests for each epoch). Each group exhibited sequence learning because the main effect of epoch was significant: ASD, $F(4, 52) = 3.07$, $p = .02$, $\eta_p^2 = .19$; control, $F(4, 52) = 3.28$, $p = .02$, $\eta_p^2 = .20$. Unpaired t tests revealed that proportional magnitude of learning was larger in ASD than control children in Epoch 5, $t(26) = 1.99$, $p = .06$, $d = 0.75$ (all other $ps > .17$, $d < 0.54$). Thus, group differences in learning persisted after controlling for baseline differences in response speed.

Discussion

Two forms of implicit learning, for spatial context and perceptual–motor sequences, did not differ between high-functioning children with ASD and controls. For spatial contextual learning, learning on the CC task did not differ between groups, despite slower visual search performance in ASD relative to control children. For sequential learning, whereas baseline ASRT performance did not differ between the groups, expression of learning was more prolonged in ASD than control children. Recognition memory for spatial configurations did not differ between groups, and therefore, differences in explicit memory ability are unlikely to account for the observed findings on the CC task. Explicit memory for sequences on the ASRT task was not tested.

In a disorder characterized by impaired functioning in multiple behavioral domains, spared learning abilities have important implications for future research and treatment. Nonetheless, accepting the null hypothesis requires caution, and we consider several alternative explanations: First, it is possible that our measures lacked sensitivity to detect group differences in learning. However,

previous studies have found reduced magnitude of learning on the ASRT task in healthy aging (Howard & Howard, 1997; Howard et al., 2004) and dyslexia (Howard, Howard, Japikse, & Eden, 2006) and on the CC task in childhood (Vaidya, Huger, Howard, & Howard, 2007) and mild cognitive impairment (Negash et al., 2007), suggesting that these tasks are sensitive to group differences in learning. Second, the small sample size could result in reduced statistical power, thereby reducing our ability to detect group differences in learning. Effect size for a group difference in total magnitude of learning (sum of the difference between trial types across epochs) was moderate for the ASRT task ($d = 0.43$) and small for the CC task ($d = 0.16$); the larger effect size for the ASRT task reflects greater rather than reduced learning in ASD relative to control children. The power to detect these effect sizes is low (ASRT: .17–.25; CC task: .06–.08). More than 70 subjects would be needed for group differences of the obtained effect sizes to be significant at $\alpha = .05$ with power = .80. Third, similar ASRT learning in the two groups may result from differential explicit awareness for sequential information between the two groups. In past studies using a variety of recognition measures, adult participants did not develop explicit awareness on the CC and ASRT tasks (Chun & Jiang, 2003; Song, Howard, & Howard, 2007). Although CC recognition was at chance in the present study, the influence of explicit awareness on the ASRT task cannot be conclusively ruled out because it was not measured. Fourth, there were children in the ASD group who did not demonstrate learning in the last epoch (see Table 1), suggesting that there may be some children with ASD who showed impaired implicit learning. However, lack of implicit learning on the last epoch at the individual level is not unusual because it was apparent in some control children (ASRT task: 5/14; CC task: 1/14).

While considering our observation of lack of group differences, it is important to note that several characteristics of our sample constrain interpretation and generalization of the present findings. First, IQ was matched across groups, and therefore, the present findings are limited to intellectually high-functioning children with ASD. Second, the present findings are limited to Asperger's syndrome, the diagnosis for 10 of the 14 children with ASD. It is also important to note that ADOS and ADI scores were unavailable on 3 children with ASD. Third, the present findings extend primarily to boys with ASD because only 1 girl was included in the ASD sample. Fourth, only 2 children with ASD were left-handed. Although hand assignment for the tasks was not changed for these participants, exclusion of their data from analyses did not influence the results. Fifth, psychotropic medications that could not be withheld during testing in some children could have influenced learning. Four of these children were on medications for attention problems that are most likely to influence learning. However, magnitude of learning did not differ between children medicated for attention problems, unmedicated children with ASD, and controls on either task (unpaired t tests, all $ps > .31$). Furthermore, magnitude of learning for these children was within 95% confidence intervals for mean magnitude of learning in control children for each task. Sixth, differences in fatigue did not appear to influence the results because both groups responded faster as epochs progressed. Faster performance, particularly on random and novel trials, is inconsistent with fatigued performance. Thus, the present findings most directly extend to right-handed, intellectually high-functioning boys diagnosed with Asperger's syndrome.

Despite no group differences in implicit spatial contextual learning, the ASD group's performance differed from that of controls in two ways. First, overall response speed on the CC task was slower in children with ASD than it was in controls, a finding that is inconsistent with reports of superior visual search in ASD (O'Riordan, Plaisted, Driver, & Baron-Cohen, 2001; Plaisted, O'Riordan, & Baron-Cohen, 1998). Superior visual search in ASD has been posited to arise from weak central coherence (Happé 1999) or a preference for visual details (O'Riordan et al., 2001). However, past studies have noted that superiority in ASD may not extend to all visual search tasks (Kenworthy et al., 2005; Kleinhans, Akshoomoff, & Delis, 2005). Our finding of slower visual search in ASD is consistent with at least one previous study examining visual search for a target letter (*T* or *F*) surrounded by similar distractors (letters that were halfway between *T*s and *F*s; Edgin & Pennington, 2005). The present CC task also required searching for a target (*T*) among similar distractors (*L*). In the present task, targets were rotated and the response required an orientation judgment for the long arm of the *T* (left/right). This added perceptual demand may have made visual search more effortful, enhancing the task's sensitivity to group differences. Thus, slower performance on tasks requiring visual search in ASD may be more apparent under certain experimental conditions. Slower visual search in children with ASD was not due to general motor impairments because baseline response speed on the ASRT task did not differ between groups. Task selectivity of performance differences suggests that slower visual search in ASD reflects atypical properties of spatial attention, possibly mediated by oculomotor dysfunction (Sweeney, Takarae, Macmillan, Luna, & Minshew, 2004) rather than perceptual–motor dysfunction. However, motivation levels could have also differed across tasks.

Second, learning on the ASRT task did not differ between the groups but its expression was more prolonged in ASD than in control children. Studies with adults indicate that the expression of sequence learning in performance can be dissociated from the acquisition of sequence knowledge. For example, participants' response latencies were modulated by task characteristics (e.g., stimulus context) and performance demands (e.g., inclusion of a secondary task), even though the structural knowledge of sequences they gained was unchanged (Jimenez, Vaquero, & Lupianez, 2006; Willingham, Greenberg, & Thomas, 1997). It is possible that prolonged expression of sequence learning in ASD reflects cognitive inflexibility that is known to characterize the ASD phenotype (Hill, 2004). Cognitive inflexibility may promote expression of learning pertaining to invariant stimulus-response contingencies, due to an inability to discard the adopted task set. Indeed, the tendency for more expression of sequence learning was observed in another psychiatric condition that is characterized by stereotypical behaviors and cognitive inflexibility, obsessive–compulsive disorder. Patients with obsessive–compulsive disorder showed numerically, albeit not statistically, greater SRT improvement relative to controls (Rauch, Savage, et al., 1997). The small sample size in the present study precludes examination of the relation between magnitude of sequence learning and cognitive inflexibility in ASD. However, this hypothesis can be tested in future studies.

Unimpaired learning of a complex sequential structure (i.e., involving second-order regularity) in children with ASD is surprising in light of impaired learning of a simpler sequential structure on the SRT task (i.e., containing zero-order regularity where some positions occur more frequently than others; Mostofsky

et al., 2000). Two factors could have contributed to these differences: First, characteristics of performance differed between the groups in the study by Mostofsky et al. (2000). Overall response speed was slower in ASD than in control children, perhaps because of motor impairments that are common in ASD. Thus, nonmnemonic aspects of SRT performance may have reduced the expression of learning in Mostofsky et al.'s ASD participants. Second, ASD is characterized by highly heterogeneous symptom expression. Perhaps differences in findings between the studies simply reflect distinct cohorts of children with ASD. Our sample consisted primarily of children diagnosed with Asperger's syndrome (10/14), whereas participants in the study by Mostofsky et al. were diagnosed with high-functioning autism. Among the 4 non-Asperger's children in the present study, learning was not below the 95% confidence interval in any child for the ASRT task but was below the 95% confidence interval in 2 children (1 with high-functioning autism, 1 with pervasive developmental disorder—not otherwise specified) for the CC task. Thus, future studies that compare ASD cohorts are needed to clarify the extent of sparing or impairment in implicit learning.

These results provide new knowledge about the functional integrity of neural systems that subserve implicit learning in ASD. First, the finding that children with ASD did not differ from controls in spatial contextual learning suggests preservation of at least one mnemonic process supported by the medial temporal lobes. Volumetric and histological studies have noted differences between individuals with ASD and controls in the hippocampus (Raymond, Bauman, & Kemper, 1996; Salmond et al., 2005; Schumann et al., 2004). Spatial contextual learning appears to rely on cortical regions surrounding the hippocampus because it was intact in amnesic patients with lesions restricted to the hippocampus (Manns & Squire, 2001). These surrounding cortices were also involved in learning of hierarchical relations among elements on a transitive inference task in monkeys (Buckmaster, Eichenbaum, Amaral, Suzuki, & Rapp, 2004). These findings suggest that medial–temporal cortices are involved in relational organization of spatial information. It would be useful to examine whether these cortical areas develop typically in ASD.

Second, the finding that sequence learning in ASD did not differ from controls suggests spared frontal–striatal–cerebellar function. No consistent finding has emerged from volumetric studies of frontal–striatal–cerebellar structures in ASD (Brambilla et al., 2003) as both larger and smaller volumes have been reported. Although there is agreement that these structures are involved in sequence learning and that their maturation supports its development (Thomas et al., 2004), the specific contribution of each structure is not fully known even in intact sequence learning. Functional imaging in ASD adults showed that despite comparable sequence learning with controls, activation was reduced in prefrontal cortex and increased in premotor cortex (Müller, Cauich, Rubio, Mizuno, & Courchesne, 2004). Thus, involvement of different cortical regions in adults with ASD and matched controls may support intact sequence learning in ASD. However, participants learned the sequence explicitly rather than implicitly in Müller et al.'s (2004) study. Prefrontal involvement in sequence learning appears to depend on the extent of explicit awareness of sequential structure in both SRT and ASRT tasks (Fletcher et al., 2005; Willingham et al., 2002). The present finding of intact ASRT learning in childhood ASD provides a basis for investigating the nature of frontal–striatal–cerebellar involvement that characterizes preserved learning.

In sum, the present findings indicate that two dissociable forms of learning, of spatial context and perceptual–motor sequences, were intact in ASD children with a diagnosis of Asperger's syndrome. If the present findings are replicated in future studies, they could be harnessed for treatment purposes. Future research could study interventions that encourage children to focus on the degree to which social cues and contextual information co-occur and how that relates to the status of implicit learning. Furthermore, findings from the ASRT task suggest that ASD may promote longer expression of learning based on invariant sequential information. Functional imaging studies of sequence learning are required to elucidate the neural basis of the current findings. The ASRT task is an optimal probe for those studies because it taps a well-operationalized learning mechanism that is rooted in frontal–striatal–cerebellar anatomy.

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Received June 12, 2007
Revision received March 17, 2008
Accepted March 18, 2008 ■