Motor-Linked Implicit Learning in Persons with Autism Spectrum Disorders

Brittany G. Travers, Mark R. Klinger, Joanna L. Mussey, and Laura G. Klinger

Fifteen adolescents and young adults with high-functioning autism spectrum disorders (ASD) and 18 age- and IQ-matched adults with typical development (TD) completed a serial reaction time task (SRT) to examine possible motor-linked implicit learning impairments in persons with ASD. Measures were taken to decrease the role of explicit learning in the SRT. Results showed that participants with ASD demonstrated intact motor-linked implicit learning. Furthermore, the motor-linked implicit learning appeared to take place at a similar rate across trials in the group with ASD compared to the group with TD. These results suggest that persons with ASD are successful in implicit learning of motor-linked behavior. The results of this study, coupled with past findings, suggest that people with ASD may be able to learn motor movements without conscious awareness, especially if the individual is older and is learning fine motor sequences.

Keywords: neuropsychology; implicit learning; sequence learning; autism spectrum disorders; serial response task

Whether engaging in ritualistic behaviors or following a social script verbatim, individuals with autism spectrum disorders (ASD) tend to be repetitive and rule-based in their interactions with the world. This rigid cognitive style may reflect the use of rote, explicit learning processes instead of the intuitive, implicit learning processes that are frequently used in interactions with the environment [Klinger, Klinger, & Pohlig, 2007]. Implicit learning is a learning that occurs without the intention to learn or learning that occurs without conscious awareness of the knowledge that is acquired [Cohen & Squire, 1980; Reber & Squire, 1994]. Implicit learning has a strong influence on the kinds of skills that are typically impaired in individuals with ASD. For example, in persons with typical development (TD), implicit learning is important for the development of early language skills [Gomez & Gerken, 1999; Saffran, Newport, Aslin, Tunick, & Barrueco, 1997] and the development of social intuitions [Lieberman, 2000], two of the three symptom domains in ASD [American Psychiatric Association, 2000]. Additionally, research with persons with obsessive–compulsive disorder (OCD) has suggested that repetitive behaviors, the third symptom domain in ASD, might also be related to differences in implicit learning. For example, neuroimaging results show that when persons with OCD complete implicit learning tasks, they are more likely to use brain regions associated with explicit learning [Rauch et al., 1997] instead of regions typically associated with implicit learning. Although these results have not been extended to persons with ASD, this finding suggests that some of the ritualistic behaviors seen in ASD may stem from overreliance on explicit learning processes and under-reliance on implicit learning processes.

Implicit Learning in Persons with ASD

Several studies suggest that individuals with ASD have impairments in implicit learning. For example, Klinger and Dawson [2001] asked children to categorize fictitious animals that differed in features like ear length, leg length, and neck length. They found that children with ASD with comorbid intellectual disability performed more poorly than verbal mental age-matched children with TD in the condition that required implicit abstraction of a category representation across multiple experiences (i.e., a prototype). However, these same children performed as well as children with TD in conditions that required rule-based category learning. This result suggests that children with ASD may have intact rule-based, explicit learning but may be impaired at implicit prototype learning. Similarly, in a group of high-functioning children and adolescents with ASD, Klinger et al. [2007] found impaired implicit learning on two tasks (i.e., a prototype formation task and an artificial grammar learning task) compared to individuals with TD. Performance on these implicit learning tasks was highly correlated with ASD symptomatology, such that poorer implicit learning task performance was related to poorer communication skills and social skills and more repetitive behaviors.
Additionally, Klinger et al. [2007] found that some people with ASD appeared to compensate for impaired explicit learning by applying more explicit (rule-based) learning to tasks. In participants with ASD, they found large positive correlations between explicit learning and performance on both implicit learning tasks, whereas in the participants with TD, there were weaker relationships between explicit learning and implicit learning. These results suggest that children and adolescents with ASD might either compensate for an implicit learning impairment by using more rote, explicit learning processes or they may simply have a cognitive set that predisposes them to prefer to engage in explicit processes as opposed to implicit ones.

These studies provide converging evidence of a possible implicit learning impairment in persons with ASD. However, it is unclear whether all types of implicit learning are impaired in persons with ASD. Research in typically developing populations has found that implicit learning is not necessarily a single, unitary construct. For example, Seger [1998] suggested at least two different types of implicit learning, that which is judgment-linked and that which is motor-linked. Judgment-linked implicit learning facilitates the categorization of stimuli (e.g., Has a prototype of the category been formed? Does the letter string follow the grammar?). Motor-linked implicit learning, on the other hand, facilitates the speed and accuracy of complex motor responses. An example of motor-linked implicit learning includes learning to play a song on an instrument (e.g., becoming faster and more accurate at performing the specific movements that correspond to the music to be played). Because the previously studied prototype and artificial grammar tasks are considered types of judgment-linked implicit learning, it is unclear whether persons with ASD may be impaired in all types of implicit learning or only judgment-linked implicit learning. With this in mind, an investigation into motor-linked implicit learning in persons with ASD was conducted.

**Motor-Linked Implicit Learning**

By definition, motor-linked implicit learning is the acquisition of patterns of movement that occur sequentially in response to our environment. The most common measure of motor-linked implicit learning is the serial reaction time task [SRT; Nissen & Bullemer, 1987]. Although the SRT has many forms, the most common form uses a display of four boxes on the computer screen with four corresponding keys. When a stimulus appears in one of the boxes, the participant must press a corresponding key as quickly as possible. Unknown to the participant, the stimulus appears in the boxes in a patterned sequence. Although most people never become consciously aware of this pattern, their faster responses to the patterned sequence of stimuli demonstrate implicit learning of the motor pattern.

Although the SRT is an implicit learning task, research using a variety of tasks suggests that pure implicit learning rarely occurs [Reingold & Merikle, 1990; Seger, 1994; Sun, Slusarz, & Terry, 2005]. Typically, learning is a result of a combination of implicit and explicit mechanisms. Hence, current research using the SRT focuses on the degree to which learning is implicit or explicit. One means of limiting explicit learning in the SRT is to decrease the response stimulus interval [RSI; i.e., the amount of time between responses and presentation of the next stimulus; Destrebecq & Cleeremans, 2001, 2003]. Presumably a decrease in the RSI limits the amount of time participants have to consciously consider the sequence of the stimuli, thereby decreasing explicit learning. A second means of reducing the amount of explicit learning in the SRT is to increase the complexity of the task [Reber & Squire, 1994]. This is often accomplished by increasing the length of the sequence or employing a second-order conditional sequence (i.e., a sequence in which each of the four locations is represented an equal number of times and is equally likely to follow each other location). In summary, an SRT that uses a longer, second-order conditional sequence with a decreased RSI is more likely to evoke implicit than explicit learning processes.

**Motor-Linked Implicit Learning in Persons with ASD**

To date, four studies have examined motor-linked implicit learning in individuals with ASD using the SRT [Barnes et al., 2008; Gordon & Stark, 2007; Mostofsky, Goldberg, Landa, & Denckla, 2000; Müller, Cauich, Rubio, Mizuno, & Courchesne, 2004]. The pattern of results found has been inconsistent. Using a 10-step sequence, Mostofsky et al. found that the participants with ASD had significantly slower reaction times and did not show the typical pattern of faster responses with increased practice as seen in persons with TD. Mostofsky and colleagues suggested that the participants with ASD were impaired in their procedural sequence learning abilities.

Müller et al. [2004] used an eight-step sequence, and found that behaviorally participants with ASD demonstrated motor-linked implicit learning similar to participants with TD. Despite similar behavioral performance, Müller et al. found different cortical activation patterns for participants with ASD and participants with TD. Specifically, there was less overall activation in the participants with ASD and more activation in the right pericentral and premotor cortex during the later stages of motor learning compared to participants with TD. Müller and colleagues interpreted these data as indicating that the persons with ASD were more stimulus-driven in their performance in the later parts of the task compared to...
participants with TD, which might suggest that the underlying sequence was learned using different processes for persons with ASD.

A third study by Gordon and Stark [2007] investigated motor-linked implicit learning in persons with ASD and comorbid intellectual disability over multiple sessions. They examined whether persons with ASD needed extra practice to learn four-step and eight-step sequences. In their first experiment, children with ASD were exposed to an eight-step sequence across six weeks. The children with ASD demonstrated motor-linked implicit learning but only after the final training session. Furthermore, the learning effects of the participants with ASD were not as robust as those of the participants with TD. Their second experiment used a four-step sequence and demonstrated similar results. However, it is important to note that this study differed from the other studies in that it required memory consolidation of the motor-linked learning over the course of weeks. Thus, impaired task performance may be due either to motor-linked implicit learning difficulties or memory consolidation difficulties in persons with ASD.

A fourth study by Barnes et al. [2008] used an alternating SRT, in which every other step in a six-step sequence included an interposed random element to control for first-order regularities (i.e., Position A then random position, Position B then random position, Position C then random position). They found that high-functioning children with ASD learned the motor sequence as well as children with TD, suggesting that motor-linked implicit learning may not be impaired in ASD. Although the alternating SRT was used to reduce explicit motor learning, the sequences to be learned in this study were short (only six steps in length) and might have been more easily learned via explicit processes.

In summary, the results have been inconsistent with two studies finding motor-linked implicit learning impairments in people with ASD [Gordon & Stark, 2007; Mostofsky et al., 2000] and two studies finding no motor-linked implicit learning impairment [Barnes et al., 2008; Müller et al., 2004], although Müller et al. reported differences in neural activation patterns. However, all four of these studies had similar methodologies that potentially increased the amount of explicit learning used: All four studies used longer RSIs [Barnes et al.: RSI = 120 msec; Gordon & Stark: RSI = 500 msec; Mostofsky et al.: RSI = 1,500 msec; Müller et al.: RSI = 550 msec]. All four studies used relatively shorter sequences [Barnes et al.: Sequence Length = 6; Gordon & Stark: SL = 4 or 8; Mostofsky et al.: SL = 10; Müller et al.: SL = 8]. Finally, all the studies except Barnes et al. had sequences that did not control for first-order conditional relations. Therefore, this study set out to test motor-linked implicit learning in persons with ASD under conditions that minimized the influence of explicit learning processes by using an RSI of 0 msec, a longer sequence (12 items), and a sequence that controlled for second-order conditional relations.

Method
Participants
Fifteen participants with high-functioning ASD (age range 14 years, 3 months to 25 years, 2 months) completed this study. All participants were required to have a Kaufman Brief Intelligence Test [K-BIT2; Kaufman & Kaufman, 2004] verbal standard score of at least 75. Two additional participants with ASD did not meet this cut-off and were not included in the analyses. The participants with ASD were recruited from the University of Alabama ASD Research Clinic and met the diagnostic standards for autism on the Autism Diagnostic Interview-Revised [ADI-R; Lord, Rutter, & LeCouteur, 1994] and had received a previous clinical diagnosis of an ASD by the fourth author based on ADI-R symptoms, Autism Diagnostic Observation Scale [ADOS; Lord et al., 2000], and clinical impressions. Because our “gold standard” diagnostic measures do not differentiate between ASD subtypes, we did not use DSM-IV diagnostic subtypes to classify the participants. However, according to previous diagnoses by our clinic, seven of the 15 participants had received a diagnosis of Asperger’s Disorder. Means and standard deviations for participants’ ADI-R are presented in Table I. Because ADI-R diagnoses are based on symptoms across the lifetime, current ASD symptoms were assessed using the Social Responsiveness Scale [SRS; Constantino, 2002]. For the ASD group, the average SRS score was 79. Because some participants were older than 18 and the SRS was normed for children from 4 to 18 years of age, raw scores rather than t-scores are reported. However, the average raw score of this sample was consistent with a t-score of 72, which falls within the mild-to-moderate range of symptom severity. Medication status was also assessed. At the time of testing, two participants with ASD were taking antidepressant medication, one participant with ASD was taking a

<table>
<thead>
<tr>
<th>ADI-R Domain Scores</th>
<th>ASD</th>
<th>TD</th>
<th>P</th>
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<tbody>
<tr>
<td>Social</td>
<td>18.2 (3.9)</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Verbal Communication</td>
<td>11.9 (4.9)</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Restrictive/Repetitive Behavior</td>
<td>5.4 (2.2)</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>SRS Scores</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Raw</td>
<td>78.7 (31.3)</td>
<td>21.0 (12.6)</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>
stimulant, and one participant with ASD was taking both an antidepressant and a stimulant.

Eighteen individuals with TD (age range 14 years, 3 months to 22 years, 9 months) completed the study. Participants with TD were recruited through advertisements at local schools or through the existing University of Alabama Department of Psychology participant database. Participants with TD were screened through a parent-report or self-report history background questionnaire that asked if the participant had ever been diagnosed with Autism, Asperger’s Disorder, PDD-NOS, Attention Deficit Hyperactivity Disorder, a Learning Disability, Mental Retardation, Cerebral Palsy, or Tourette’s/Tic Disorder. For participants younger than 18 years, the background questionnaire was done via parent-report. For participants 18 years or older, the background questionnaire was done via self-report. Because participant exclusion criteria were outlined when an appointment was scheduled, no participants with TD reported the presence of one of these neurological disorders that could potentially confound the results. In terms of medication, one participant with TD was taking anti-seizure medication at the time of testing.

Participant groups were matched on age and verbal ability [i.e., raw score on the Kaufman Brief Intelligence Test 2; K-BIT2; Kaufman & Kaufman, 2004]. Table II contains means and standard deviations for the age and intellectual functioning variables that defined the participant groups. Independent sample t-tests revealed that the ASD and TD groups were well matched on age, $t(31) = 0.03, P = 0.98$, K-BIT2 verbal raw scores, $t(31) = 0.71, P = 0.48$, and IQ, $t(31) = -0.59, P = 0.56$. There were no significant group differences in verbal standardized scores, $t(31) = 0.11, P = 0.91$, nonverbal standardized scores, $t(31) = -1.38, P = 0.18$, or SES, $t(20) = 0.34, P = 0.74$.

**Apparatus**

The experiment was programmed using Inquisit 2.0 software and was run on a Windows-based laptop computer with a 15 in. monitor. The keyboard was used by participants to enter responses.

**Measures**

**Social Responsiveness Scale (SRS).** The SRS [Constantino, 2002] is a 65-item parent report measure that examines ASD symptom severity over the last six months. Each item asks about an aspect of observed reciprocal social behavior and is rated on a scale from ‘0’ (never true) to ‘3’ (almost always true). The SRS includes a social awareness, social information processing, capacity for reciprocal social responses, social anxiety/avoidance, and characteristic autistic preoccupations/traits subscales. According to Constantino [2002], the test-retest reliability after 27 months was 0.83. The SRS is normed for persons 4 to 18 years of age. However, we used the SRS for all our participants (up to age 25) in order to have a reliable measure of current symptom severity. Subsequently, only SRS raw scores were used in analyses.

**Procedure**

IRB approval was received from the University of Alabama. After informed consent procedures, parents were asked to complete the SRS. If the participant was younger than 18 years, the parents were additionally asked to complete a background history questionnaire, which requested information regarding the participants’ medications, diagnoses, and family income. For participants 18 years or older, the participant completed the background questionnaire prior to the SRT. If the parent was present at the testing session, the parent completed the forms while the participant completed the SRT. If the parent was not present, the background history form (for participants younger than 18) and SRS were sent home to be completed. For the ASD group, the response rate for the parent forms was 15 out of 15; for the TD group, the response rate was 8 out of 18.

**Serial Reaction Time Task (SRT).** Participants were instructed to respond to a black-and-white racecar that popped up in one of four rectangles on the screen by pressing the corresponding keyboard key as fast as possible. The participants were told that this was their primary task and both accuracy and reaction time were recorded. On this task, blocks of sequenced or non-sequenced trials were presented to the participants. Sequenced trials consisted of a 12-step sequence of racecar locations in boxes 1-2-1-2-4-1-3-4-2-3 (1 = the position of the stimulus in the farthest left rectangle). This sequence was taken from Jiménez and Vázquez [2005] and required that each position appear in each ordinal location equally often and that no location be repeated back-to-back. Also, this sequence was a second-order-conditional sequence, meaning that each position was equally as likely to follow each of the other three positions. Each block began at a randomly selected point in the 12-step sequence.

**Table II. Mean and (Standard Deviation) of Participant Characteristics and Significance Levels of T-test Comparing the Groups (P)**

<table>
<thead>
<tr>
<th></th>
<th>ASD</th>
<th>TD</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>15</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>Age (years–months)</td>
<td>19–0 (2–11)</td>
<td>19–0 (2–1)</td>
<td>0.98</td>
</tr>
<tr>
<td>K-BIT IQ</td>
<td>103 (17.8)</td>
<td>100 (14.1)</td>
<td>0.56</td>
</tr>
<tr>
<td>Verbal Raw</td>
<td>81 (14.9)</td>
<td>84 (10.2)</td>
<td>0.48</td>
</tr>
<tr>
<td>Nonverbal Raw</td>
<td>38 (5.6)</td>
<td>36 (4.4)</td>
<td>0.45</td>
</tr>
<tr>
<td>Verbal Standardized</td>
<td>99 (19.1)</td>
<td>100 (15.3)</td>
<td>0.91</td>
</tr>
<tr>
<td>Nonverbal Standardized</td>
<td>106 (14.4)</td>
<td>99 (12.0)</td>
<td>0.18</td>
</tr>
</tbody>
</table>
Vaquero, Jiménez, and Lupiáñez [2006] found that reversals (e.g., when the stimulus jumps from position one to position three and then returns to position one) were typically more present in non-sequenced trials and increased response times in these trials because of inhibition of return [e.g., attentional difficulties in processing stimuli at just-seen locations; Posner & Cohen, 1984]. Thus, they found that reversals artificially inflated learning effects by making participants slower at non-sequenced blocks. In order to avoid reversal effects in this study, the pattern of the racecar in the non-sequenced condition was not purely randomized. Non-sequenced trials were constructed using the Research Randomizer website (http://www.randomizer.org), but all numbers that repeated back-to-back were omitted in order to prevent the racecar from appearing stuck in one of the locations. Also, the non-sequenced trials were edited to allow for only one reversal (e.g., 2-4-2 or 3-1-3) for every 12 trials in order to make the number of reversals identical to the sequenced trials.

The SRT consisted of nine blocks of trials with one-minute breaks between each block. Each block had 120 trials (i.e., 10 repetitions of the sequence in sequenced blocks), and there were no pauses between trials (RSI = 0). The first three blocks were practice trials that consisted of non-sequenced trials instead of sequenced trials to acclimate participants to the task. The responses from the practice blocks were not analyzed.

After practice, participants began six blocks of 120 experimental trials. The first four of these blocks consisted of sequenced trials. The fifth block consisted of non-sequenced trials, followed by the sixth block, which was sequenced. The entire SRT took approximately 20 min to complete.

Immediately after the SRT, the experimenter administered an explicit post-test to assess how much of the sequence could be reproduced from memory by both groups of participants. The post-test used a sheet of paper that had 24 numbered rows with four rectangles in each row. The participants were told that there was a sequenced pattern to some of the movements of the racecar, and they were instructed to use each row to indicate how the racecar moved. The first row always had an “X” in the first box, and it was explained that this “X” represented the car starting in the first rectangle of that row. We instructed the participants to guess where the car would jump next by making an “X” in one of the four rectangles in the second row and on through the remaining 22 rows.

After completing the SRT and explicit post-test, the participants were given the K-BIT2 by the experimenter, which lasted approximately 30 min. After the K-BIT2, if the participant’s parent had not previously completed an ADI-R at the ASD Research Clinic at University of Alabama, an ADI-R was administered; this occurred with only one participant. Finally, the participant and the parent(s) were debriefed about the experiment. The entire experimental session lasted less than one hour for those not needing a new ADI-R. For the participant who did need a new ADI-R, the session lasted approximately 2 1/2 hr. Participants were reimbursed $10 for their participation.

**Results**

**SRT Task**

Initial analyses looked at accuracy for the SRT. For each trial, the stimulus remained on the monitor until the correct response was given. However, if an incorrect response was initially given, this would affect the final reaction time, so the accuracy of initial responses for the two diagnostic groups was examined. Overall, both groups were very accurate. The mean accuracy for the ASD group was 0.95 (SD = 0.05), and the mean accuracy for the TD group was 0.94 (SD = 0.04), which did not significantly differ, t(31) = −0.60, P = 0.55.

Reaction times were used as the main dependent variable for the SRT and were only analyzed for the correct trials. Additionally, reaction times that were deemed too fast to truly represent responses to the stimuli (less than 200 ms, 0.3% of correct trials) or that were deemed extremely slow indicating distraction from the task (greater than 1,500 ms, 0.1% of correct trials) were eliminated. After the data were trimmed, we transformed raw reaction times by taking the reciprocal of the reaction time to each trial1 to normalize the distribution of reaction times and to reduce the role of outliers. Mean reciprocal reaction times were then computed for each block, and these means were transformed back to millisecond response time units. The mean reaction time for each diagnostic group in each block of trials is presented in Figure 1. As can be seen, both diagnostic groups showed reaction times that decreased across sequenced blocks one through four, increased during non-sequenced block five, and decreased again in sequenced block six.

To examine motor-linked implicit learning we averaged the reaction times of sequenced blocks four and six, and we contrasted this mean with the reaction times from non-sequenced block five. Learning was considered demonstrated if reaction times to sequenced blocks four and six were significantly faster than reaction times to non-sequenced block five. A 2 (sequenced vs.

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1The reciprocal reaction time was calculated by dividing one by the raw reaction time of each trial (1/RT). This is a common transformation used in reaction time data that addresses and controls for the positive skew and outliers inherent to RT data [i.e., Greenwald, Nosek, & Banaji, 2003; Imam, 2006; Spencer & Chase, 1996]. We conducted the same analyses using medians instead of reciprocal reaction times, and we found the same pattern of group level and correlational results.
The 2 × 2 ANOVA revealed a significant main effect for the type of trial (sequenced vs. non-sequenced), $F(1,31) = 44.26$, $P < 0.001$, $\eta^2_p = 0.59$, indicating faster reaction times to sequenced trials across diagnostic groups. Also, there was a significant main effect for diagnosis, $F(1,31) = 5.47$, $P = 0.03$, $\eta^2_p = 0.15$, indicating slightly slower reaction times to all conditions by participants with ASD. Most importantly, there was no significant interaction between type of trial and diagnosis, $F(1,31) = 0.08$, $P = 0.78$, $\eta^2_p = 0.003$, indicating the participants with ASD and TD showed similar amounts of motor learning of the sequence. To further examine motor-linked implicit learning in each group, we conducted paired sample $t$-tests examining the difference between sequenced and non-sequenced blocks within each diagnostic group. In the TD group, sequenced blocks were significantly faster than the non-sequenced block, $t(17) = -5.24$, $P < 0.001$. Similarly, in the ASD group the sequenced blocks were significantly faster than the non-sequenced block, $t(14) = -4.22$, $P = 0.001$. Additionally, we analyzed whether those participants with a previous diagnosis of Asperger’s disorder’s diagnosis differed in their motor-linked implicit learning from those with autistic disorder. The results indicated that the two groups did not differ in their learning of the motor sequence, $F(1,13) = 0.01$, $P = 0.94$.

Although the two groups showed similar amounts of learning by the time they got to blocks four through six, it is possible that the two groups arrived at these similar amounts of learning by learning at different rates during the first four blocks of trials as was seen in Gordon and Stark (2007). To test this, we examined the amount of learning that took place over the first four blocks of sequenced trials using a 4 (block) × 2 (diagnosis) ANOVA with block treated as a linear variable. The analysis found a linear effect for block, $F(1,31) = 13.77$, $P = 0.001$, $\eta^2_p = 0.31$. This result indicates that learning took place across the first four blocks with reaction times getting faster in a linear fashion. However, no interaction between this linear effect of block and diagnosis was observed, $F(1,31) = 0.390$, $P = 0.54$, $\eta^2_p = 0.01$. That is, both groups showed similar learning effects across the first four blocks. These analyses suggest that the rate of learning between participants with ASD and participants with TD was not significantly different.

After examining the reaction time data, we calculated the results from the explicit post-test. Because of experimenter error, one participant with ASD did not complete the explicit post-test. Thus, the post-test results reflect the performance of 18 participants with TD and 14 participants with ASD. In line with the procedures of Destrebecqz and Cleeremans (2001, 2003), we scored the explicit post-test by breaking the sequence into chunks of three and counting the triads that were correctly identified by the participants. If any triad was identified by the participant more than twice in the 24 blocks, it was only counted as correct the first two times to reflect its true frequency in a sequence of 24 trials. The number of correct triads was then divided by the number of possible correct triads to calculate the percent correct. The participants with ASD averaged 37% correct (SD = 0.16) and the participants with TD averaged 38% correct (SD = 0.14). Thus, the diagnostic groups did not perform significantly different on the explicit post-test, $t(30) = 0.27$, $P = 0.79$. With 36 possible triads and 12 triads in the sequence, 33% correct was considered chance performance on this post-test. A one-sample $t$-test revealed that the post-test performance of both groups was marginally but not significantly better than chance, $t(31) = 1.90$, $P = 0.07$. These results indicate that participants may have explicitly learned part of the sequence, although this was not a large effect.

**Correlational Results**

We conducted exploratory correlations to investigate possible relationships between motor-linked implicit learning, age, IQ, post-test performance, and current ASD symptom severity. The amount of motor-linked implicit learning (e.g., the reaction time difference between the non-sequenced and sequenced blocks of trials) was calculated for each participant. Then, the relation between this measure of motor learning and age, IQ, and post-test performance was tested across participants. The amount of motor-linked implicit learning was not significantly correlated with the age, $r(32) = 0.13$, 

Figure 1. Reaction times by diagnosis in the SRT. Block five is the non-sequenced block among sequenced blocks.
Discussion

This study used an SRT that was designed to limit explicit learning in order to better compare motor-linked implicit learning ability in participants with ASD and matched participants with TD. Explicit learning was minimized by increasing the length of the sequence, making a second-order conditional sequence, and eliminating the time gap between stimuli [Destrebecqz & Cleeremans, 2001, 2003]. The explicit post-test results suggest that we were mostly successful in this endeavor. Participants only correctly identified sequenced triads 37–38% of the time where 33% represented chance performance, and recall of the sequence was marginally but not significantly different from chance across participants. Also, this study minimized “reversal effects,” which can create illusory learning effects by artificially increasing the reaction time to the non-sequenced blocks [Vaqueiro et al., 2006].

This study found that the participants with ASD and participants with TD showed similar amounts of learning of a 12-step sequence. The lack of a diagnostic effect was observed both when comparing sequenced to non-sequenced blocks of trials and when looking at the rate of learning across the first four blocks. These results suggest that motor-linked implicit learning is likely intact in high functioning adolescents and young adults with ASD. Also, no significant correlations between motor-linked implicit learning scores and age, IQ, or explicit post-test scores were found. Furthermore, no significant correlation between motor-linked implicit learning and symptom severity in the group with ASD was found. This suggests that all participants with ASD, both those with high and low symptom severity, showed similar levels of motor-linked implicit learning performance. However, one limitation of this study is that there might have been too few participants to detect significant correlations between motor-linked implicit learning and symptom severity.

Our SRT results replicated the behavioral results of both Müller et al. [2004; adolescents and adults] and Barnes et al. [2008; children and adolescents], finding that participants with ASD demonstrated motor-linked implicit learning at a similar rate to participants with TD. Because special care was taken to limit the amount of explicit learning, it is unlikely that the present results are due to participants with ASD compensating for motor-linked implicit learning impairments by engaging in more explicit learning processes. The explicit post-test results support this conclusion by demonstrating that participants with ASD and participants with TD did not significantly differ in their explicit knowledge of the sequence and that their explicit knowledge was only marginally greater than chance levels. However, an additional limitation to this study may be that the explicit post-test measure encouraged participants to guess at the sequence if they did not know it. This may have led participants to rely on their implicit learning in this explicit post-test. Indeed, it is thought that most learning tasks typically engage both implicit and explicit learning in tandem [Seger, 1994; Sun, Merrill, & Peterson, 2001; Sun et al., 2005], which makes it difficult to definitively separate the two. However, in terms of the degree to which the sequence was learned implicitly or explicitly, our post-test results suggest that the sequence was primarily learned in an implicit fashion. Furthermore, reaction time indications of implicit learning in the SRT were not correlated with performance on the explicit post-test measure, suggesting that explicit learning likely had minimal impact on the learning effects shown by the reaction times. Thus, the present results in addition to the results of Müller et al. and Barnes et al. provide converging evidence that high-functioning persons with ASD may not be impaired in the implicit learning of motor sequences. Nevertheless, as Müller et al. found, differing patterns of neural activation may underlie these results. Future research should further examine the neural correlates of motor-linked implicit learning in this population.

A similarity between this study and the study of Barnes et al. [2008] is that both studies had a high number of participants with ASD who had received a DSM-IV diagnosis of Asperger’s disorder. However, the present results indicated no difference in the learning of the sequence between the participants with a DSM-IV diagnosis of Asperger’s disorder and the participants with a DSM-IV diagnosis of autistic disorder. This suggests that the demonstration of equivalent motor-linked implicit learning in participants with ASD was not due to the high proportion of participants with Asperger’s disorder in this study. The results of this study are inconsistent with Mostofsky et al.’s [2000] finding that participants with

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We have not included data from the TD participants here because of the restricted range of ASD symptoms in this group and because of low power (only eight SRS’s were returned by the parents of TD participants).
ASD showed impaired motor-linked implicit learning and Gordon and Stark [2007] finding that participants with ASD showed delayed motor-linked implicit learning. However, the SRT studies conducted by Mostofsky and colleagues and by Gordon and Stark differed from this study in a couple of important ways. Specifically, Gordon and Stark had participants learn the motor sequence over multiple sessions. Second, the studies of Gordon and Stark and of Mostofsky and colleagues included younger participants than this study, and their task registered responses using the entire hand of the participant rather than the individual fingers of the participant.

Because Gordon and Stark [2007] had participants learn the motor sequence over multiple sessions, it was suggested in the introduction that the results of Gordon and Stark may be due either to motor-linked implicit learning difficulties or memory consolidation difficulties in persons with ASD. However, in looking at the first session alone, Gordon and Stark's presented participants with 576 sequenced trials (12 blocks of 48 trials each), and this study similarly presented participants with 600 sequenced trials (5 blocks of 120 trials each). Thus, participants of Gordon and Stark's first session had almost the same amount of exposure to the sequence as participants of this study, but the participants in this study demonstrated learning of the motor sequence, whereas the participants of Gordon and Stark's study did not. This result suggests that the differing results between Gordon and Stark's study and this study were most likely not solely due to difficulties in memory consolidation.

In terms of the age differences between this study and the studies of Mostofsky et al. [2000] and Gordon and Stark [2007], it is possible that there is a developmental trend in motor-linked implicit learning, such that younger persons with ASD may have poorer motor-linked implicit learning compared to persons with TD, whereas older persons with ASD have similar motor-linked implicit learning. One argument against this age hypothesis is that Barnes et al. [2008] found no motor-linked implicit learning impairments in children with ASD who were approximately the same age as the children in the studies of Mostofsky et al. and Gordon and Stark. Furthermore, no correlation between motor-linked implicit learning and age was found in this study. Nevertheless, future studies should examine motor-linked implicit learning longitudinally in order to examine the developmental trajectory of this type of learning in both persons with ASD and persons with TD.

A second major difference between this study and studies by Mostofsky et al. [2000] and Gordon and Stark [2007] is that the participants in those studies used their entire hand to respond to the stimuli instead of just using individual fingers. Thus, it is possible that Mostofsky et al.'s and Gordon and Stark's studies tested motor-linked implicit learning of gross motor movements of the arms and hands, whereas this study, as well as the studies of Barnes et al. [2008] and Müller et al. [2004], tested the motor-linked implicit learning of fine motor movements of the fingers. Both gross and fine motor impairments have been reported in persons with ASD [for a review see Dawson & Watling, 2000 or Gidley Larson & Mostofsky, 2008]. However, in the context of a learned motor sequence, it is possible that gross motor movements may be more difficult for persons with ASD to integrate into a motor sequence than fine motor movements. The larger movements entailed by gross motor sequences may require increased attention to extrinsic space (i.e., attention to the spatial configuration and constraints of the external environment), and there is evidence for circumscribed spatial attention and perception in some persons with ASD [e.g., Lovaas, Koegel, & Schreibman, 1979; Townsend & Courchesne, 1994; Wang, Mottron, Peng, Berthiaume, & Dawson, 2007]. Subsequently, persons with ASD may show poorer learning of motor sequences that involve gross motor movements because of the difficulty of attending to a broader extrinsic space. This study was not designed to examine possible differences between gross and fine motor-linked implicit learning. However, this could be an important avenue for future study.

Research examining motor-linked implicit learning has important implications for understanding the motor abilities of persons with ASD. Clinically, it is often reported that children with ASD have difficulty learning how to ride a bike, which requires the sequencing of gross motor movements. At the same time, it is often reported that children with ASD can excel at computer and video games, which require the sequencing of fine motor movements. This seemingly paradoxical motor symptom profile seems to be reflected in the results of the research examining motor-linked implicit learning. Studies using more gross motor movements have found impairments in persons with ASD, whereas studies using more fine motor movements did not find impairments. This result suggests that the implicit learning of motor sequences is likely not a global impairment in this population, but that under certain conditions (i.e., older, high-functioning individuals with ASD learning fine motor scripts) persons with ASD may implicitly learn these motor sequences as well as persons with TD.

In summary, the results of this study found that adolescents and young adults with ASD were able to implicitly learn a 12-step sequence as well as and at the same rate as age and IQ-matched participants with TD. In comparison to previous research finding impaired judgment-based implicit learning [prototype learning and artificial grammar learning, Klinger & Dawson, 2001; Klinger et al., 2007], these results suggest that fine motor-linked implicit learning mechanisms are intact in persons with ASD. Future research is needed to further examine
age effects, gross vs. fine motor sequence learning, and the underlying neurological connections that allow for both judgment-linked and motor-linked implicit learning.

References


