Two Forms of Implicit Learning in Young Adults with Dyslexia

Ilana J. Bennett,[a] Jennifer C. Romano,[b] James H. Howard, Jr.,[b,c] and Darlene V. Howard[a]

[a]*Department of Psychology, Georgetown University, Washington, DC, USA*

[b]*Department of Psychology, Catholic University of America, Washington, DC, USA*

[c]*Department of Neurology, Georgetown University, Washington, DC, USA*

Implicit learning is thought to underlie the acquisition of many skills including reading. Previous research has shown that some forms of implicit learning are reduced in individuals with dyslexia (e.g., sequence learning), whereas other forms are spared (e.g., spatial context learning). However, it has been proposed that dyslexia-related motor dysfunction may have contributed to the implicit sequence learning deficits reported earlier. To assess implicit sequence learning in the absence of a motor sequence, 16 young adults diagnosed with dyslexia (20.6 ± 1.5 years) and 18 healthy controls (20.8 ± 2.0 years) completed a triplet frequency learning task (TRIP) that involved learning a sequential regularity in which the location of certain events followed a repeating pattern, but motor responses did not. Participants also completed the spatial contextual cueing task (SCCT), which involved learning a spatial regularity in which the location of distractors in some visual arrays predicted the target location. In addition, neuropsychological tests of real-word and pseudo-word reading were administered. TRIP task analyses revealed no between-group differences in pattern learning, but a positive correlation between individual learning scores and reading ability indicated that poor readers learned less well than did good readers. Thus, earlier reports of reduced implicit sequence learning in dyslexics cannot be entirely accounted for by motor sequencing deficits. No significant correlations or group differences in learning were found for SCCT. These findings offer additional evidence for a link between poor reading and impaired implicit sequence learning.

Key words: **implicit learning; sequence learning; spatial context learning; dyslexia; reading ability**

Introduction

Developmental dyslexia is characterized by low reading achievement despite normal intelligence and ample education or learning opportunity (American Psychiatric Association [APA], 2000). The reading weakness is typically attributed to phonological processing deficits whereby individuals with dyslexia have difficulty learning associations between how words appear in print (graphemes) and how they sound (phonemes) (Bradley & Bryant, 1983; Ramus *et al.*, 2003; Snowling, 2001). However, this explanation does not account for the wide range of sensory, cognitive, and motor deficits also observed in dyslexia (Habib, 2000; Ramus *et al.*, 2003).

An alternative theory is that deficits associated with dyslexia are due to underlying impairments in skill learning (e.g., Nicolson & Fawcett, 1990; Rudel, 1985). This view is in line with dyslexia technically being classified as a learning disorder (APA, 2000). Skills

Address for correspondence: Ilana J. Bennett, Georgetown University, Department of Psychology, 301 N White Gravenor Hall, Washington, DC 20057. Voice: +202-687-4099; fax: +202-687-6050. ijb5@georgetown.edu

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such as reading can be acquired through both explicit and implicit processes. For example, grapheme–phoneme associations are initially learned through explicit memorization, but implicit rule-based decoding skill evolves through repeated exposures to regularly formed words (Gombert, 2003; Uhry & Clark, 2005). Research has shown that explicit, effortful forms of skill learning are spared in poor readers and dyslexics (Sperling, Lu, & Manis, 2004; Vicari, Marotta, Menghini, Molinari, & Petrosini, 2003, Exp. 2), whereas studies of implicit learning have revealed a mixed pattern of spared (Howard, Howard, Japikse, & Eden, 2006; Kelly, Griffiths, & Frith, 2002; Russeler, Gerth, & Munte, 2006) and impaired (Howard *et al.*, 2006; Sperling *et al.*, 2004; Vicari *et al.*, 2005) learning.

Implicit learning occurs in a wide range of tasks that reveal nonconscious, unintentional sensitivity to regularities among stimuli (Seger, 1994). Studies have shown that these tasks differ not only in the nature of the regularity present, but also in the underlying neural systems they engage (Forkstam & Petersson, 2005; Stadler & Frensch, 1997). For example, implicit sequence learning tasks examine the learning of sequential regularities. In the serial reaction time task (SRTT) (Nissen & Bullemer, 1987), participants respond faster and more accurately to visual stimuli that follow a repeating sequence of locations versus stimuli that occur at randomly determined locations. On the other hand, implicit spatial context learning tasks investigate how spatial regularities are learned. In the spatial contextual cueing task (SCCT) (Chun & Jiang, 1998), search performance is better for visual arrays in which the configuration of distractors predicts the location of a target compared to nonpredictive arrays. Sequence learning tasks such as the SRTT have been shown to rely on a frontal-striatal-cerebellar network, whereas spatial context learning in the SCCT is mediated by medial temporal lobe structures, specifically the hippocampus and/or parahippocampal cortex (Chun & Phelps, 1999; Greene, Gross, Elsinger, & Rao, 2007; Prull, Gabrieli, & Bunge, 2000).

One study by Howard and colleagues (2006) found a dissociation between these two forms of implicit learning in the same group of young adults with dyslexia. Sequence learning was measured with a modified version of the SRTT, the alternating serial reaction time task (ASRT) (Howard & Howard, 1997), in which stimuli that follow a repeating sequence of locations (pattern) alternate with randomly determined stimuli (random). Analyses showed that the dyslexic group learned significantly less than age-matched controls on the ASRT task as determined by faster and more accurate responses to pattern versus random stimuli. But on the SCCT, there was no group difference in spatial context learning. In addition, correlations between reading ability and implicit learning revealed that poor reading ability was associated with reduced sequence learning, but preserved spatial context learning. These outcomes are consistent with data indicating that differences in brain function associated with dyslexia overlap with the neural systems involved in implicit sequence learning, but not with those involved in implicit spatial context learning. That is, compared to controls, individuals with dyslexia show reduced activation in inferior frontal and left temporal-parietal areas during language-based tasks (Collins & Rourke, 2003; Habib, 2000). Other imaging studies find that dyslexics have abnormal structure and function of the cerebellum (Eckert *et al.*, 2003; Finch, Nicolson, & Fawcett, 2002; Menghini, Hagberg, Caltagirone, Petrosini, & Vicari, 2006; Nicolson *et al.*, 1999; Rae *et al.*, 2002) and striatum (Brown *et al.*, 2001). Together these results suggest that frontal-striatal-cerebellar regions are affected in dyslexia. In contrast, abnormalities in medial temporal lobe structures are not known to be characteristic of dyslexia.

Implicit sequence learning deficits, like those observed by Howard and colleagues in 2006, have been reported in multiple studies of children and young adults with dyslexia (Menghini *et al.*, 2006; cf. Russeler *et al.*, 2006; Stoodley, Harrison, & Stein, 2006; Vicari *et al.*, 2005; Waber *et al.*, 2003). However, all of these studies used tasks in which a motor sequence was present. This is potentially important because there is evidence that dyslexic individuals have problems executing sequential motor movements. For example, deficient planning and timing of the sequential motor plans involved in speech production have been proposed to underlie dyslexia-related difficulties in repeating series of syllables and reading complex phrases (Catts, 1989; Wolff, Cohen, & Drake, 1984; Wolff, Michel, & Ovrut, 1990a). Nonlinguistic tasks also reveal motor sequencing problems in dyslexia. For instance, poor readers perform worse on finger-tapping tasks when they require alternating movements between hands versus repeating them with a single finger (Wolff, Michel, Ovrut, & Drake, 1990b), and dyslexic children demonstrate inferior coordination of movements during copying tasks (Denckla, 1985). Therefore, the question arises as to whether such motor sequencing deficits may have been the sole source of impairment reported in the earlier implicit sequence learning studies.

The present study was designed to assess implicit sequence learning in the absence of motor sequencing in young adults with and without dyslexia using a variation of the ASRT that contained no motor sequence (Howard, Howard, Dennis, & Kelly, 2008; Howard *et al.*, 2004). The same individuals completed the SCCT, which also does not require participants to use motor sequencing. In addition to examining group differences, correlation analyses were performed using measures of the two types of implicit learning and reading ability because previous studies have indicated that continuous measures of reading skill may be more sensitive than the dichotomous group variable (Conlon, Sanders, & Zapart, 2004; Howard *et al.*, 2006; Shaywitz, Escobar, Shaywitz, Fletcher, & Makuch, 1992). It was expected that if earlier reports of reduced implicit sequence learning in poor readers and individuals with dyslexia were solely due to motor sequencing deficits, then there should be no group differences on the nonmotor sequence learning task and no relationship between nonmotor sequence learning and reading ability. However, if the deficits were due at least in part to a more general sequencing deficit, then the dyslexic group should learn less than the nondyslexic group in the present task, and poor reading should be associated with less learning. For spatial context learning, it was expected that there would be no group differences in learning and no relationship between measures of learning and reading ability, indicating preserved spatial context learning in young adult poor readers.

Methods

Participants

Participants were 16 individuals with dyslexia and 18 nondyslexic controls. Inclusion criteria for all participants were being an undergraduate student at the Catholic University of America between the ages of 18 and 25 years. Participants in the dyslexic group met criteria for a diagnosis of dyslexia according to the Catholic University Disability Support Services Office, which was based on current and comprehensive neuropsychological evaluations and interviews with qualified professionals. Individuals were excluded from the dyslexic group if they also met criteria for dysgraphia, or had an unspecified learning disorder. Participants in the control group had no history of learning disability. Table 1 presents demographic and neuropsychological characterizations for each group. Participants received either payment or course credit and gave informed consent for experimental procedures approved by the Catholic University of America Institutional Review Board.

General Procedure

Participants completed 1-hour testing sessions on each of three separate days. On the first day, they signed an informed consent form and then completed the triplet task (TRIP). The

TABLE 1. Demographics and Neuropsychological Test Results

	Dyslexic ($n = 16$)	Control ($n = 18$)	t
Demographics			
Age	20.6 ± 1.5	20.8 ± 2.0	n.s.
Male/female	4/12	5/13	
Neuropsychological tests			
WASI Two-Subtest IQ SS	109.8 ± 10.5	115.6 ± 9.1	n.s.
WJ-III Word Identification SS	92.0 ± 8.2	103.5 ± 6.8	4.1**
WJ-III Word Attack SS	87.1 ± 10.0	98.8 ± 10.7	3.6*
WJ-III Spelling SS	93.4 ± 10.4	110.2 ± 7.4	5.4**
RAN average speed	28.3 ± 3.7	23.9 ± 3.9	−3.4*
RAN average errors	1.8 ± 4.1	0.9 ± 0.7	n.s.
WAIS-III Digit Symbol coding	69.4 ± 16.0	85.1 ± 23.3	2.3*
WAIS-III Digit Symbol pairing	14.8 ± 2.8	14.8 ± 3.2	n.s.
WAIS-III Digit Symbol recall	7.7 ± 1.4	7.8 ± 1.1	n.s.
WAIS-III Digit Span forward	9.8 ± 2.1	11.7 ± 2.1	2.7*
WAIS-III Digit Span backward	6.6 ± 2.5	8.1 ± 2.1	n.s.
Auditory Consonant Trigrams	5.4 ± 2.9	8.1 ± 1.8	3.2**

Notes. All scores are given as mean ± SD based on raw data, except where standard scores are noted. Independent sample t-tests show group effects (*$P < .05$, **$P < .001$, n.s. = not significant). WASI = Wechsler Abbreviated Scale of Intelligence; WJ-III = Woodcock-Johnson, 3rd edition; SS = age-adjusted standard score with a mean of 100 and standard deviation of 15; RAN = Rapid Automatized Naming; and WAIS-III = Wechsler Adult Intelligence Scale, 3rd edition.

spatial contextual cueing task (SCCT) was completed on the second day. Neuropsychological tests were administered on the third day. The three testing sessions were completed within a 1-week period for all participants, except for one dyslexic subject whose testing spanned 12 weeks.

Triplet Frequency Learning Task (TRIP)

For the TRIP task, participants viewed four black outlined open circles presented in a horizontal row on a 15 in. (38 cm) Apple iMac computer monitor. For purposes of description below, the four stimulus locations are referred to as 1, 2, 3, and 4, where 1 is the leftmost position and 4 is the rightmost position. However, numbers never appeared on the screen. Each trial, referred to as a triplet, comprised three discrete events, in which two red circles appear, one after the other, followed by a green circle. Participants were instructed to respond to the location of the green event using the middle and index fingers of each hand to press the corresponding buttons ("z", "x", "/" and "." on the keyboard). Each of the three events was presented for 120 ms with a 150 ms interstimulus interval. The green event remained on the screen until the correct response was made, and 650 ms later the next trial began. Participants completed thirty 50-trial blocks. They were encouraged to take short breaks after each block.

Like the ASRT (Howard *et al.*, 2006), the TRIP task contained a second-order sequential structure, in which the location of every other stimulus follows a repeating pattern. As a result of this sequential regularity in the ASRT task, stimulus location on trial n predicts the location of trial $n + 2$. For example, in the sequence 1r2r3r4r, numbers represent the predictable, alternating trials that follow the repeating pattern, with 1 through 4 denoting the location of the filled-in circle, and the letter "r" referring to trials where the stimulus could occur at any of the four locations. The same sequential regularity occurred in the TRIP task, with the location of the first event within a triplet predicting the location of the third event. For example, in the triplet 1r2, where 1 and "r" refer to red events and 2 refers to the green event, the first red circle at location 1 predicts that the green circle will occur at location 2, with the location of the second red event being randomly determined. Thus, the triplet 1r2 is consistent with the repeating pattern 1r2r3r4r. In the ASRT, runs of three consecutive trials (i.e., triplets) that were consistent with the pattern (high-frequency triplets) occurred 75% of the time, and pattern-inconsistent triplets (low-frequency triplets) occurred 25% of the time. However, in this TRIP task, high-frequency and low-frequency triplets occurred 90% and 10% of the time, respectively.

Participants received feedback at the end of each block that was designed to direct responding to 92% accuracy. The feedback consisted of mean reaction time and mean accuracy for a given block, plus a statement prompting them to "focus more on accuracy" if their mean accuracy was below 90% or to "focus more on speed" if their mean accuracy was above 94%.

A recognition task and an interview were used to assess explicit knowledge of the sequential regularity. In a 24-trial recognition task (Howard *et al.*, 2004), all possible combinations of triplet events were presented with the black circles, not red and green circles. For each triplet, participants were instructed to indicate whether that combination of events occurred "frequently" or "infrequently" during the task by pressing one of two buttons. A postexperiment interview was also administered. Questions ranged from general inquiries about strategies used to improve performance and the frequency of events occurring at each location to more specific questions about the relationships between the red and green events, asking participants to describe the regularity if they noticed one.

Spatial Contextual Cueing Task

Stimuli and procedures for the SCCT used here are identical to those described previously (Howard *et al.*, 2006). Participants viewed visual arrays on a 15 in. (38 cm) Apple iMac computer monitor. Arrays were made up of 11 distractors (the letter *L* rotated by 0, 90, 180, or 270 degrees) and one target (horizontal letter T) that were white against a gray background. Distractors were made more similar to the target by offsetting the L legs by 3 pixels (Chun & Phelps, 1999, Exp. 2). On each trial, a fixation dot appeared for one second, followed by an array. Participants were instructed to search the array for the target and respond as quickly and accurately as possible by pressing "z" if the tail of the horizontal T was pointing left or "/" if it was pointing right, using their left and right index fingers, respectively. Auditory feedback after each response indicated correct (short beep) and incorrect (long tone) responses. If responses did not occur within 6 seconds, the trial ended with a long tone indicating an incorrect response, and the next trial began. Participants completed one practice block of 24 novel arrays, and then thirty 24-trial test blocks. They were encouraged to take short breaks after each block.

Twelve arrays repeated across all test blocks. In these familiar arrays, the locations of the distractors predicted the location of the target but not its orientation. Therefore, this regularity could not be used to predict the correct response. The remaining 12 arrays for each block were novel across the experiment. Within each block, presentation of familiar and novel arrays was randomized.

A recognition task and an interview were used to assess explicit knowledge of the spatial regularity. In a 24-trial recognition task (Chun & Jiang, 2003) the screen was divided into four quadrants by short lines placed at the midpoints of each side of the screen. The 12 familiar arrays from the test blocks and 12 novel arrays were presented with a distractor in place of the target location. For each array, participants were instructed to indicate which quadrant the target would most likely have occurred in by pressing one of four buttons on the keyboard. A postexperiment interview was also administered, with questions ranging from general inquiries about the task and material to more specific questions asking participants whether they noticed that certain displays repeated across trials.

Neuropsychological Testing

A battery of neuropsychological tests was administered to characterize the cognitive profiles of each group. Some tests were later correlated with measures of implicit learning. An intelligence quotient (IQ) was calculated using two subtests of the Wechsler Abbreviated Scale of Intelligence (WASI) (Wechsler, 1999): the Vocabulary subtest that involved defining orally presented words, and the Matrix Reasoning subtest that entailed identifying the missing piece of an abstract visual display. Real-word and pseudo-word reading were assessed with the Woodcock–Johnson (WJ-III) (Woodcock, McGrew, & Mather, 2001) Word Identification and Word Attack subtests, respectively, in which participants read aloud lists of English words or pronounceable nonsense words. The WJ-III Spelling subtest measured participants' ability to write orally presented words. Rapid Automatized Naming (RAN) (Denckla & Rudel, 1974) assessed the speed of naming separate series of colors, objects, letters, and numbers. The Wechsler Adult Intelligence Scale (WAIS-III) (Wechsler, 1997) Digit Symbol Coding subtest measured hand–eye coordination and processing speed by giving participants 2 minutes to fill in the symbols that corresponded to a series of digits. Cued recall of the digit–symbol pairs and free recall of the symbols were assessed with the WAIS-III Digit Symbol Pairing and Recall subtests, respectively. Working memory was measured with WAIS-III Digit Span Forward and Backward, and Consonant Trigrams (Peterson & Peterson, 1959). The digit span task involved repeating progressively longer strings of numbers in the same (forward) or reverse (backward) order they were presented, and Consonant Trigrams required that participants recall three consonants after short intervals during which they performed a distracting counting task.

Results

Demographics and Neuropsychological Data

Demographic information and neuropsychological test results are presented in Table 1. The dyslexic and control groups were matched on age and gender. Neuropsychological tests revealed a pattern characteristic of dyslexia in that both groups were of normal intelligence, but the dyslexic group performed significantly worse than the control group on measures of real-word and pseudo-word reading (WJ-III Word Identification and Word Attack subtests, respectively), spelling (WJ-III Spelling), naming speed (RAN average speed of the four stimulus sets), hand–eye coordination and processing speed (WAIS-III Digit Symbol Coding), and working memory (WAIS-III Digit Span Forward and Consonant Trigrams).

Implicit Learning Data: Group Analyses

Implicit learning was examined in each task using separate repeated-measures ANOVAs for reaction time and accuracy measures. For each block, median reaction times on correct trials and mean accuracy scores were calculated for high-frequency and low-frequency triplets in the TRIP task and for familiar and novel arrays in the SCCT. A variable of epoch was then created by taking the mean of these scores across groups of five blocks.

Implicit Sequence Learning (TRIP)

To assess potential group differences in implicit sequence learning, group (dyslexic, control) × triplet type (high-frequency, low-frequency) × epoch (1–6) mixed-design ANOVAs were conducted separately for reaction time and accuracy measures (Fig. 1).

For reaction time, the dyslexic group (423.4 ± 51.8 ms) responded significantly slower than the control group (390.1 ± 54.6 ms), $F(1, 32) = 5.9$, $P < .03$. A main effect of epoch, $F(5, 160) = 67.7$, $P < .001$, and a

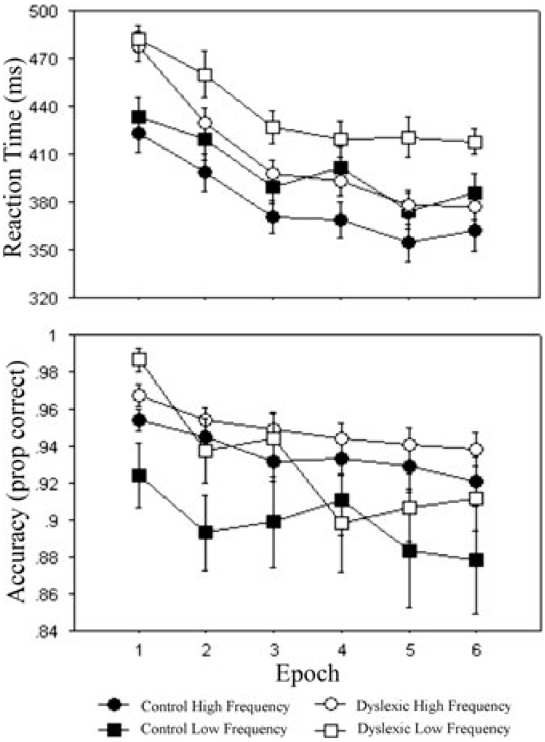

Figure 1. For the TRIP task, responses to high-frequency (*circles*) and low-frequency (*squares*) triplets for the control (*solid symbols*) and dyslexic (*open symbols*) groups on mean of median reaction time (ms) and mean accuracy (proportion correct) measures.

group × epoch interaction, $F(5, 160) = 2.5$, $P < .04$, showed that overall speed increased more across epochs for the dyslexic group compared to controls. Sequence learning was revealed by significant effects of triplet type, $F(1, 32) = 112.9$, $P < .001$, and triplet type × epoch, $F(5, 160) = 4.4$, $P < .001$, with faster responses to high-frequency (393.4 ± 54.0 ms) versus low-frequency (418.1 ± 54.8 ms) triplets, a difference that increased across epochs. Group × triplet type and group × triplet type × epoch interactions were not significant, P's > .10, indicating that we did not detect group differences in sequence learning.

For accuracy, the dyslexic group (94.0 ± 5.9%) did not differ from the control group (91.7 ± 8.0%), $P > .15$, showing that, as intended, the feedback provided after every block successfully matched the groups on overall accuracy. A significant main effect of epoch, $F(5, 160) = 7.2$, $P < .001$, showed that accuracy decreased across epochs, which is typical in sequence learning tasks as participants make increasingly more errors on pattern-inconsistent trials as they learn the regularity. Sequence learning was seen as a main effect of triplet type, $F(1, 32) = 13.6$, $P < .001$, with more accurate responses to high-frequency (94.2 ± 4.0%) versus low-frequency (91.4 ± 9.2%) triplets. In line with the reaction time results, group differences in sequence learning were not observed in either the group × triplet type or group × triplet type × epoch interactions, P's > .21.

Implicit Spatial Context Learning (SCCT)

To assess implicit spatial context learning, group (dyslexic, control) × array type (familiar, novel) × epoch (1–6) mixed-design ANOVAs were conducted for both behavioral measures (Fig. 2). One control participant was not included in this analysis because the data were lost because of a computer error.

For reaction time, responses were significantly slower in the dyslexic group (2.1 ± 0.4 sec) compared to the control group (1.8 ± 0.5 sec), $F(1, 31) = 4.8$, $P < .04$. There was a significant main effect of epoch, $F(5, 155) = 64.8$, $P < .001$, with responses speeding up across epochs. Spatial context learning was revealed by faster responses to familiar arrays (1.9 ± 0.5 sec) compared to novel arrays (2.0 ± 0.4 sec), $F(1, 31) = 4.3$, $P < .05$. There were no significant group differences in learning (group × array type, $P > .68$; group × array type × epoch, $P > .06$). However, the marginal three-way interaction was followed up with separate array type × epoch ANOVAs for each group, which revealed significant learning in the control group (array type, $F(1, 16) = 5.1$, $P < .04$; array type × epoch, $F(5, 80) = 2.9$, $P < .03$), but not in the dyslexic group (P's > .34).

For accuracy, the dyslexic group (92.9 ± 6.2%) made significantly more errors than the control group (96.0 ± 3.5%), $F(1, 31) = 6.9$, $P < .02$. A main effect of epoch, F(5,

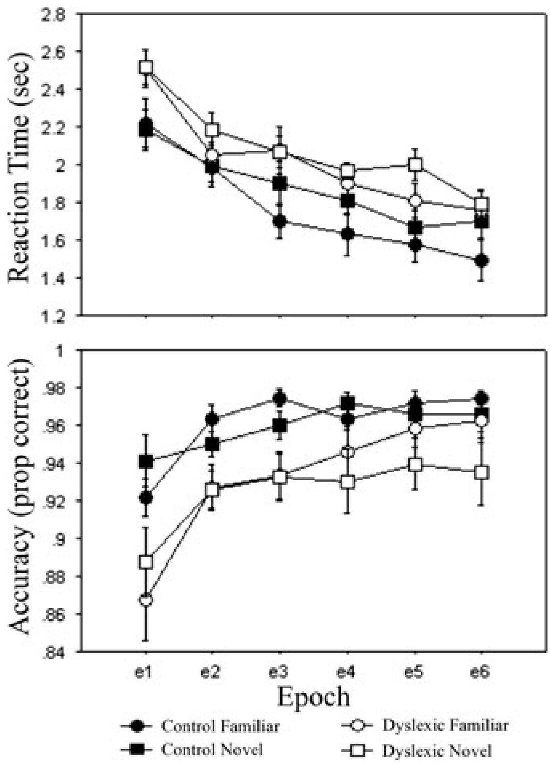

Figure 2. For the SCCT, responses to familiar (*circle*) and novel (*square*) arrays for the control (*solid symbols*) and dyslexic (*open symbols*) groups on mean of median reaction time (sec) and mean accuracy (proportion correct) measures.

155) = 22.1, $P < .001$, showed that accuracy increased across epochs. The array type effect did not attain significance, $P > .19$, but spatial context learning was seen with a significant array–type × epoch interaction, $F(5, 155) = 3.3$, $P < .01$. Group × array type and group × array type × epoch interactions were not significant, P's > .29, indicating that there were no group differences in learning.

Correlations between Implicit Learning and Reading Ability

As indicated earlier, it is important to conduct correlations between individual measures of reading ability and implicit learning because these analyses may better capture relationships with reading skill, especially when there is a broad range of reading ability within both groups, and an overlap between the groups. Learning scores for each behavioral measure were calculated for each participant by taking the difference, in the final epoch, between high-frequency versus low-frequency triplets for the TRIP task and familiar versus novel arrays for the SCCT. Real-word and pseudo-word reading were measured for each participant, using age-adjusted standard scores from the WJ-III Word Identification and Word Attack subtests.

A significant positive correlation was observed for the TRIP accuracy learning score and pseudo-word reading, $r = +.38$, $P < .03$. Thus, although there were no group differences in sequence learning, this correlation shows that poor reading is associated with reduced sequence learning. There was also a nonsignificant trend, $r = +.31$, $P < .09$, for poor pseudo-word reading to be associated with lower SCCT reaction time learning scores, which is in line with the group analyses that revealed spatial context learning on the reaction time measure in the control group, but not the dyslexic group. Scatter plots for these correlations are presented in Figure 3. Correlations between implicit learning scores and real-word reading were in the same direction as above, but they did not attain significance, P's > .40.

Correlations between Implicit Learning and Rapid Naming

Because of the similarities between sequential processing in implicit sequence learning and rapid naming (e.g., sequential eye movements, processing sequentially presented stimuli, and executing sequential motor responses), correlations were also conducted between TRIP learning scores and measures of average speed and average errors from the four stimulus sets of the RAN. In line with previous studies that show that poor reading is associated with worse performance on the RAN (Denckla & Rudel, 1976; Wolf, Bowers, & Biddle, 2000), a significant negative correlation was seen between pseudo-word reading and average RAN

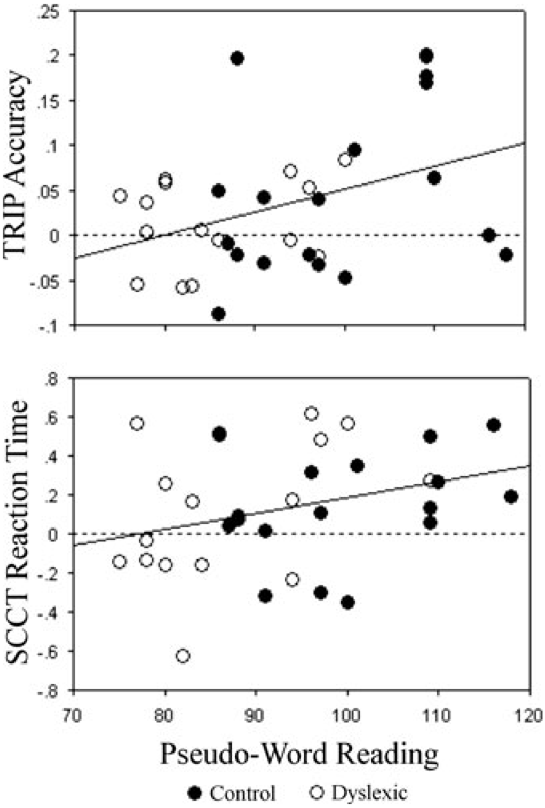

Figure 3. Scatter plots separately comparing learning scores for the TRIP task (accuracy) and SCCT (reaction time) to the measure of pseudo-word reading (age-scaled score) for the control (*solid circle*) and dyslexic (*open circle*) groups.

speed, $r = -.44$, $P < .01$. More importantly, results revealed a significant negative correlation between RAN speed and the TRIP accuracy learning score, $r = -.39$, $P < .03$, indicating that individuals who performed more slowly on the rapid naming task also learned less on the TRIP task.

Measures of Implicitness

After the TRIP task, participants completed a recognition task in which they judged the frequency of all combinations of triplet events. Mean recognition ratings were calculated for each participant as the proportion of times high-frequency and low-frequency triplets were reported as having occurred "frequently" during the task. A group (dyslexic, control) × triplet type (high-frequency, low-frequency) mixed-design ANOVA showed no significant effects (P's $> .14$), indicating that high-frequency ($.42 \pm .14$) and low-frequency ($.45 \pm .08$) triplets were rated as occurring equally often in both the dyslexic and control groups. Similarly, analyses of the postexperiment interview did not reveal any explicit awareness. Three dyslexic and six control participants indicated that they noticed a relationship between either of the two red events and the third green event, but no individual accurately described the nature of the regularity.

After the SCCT, participants completed a recognition task that involved viewing arrays in which the targets were replaced by distractors and indicated in which quadrant the target would most likely have occurred. Mean accuracy scores were calculated for each participant for familiar and novel arrays. A group (dyslexic, control) × array type (familiar, novel) mixed-design ANOVA revealed no significant effects (P's $> .08$). That is, target quadrants were recognized equally often for familiar and novel arrays for both groups. Thus, as for the TRIP task, analyses of the postexperiment interviews did not reveal any explicit awareness of the spatial regularity. Eight dyslexic and five control participants indicated that they noticed certain displays repeated across trials. However, none of them reported explicitly trying to memorize the displays to facilitate performance.

Taken together, recognition tests and postexperiment interviews for both the TRIP and SCCT indicated that no participant had explicit awareness of either regularity even though they responded faster and/or more accurately to high-frequency versus low-frequency triplets and familiar versus novel arrays.

Discussion

This study examined the relationship between two forms of implicit learning (sequence learning and spatial context learning) and reading ability in young adults with and without dyslexia. Implicit sequence learning was assessed in the absence of motor sequencing using the TRIP task to determine whether motor sequencing deficits could be the sole source of sequence learning impairment previously seen in poor readers and individuals with dyslexia (Howard *et al.*, 2006; Menghini *et al.*, 2006; Stoodley *et al.*, 2006; Vicari *et al.*, 2005). In contrast to previous studies that used motor sequence learning tasks, between-group analyses revealed no group differences in learning. However, in line with those studies, pseudo-word reading was positively correlated with the TRIP accuracy learning score, indicating that poor readers had sequence learning deficits even when there was no motor sequence to be learned. Implicit spatial context learning, measured with the SCCT task, revealed no group differences in learning as previously reported (Howard *et al.*, 2006), and there were no significant correlations between spatial context learning and reading ability. Unlike some previous studies that could not rule out explicit learning, results observed here must be due to implicit learning because there was no evidence of explicit awareness in either the TRIP or SCCT task, as assessed via recognition tests and verbal reports. The findings are discussed in more detail below.

Implicit Sequence Learning

A significant positive correlation between pseudo-word reading and TRIP learning on the accuracy measure was found in the current study. The analogous correlation was also observed in a study by Howard and colleagues (2006), using the ASRT learning task. This suggests that poor (pseudo-word) readers are relatively worse at sequence learning whether or not a motor sequence is present, because the ASRT task contained a sequence of motor responses but the TRIP task does not. Thus, earlier reports of sequence learning deficits (Howard *et al.*, 2006; Menghini *et al.*, 2006; Stoodley *et al.*, 2006; Vicari *et al.*, 2005) cannot be explained by motor sequencing deficits alone. Instead, implicit sequence learning deficits in poor readers are likely due, at least in part, to difficulty learning other forms of sequential information that are present in both the TRIP and ASRT tasks, such as the perceptual sequence of stimuli and/or the sequence of eye movements to fixate the target stimuli (Goschke, 1998; Mayr, 1996; Seger, 1997).

In fact, there is existing evidence that poor readers have perceptual sequence learning deficits. For example, one study found significantly less learning in dyslexics versus controls using a task that contained a perceptual sequence, but not motor response or eye movement sequences (Vicari *et al.*, 2003). Perceptual sequence learning deficits are predicted by the temporal processing theory, which states that individuals with dyslexia are poorer at integrating sequential sensory information, especially when stimuli are presented rapidly (Habib, 2000). This theory developed from work showing that children and young adults with dyslexia have difficulty on tasks that involve processing rapid sequences of auditory (Helenius, Uutela, & Hari, 1999; Tallal, 1980) and visual (Conlon *et al.*, 2004; Eden, Stein, Wood, & Wood, 1995) stimuli. Other explanations have been proposed for the perceptual sequencing deficits in dyslexia, including deficient sensory processing in the magnocellular pathway (Stein, 2001), delayed attention shifting (Hari & Renvall, 2001), and limited perceptual memory (Ben-Yehudah, Sackett, Malchi-Ginzberg, & Ahissar, 2001). According to the latter explanation, individuals with dyslexia have a limited capacity to retain perceptual traces and compare them across short intervals. In the TRIP task, learning involves retaining perceptual traces across the three events within a trial, binding these events into a triplet, and then comparing triplets across trials. Thus, an inability to retain and compare perceptual traces could manifest as implicit sequence learning deficits in poor readers.

It could also be argued that difficulty learning the sequence of eye movements to fixate the targets contributes to sequence learning deficits in poor readers. However, support for this view is hard to establish because there are conflicting results from examinations of oculomotor control in poor readers. Some studies report that individuals with dyslexia make more eye movements and have difficulty maintaining fixation compared to controls (Biscaldi, Gezeck, & Stuhr, 1998; Eden, Stein, Wood, & Wood, 1994; Pavlidis, 1981), whereas others find no group differences (Black, Collins, De Roach, & Zubrick, 1984; Olson, Kliegl, & Davidson, 1983; Stanley, Smith, & Howell, 1983). If present, abnormal eye movements in poor readers would affect their ability to fixate the targets during sequence learning tasks, which may influence their perception of the sequential stimuli, and ultimately affect their sequence learning performance. In either case, the TRIP task does not allow us to separate perceptual and eye movement sequencing deficits in poor readers

Sequencing deficits in poor readers have also been observed in analyses of the rapid automatized naming task (RAN). Although the RAN is usually thought of as a measure of phonological retrieval (Wagner & Torgesen, 1987) or processing speed (Wolf & Bowers, 1999), the nature of the task suggests that sequential processing is also involved. Stimuli for the RAN include separate cards that display series of colored squares, objects, letters, and numbers. Participants are instructed to name the items on each card out loud as fast as possible. Thus, successful completion of the task involves making sequential eye movements to fixate the items, processing the perceptual sequence of stimuli, and then executing the speech-related sequence of motor movements. Results from both group analyses and correlations between pseudo-word reading and RAN average speed replicated previous findings of reduced rapid naming ability in poor readers (Denckla & Rudel, 1976; Wolf *et al.*, 2000). Interestingly, slow naming was significantly associated with less learning on the TRIP accuracy learning score, supporting the notion that both RAN and TRIP tasks reflect a sequencing deficit in poor readers.

The relationship between implicit sequence learning, reading ability, and speech production makes sense from an evolutionary perspective. According to this view, language skills such as speech and reading may have evolved from similar but more basic processes like sequence learning. Speech production involves sequential motor movements and is therefore thought to have been adapted from neural networks involved in motor sequencing (Lieberman, 2002). Similarly, reading, an even more recent sequential skill than speech, may have evolved from more primitive sequencing functions (Dehaene, 2004). This perspective is strengthened by the fact that these three processes rely on similar neural structures including frontal regions, cortical motor areas, the striatum, and the cerebellum (Bohland & Guenther, 2006; Fiez & Petersen, 1998; Lieberman, 2002; Riecker *et al.*, 2005; Wildgruber, Ackerman, & Grodd, 2001).

When dyslexic and control groups were combined, both the present TRIP study and a previous study that employed the ASRT (Howard *et al.*, 2006) found positive correlations between reading ability (pseudo-word reading) and implicit sequence learning. However, unlike the previous study, the current study did not find significant group differences in learning. Interpreting the between-group effects is complicated because, in addition to differences in the presence (ASRT) or absence (TRIP) of motor sequencing, the TRIP and ASRT tasks differ in ways that do not allow for direct comparison across tasks. For example, although both tasks had the same structural complexity (i.e., event $n + 2$ is predicted by event n), the ratio of high-frequency triplets to low-frequency triplets was higher in the TRIP task (9:1) compared to the ASRT task (3:1), perhaps making the TRIP task easier to learn. The TRIP task also isolated the triplets from the sequence by presenting each triplet as a discrete trial, whereas triplets in the ASRT task occur in a continuous overlapping stream. Nonetheless, because correlation analyses revealed similar effects for reading ability across studies, it suggests that, as previously indicated by others (Conlon *et al.*, 2004; Howard *et al.*, 2006; Shaywitz et al., 1992), our understanding of this heterogeneous disorder might be clarified if future research includes correlation analyses that treat reading ability as a continuous variable in addition to group analyses that treat reading skill as a dichotomous variable based on diagnoses of dyslexia.

Implicit Spatial Context Learning

Results for implicit spatial context learning in this study were only partially consistent with our predictions based on an earlier examination of spatial context learning in young adults with dyslexia (Howard *et al.*, 2006). As expected, there were no significant group differences in learning on the SCCT. However, there was a trend for a positive correlation between pseudo-word reading and SCCT learning on the reaction time measure, whereas a negative correlation had been reported previously (Howard *et al.*, 2006). Direct comparisons of the results from these two studies are complicated because in the present study, but not in the earlier study, the dyslexic group was significantly less accurate than the control group. In addition, none of the group comparisons or correlations between reading ability and SCCT learning in the present study is significant, revealing only marginal trends. Thus, results from both studies suggest that implicit spatial context learning is preserved in poor readers.

Future Considerations

Additional research is necessary to clarify the impaired and spared implicit learning abilities in poor readers and individuals diagnosed with dyslexia. Deficits have been reported for sequence learning (Howard *et al.*, 2006; Menghini *et al.*, 2006; Stoodley *et al.*, 2006; Vicari *et al.*, 2005), mirror drawing (Vicari *et al.*, 2005), and categorical learning (Sperling *et al.*, 2004). However, other forms of implicit learning, such as spatial context learning (Howard *et al.*, 2006) and some types of artificial grammar learning (Pothos & Kirk, 2004; Russeler *et al.*, 2006), appear to be relatively spared. This information may be relevant to training programs that could improve reading fluency in dyslexia by either targeting underlying deficits in implicit learning or by capitalizing on intact implicit learning processes.

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Conflicts of Interest

The authors declare no conflicts of interest.

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