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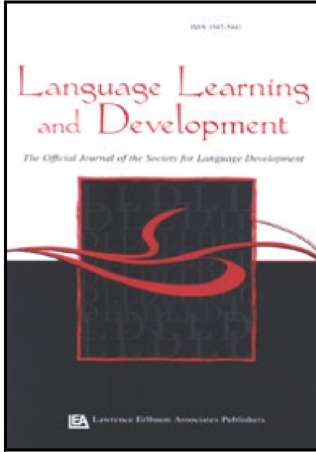

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Procedural Learning in Adolescents With and Without Specific Language Impairment

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Procedural Learning in Adolescents With and Without Specific Language Impairment

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Deficits in procedural learning have been hypothesized to contribute to the language and in particular grammatical difficulties of individuals with specific language impairment (SLI). This study tested this hypothesis by examining serial reaction time (SRT) learning in adolescents with and without SLI. The SRT task involved blocks of random sequences and pattern sequences. Response times for correct trials showed that responses for both groups improved in the trial blocks containing the pattern sequence. Adolescents with SLI showed slower learning rates during the pattern learning in comparison to the controls. When the language impairment was defined in terms of grammar impairments similar slower learning rates were found, but when language impairment was based on vocabulary group differences were not found. The results suggest that deficits in procedural learning system may account for some of the individual differences in language and grammar learning as well as problems of individuals with SLI.

INTRODUCTION

Individual differences in ability for spoken language learning can inform us about the cognitive mechanisms involved in language acquisition. There is a debate that language acquisition utilizes a general purpose learning mechanism or if humans possess a language learning mechanism that is specific only to language and not used for other purposes (Hauser et al., 2002). If low language and grammatical abilities are directly associated with poor ability in learning

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regularities in nonverbal sequences, it is possible that a cognitive mechanism associated with language and grammar learning is a general purpose sequential pattern tracker.

Given that explanatory theories of language development must provide accounts about the mechanisms that contribute to individual differences in spoken language achievement, it becomes important to contrast children who are particularly poor language learners with those who are typical learners. One group of poor language learners is those referred to as children with specific language impairment (SLI). SLI refers to a developmental condition in which children present a slow development of spoken language that in most cases results in long-term restrictions in listening and speaking skills in the absence of hearing loss or other neurodevelopmental disorders, including autism and mental retardation (Tomblin & Zhang, 2006). One view of these children is that they represent the tail end of the distribution of language learning abilities and therefore the systems that cause these children to be poor learners are the same as those that result in average or even above average skills (Dale & Cole, 1991; Leonard, 1987; Tomblin & Zhang, 1999).

Theories concerning the cause of SLI have drawn on the same theoretical systems that have been offered as explanations to language development in general. Some theoretical accounts of SLI have focused exclusively on linguistic impairments and argue that features in the child's abstract grammatical system may either be impaired or absent (Gopnik & Crago, 1991; Rice & Wexler, 1996). Extensive research has shown that children with SLI have particular difficulties with the grammatical morphology of English (e.g., Bedore & Leonard, 1998; Cleave & Rice, 1997) and other languages (Clahsen, 1989; Leonard, 2000). These difficulties in grammar have been explained by some through variations of the Principles and Parameters linguistic theory (e.g., Clahsen, Bartke & Goellner, 1997; Wexler, 2003). Other theoretical accounts have focused on a more general purpose processing or cognitive mechanism that might be compromised in SLI. These accounts of SLI have postulated that the grammatical impairments seen in these children are *not* specific to an abstract linguistic rule system but rather are secondary to perceptual and/or cognitive processing deficits. Thus, in this regard the specificity of the impairment to language alone as suggested by the term specific language impairment is a misnomer. These accounts have proposed that the deficits in SLI underlying impairment in SLI have to do with, for example, auditory temporal processing (Tallal et al., 1996), limited working memory capacity (Gathercole & Baddeley, 1990; Weismer et al., 1999b) or slower general speed of processing (Miller et al., 2001). These processing accounts have pinpointed tasks that pose difficulties for children with SLI but have failed to make a clear-cut connection between the grammatical difficulties these children exhibit and the proposed processing/ perceptual deficits.

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In a recent review of SLI literature, Ullman and Pierpont (2005) propose a "Procedural Deficit Hypothesis", which combines key elements from the linguistic and processing/cognitive accounts of SLI. They argue that the grammatical impairments seen in SLI may be explained by impairment in the general purpose learning mechanism. They suggest that children with SLI may have abnormalities in brain areas associated with procedural memory; namely, cortico striatum and the network of areas connected to these areas. The procedural memory system is integral when new sequential cognitive and motor skills, such as typing and bike riding, are learned. Learning is gradual and often unconscious, but the learned skills soon become automatic and efficient. Grammatical impairments seen in SLI may be explained by impairments in procedural learning, i.e., in learning of regularities in sequential patterns. Relative strengths in word learning as compared to learning of grammar seen in SLI could be explained by a relatively spared lexical declarative memory system, which is supported by brain systems involving the hippocampus and neocortex. Ullman and Pierpont also argue that non-linguistic impairments seen in SLI, such as reduced performance on working memory tasks (Weismer et al., 1999a), temporal processing (Tallal et al., 1996), motor sequencing (Bishop, 2002), and mental imagery (Johnston & Weismer, 1983) could be explained by impairments in procedural learning of sequences.

Although Ullman and Pierpont (2005) outlined several pieces of converging evidence for the existence of a procedural learning deficit in children with SLI, no direct tests of the procedural learning abilities of these children have been conducted. A classic task for studying procedural learning of sequential patterns is the serial reaction time task (SRT; Jimenez, 2002). On the SRT task, participants are asked to press a button corresponding to a spatial location of a visual stimulus trial by trial. A random order of stimulus locations is followed by a pattern of locations, which can be either deterministic or probabilistic. Decreased response times during the pattern are taken as evidence of learning as the participants learn to anticipate where the next stimulus will appear. Pattern learning such as that found in the SRT task and other sequential pattern learning tasks is fast, robust, automatic, and general in nature (e.g., Cleeremans & Mcclelland, 1991; Cleeremans et al., 1998; Clegg et al., 1998; Saffran, 2003). Such learning has been demonstrated across a variety of situations, including speech segmentation (Saffran et al., 1996a; Saffran et al., 1996b; Christiansen et al., 1998), learning the orthographic regularities of written words (Pacton et al., 2001), visuomotor learning (Hunt & Aslin, 2001), and tone sequences (Saffran et al., 1999).

Because these tasks often require little if any intent to learn, or awareness of having learned a pattern, these tasks are viewed as examples of implicit learning. Reber and colleagues (Reber et al., 1991) have proposed that implicit learning is an early evolved cognitive ability and that there should therefore be no substantial individual differences in implicit learning. However, considerable individual

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differences in learning of patterns have been found. Differences have been observed between children and adults (Saffran, 2001), children of varying ages and mental abilities (Fletcher et al., 2000) and children and adolescents with dyslexia when compared to normal readers (Vicari et al., 2003). Similarly, individual differences on the SRT task have also been shown to correlate with variations in educational attainment, occupational status, and verbal ability in older adults (Cherry & Stadler, 1995). Thus, although learning of regularities in sequences appears to be a skill that is present across development, systematic individual differences have been found and are perhaps associated with language ability.

Interestingly, there may be an important link between the difficulty the children with language learning difficulties have with language learning and limitations on their ability to exploit both probabilistic and deterministic sequence structure. Consistent with Ullman and Pierpont's view (2005), we hypothesized that the unusual difficulties experienced by children with SLI with aspects of grammar may reflect a limitation in procedural learning of sequences. Further support for this hypothesis comes from the recent findings by Plante, Gómez, and Gerken (2002) showing that young adults with language/learning disabilities were less capable of learning word patterns generated by a finite state grammar than adult controls.

Further evidence in support of a role for procedural learning in the etiology of developmental speech and language impairment comes from the recent discovery of the *FOXP2* gene (Lai et al., 2001). A mutation in this gene resulted in a form of specific speech and language disorder in the affected family members of one large pedigree (KE) in the UK. Studies of expression of this gene in mice and imaging studies of the affected family members provided evidence that this gene is important to the development and function of the corticostriatal system among other neural systems (Lai et al., 2003). In particular, the volume of the caudate nucleus, a structure that is part of the procedural learning system, was found to be smaller in affected family members than unaffected family members (Watkins et al., 2002). These results are consistent with a large amount of recent literature involving animals and humans showing that the striatum is very likely to play an important role in procedural learning (Packard & Knowlton, 2002). Lai et al. (2003) hypothesized that the language deficits of the affected individuals in their study were the result, in part, of deficits of procedural learning arising from the action of the *FOXP2* mutation on these corticostriatal circuits. To date, there is no evidence that mutations in *FOXP2* cause SLI (Meaburn et al., 2002; O'Brien et al., 2003). Therefore, these findings regarding procedural learning and *FOXP2* cannot be extended directly to SLI. However, these data do show that what appear to be deficits of procedural learning can be associated with developmental speech and language impairments.

Given that abilities to learn pattern regularities have been implicated in language learning in several ways, and given that this learning trait appears to vary

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among learners, it is reasonable to predict that individuals with SLI would be less adept in procedural learning tasks than typical language learners. Specifically, we would predict learning rates and/or the amount of sequential learning to be poorer among individuals with SLI, when compared with individuals with typical language learning abilities. To test this prediction, a serial response time (SRT) task was employed in order to measure the rate and amount of learning within this paradigm.

METHOD

Participants

A group of 85 8th grade adolescents, 38 (*Mean age* 15.00, *SD* = .60) who had been identified as having SLI when they were in kindergarten, and 47 classmates (*Mean age* 14.76, *SD* = .64) who had normal language (NL) skills participated in this study[1]. All these adolescents were members of a longitudinal cohort that had initially been recruited and their language status initially characterized when they were in kindergarten (see Tomblin et al., 1997 for details of sampling and assessment). Twelve out of the 38 children with SLI (32%) and 15 out of the 47 typical language learners (32%) were females. The mean age of assessment was 5.91 (*SD* = .37) for SLI and 5.94 (*SD* = .31) for typical development. All participants were administered a battery of standardized language and nonverbal IQ, and hearing tests. The kindergarten criteria for inclusion in the SLI group were language skills below −1.25 in *z*-scores in 2 or more of 5 areas of language in conjunction with IQ levels of 85 and above. Figure 1 shows that during the kindergarten testing, the SLI group exhibited a performance pattern typically seen in SLI in comparison to typical language peers. The two groups of adolescents were matched for nonverbal IQ, $t(84) = .67$, $p = .50$, and all children had nonverbal IQs above 85. The SLI group exhibited significant difficulties in producing and comprehending language, vocabulary, grammar, and narrative. The groups did differ with respect to handness. Twice as many adolescents with SLI were left handed (18%) than the normals (9%). Figure 1 also lists the tests used to compute composite scores for the different areas ability. Local norms for each of these composite scores were computed using a method described by Tomblin and

[1]We consider the classification of children into groups as simply a categorical assignment based on relative standing on specified language measures. Thus the terms “impaired” and “normal” are not being used to refer to invariant traits of the children, but rather assigned status that can vary depending upon among other things the language measures used. Thus, the group status of children can and will change. Throughout this paper SLI will refer to an assignment based on language measures spanning vocabulary, sentence use and narration.

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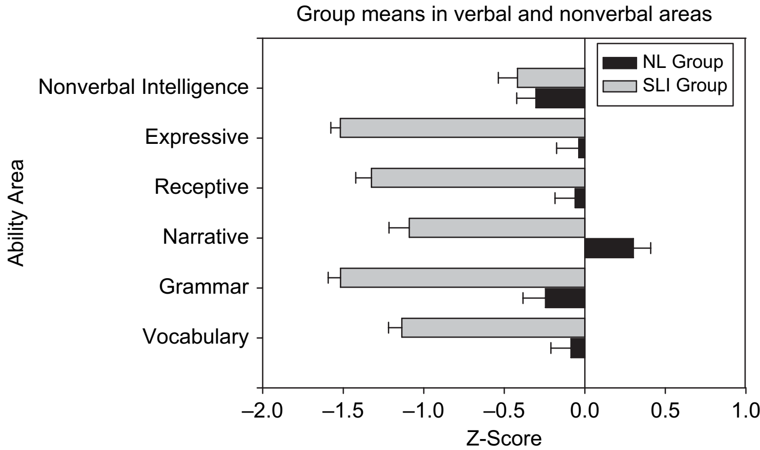

FIGURE 1 *z*-score differences between the SLI and normal language (NL) groups on the nonverbal IQ, composite expressive and receptive language, narrative, grammar and vocabulary. The *z*-scores were based on performance on language testing in children in the state of Iowa. Negative *z*-scores present below average performance, positive *z*-scores present above average performance. The error bars represent standard errors. When compared to the normal language group, the SLI group exhibited comparable nonverbal IQ scores, but significantly lower composite expressive and receptive language, narrative, grammar and vocabulary scores.

Note:

Nonverbal IQ = Block Design and Picture Completion subtests of the Wechsler Preschool and Primary Scale of Intelligence—Revised (Wechsler, 1989).

Expressive = Expressive language composite score: A combination of scores from Expressive Vocabulary, Grammatic Completion, and Sentence Imitation subtest from the Test of Language Development – Primary: Second Edition (Newcomer & Hammill, 1988), and the Cullata Narrative Recall (Culatta et al., 1983).

Receptive = Receptive language composite score: A combination of scores from Picture Identification and Grammatic Understanding subtests from the TOLD-P2, and Cullata Narrative Comprehension (Culatta et al., 1983).

Vocabulary = Composite vocabulary score: A combination of scores from Picture Identification and Expressive Vocabulary subtests from the TOLD-P2.

Narration = Composite narration score: A combination of scores from the Cullata Narrative Comprehension and Cullata Narrative Recall.

Grammar = Composite grammar score: A combination of scores from Grammatic Understanding, Grammatic Completion, and Sentence Imitation subtests from the TOLD-P2.

colleagues (1997). Furthermore, none of the children had any additional disabilities such as hearing impairments or emotional disorders that also might influence language development. The language abilities of these children have been followed from kindergarten to 8th grade and their language skills remained stable throughout this time period (Tomblin et al., 2003). Although the language status

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of these participants was obtained at kindergarten and 2, 4, and 8 years after kindergarten, we chose the kindergarten measures to characterize the participants in the current study for two reasons. First, at this age considerable individual differences remain among children with regard to grammatical and lexical knowledge. We have found that by 8th grade, the individual differences in grammatical skills are diminished due to ceiling effects on the tests we used. Thus, the effects of mechanisms such as procedural learning that contribute to these individual differences in language should be better reflected in these individual differences at kindergarten. Second, an association between individual differences in kindergarten language status and SRT learning 8 years later provides for a strong test of the association between a learning trait and language achievement.

Serial Response Time Task

Stimuli. The SRT task used in this study was modeled after one used by Thomas and Nelson (2001b). The stimuli were images of four horizontally arranged boxes. The image with all empty boxes would appear for 500 msec, followed immediately by an image containing a creature in a specified box, which would remain for 1000 msec, after which another empty set of boxes would appear. This presentation resulted in the percept of the creature being present in one box, disappearing briefly and reappearing in another box. The participants completed four phases. First, in the Random Phase 1, the creature appeared pseudo randomly for 100 trials. Then, in the Pattern Phase 1 a sequence (1-3-2-4-4-2-3-4-2-4) repeated for a 100 trials and in the Pattern Phase 2 the same sequence repeated for another 100 trials. After Pattern Phases 1 and 2, the participants completed the Random Phase 2, in which the creature again appeared pseudo randomly for a 100 trials. We collapsed the trial-by-trial reaction times of each participant in the SRT task into the median response speed on correct trials across successive sets of 20 trials.

Procedure. The control of the image presentation and recording of response speed and accuracy was accomplished by E-Prime Software and an E-Prime button box which was run on a Toshiba laptop running a Windows XP operating system. The task presented to the participants was a continuous choice reaction time procedure. The participants were instructed as follows: “You will see four squares. Each of the squares goes with a button from 1 to 4. A green creature will pop up in one of the squares. Your job is to press the button that goes with the square with the creature in it as soon as it pops up.” The participants were then shown how to arrange their fingers using their preferred hand on four of the buttons on the button box and to push the button

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corresponding to the box in which the creature appeared as soon as the creature appeared. A series of practice trials with feedback was provided to all participants to learn the association of the buttons with the location of the box on the computer screen before the training trials began. After each block of 100 trials, the subjects were given a short break followed by two "warm-up" trials. The primary dependent variable was the reaction time (RT) on correct trials.

Analysis. This study was concerned with whether individual differences in language status (SLI, NL) were associated with individual differences in the rate of learning sequence specific information during the pattern learning, as reflected in decreases in reaction time. Within the SRT task, decreases in RT can also arise as a result of generalized skill learning that is not related to the pattern or sequence. This generalized skill learning that is not specific to sequences is greatest during the initial trials of the task. Traditionally, the SRT task has involved a series of four blocks of patterned sequences followed by a random block. Thus, during the initial pattern block, generalized skill learning and sequence specific learning are confounded. Evidence for sequence specific learning has often been obtained by comparing the reaction time during the last set of pattern trials with the reaction time in the subsequent initial random set (Nissen & Bullemer, 1987; Meulemans et al., 1998). When comparing groups, this difference is often adjusted to a proportional change in RT in order to accommodate differences in overall reaction times within groups (Cherry & Stadler, 1995; Thomas & Nelson, 2001a). However this method has been questioned on several grounds (Chapman et al., 1994; Howard & Howard, 1989). Most importantly, although these methods allow investigators to address the question of whether sequence learning occurred during the pattern trials, they do not provide for an analysis of the pattern and rate of learning across the blocks with a random or pattern condition.

Given that the research question in this study concerned learning rates, the data in this study was analyzed using growth curve analysis methods. These analyses not only provide us with effects that can be discovered using more traditional methods such as analysis of variance (ANOVA), but they also model the data in a more accurate manner and give us more specific information about the shape of the learning curves. Growth curve analysis allows for the differences in overall performance levels versus change across bocks to be tested as separate sources of variance in the form of slopes and intercepts. These analysis methods also handle the correlated error variance across trial blocks due to repeated measures more appropriately than traditional ANOVA does. Furthermore, in contrast with an ANOVA, the time variable (trials) is treated as a continuous variable rather than a nominal or classification variable. As a result arithmetic operations can be performed to transform the time scale.

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In this study, the Proc Mixed procedure within SAS was used for modeling growth. This method is very similar to other multilevel modeling methods such as Hierarchical Linear Modeling (HLM). These multilevel methods allow for the patterns of change in RT over blocks within each phase to be statistically modeled. The model being tested contains parameters concerned with overall performance levels (intercept) and features of rates of change (linear and higher order terms). When the trial blocks are numbered in consecutive integers and treated as values on a continuous variable (X), the RT (Y) on different trial blocks can be modeled as a polynomial function of the continuous variable (X), i.e., $Y = a + bX + cX^2 + dX^3 + \ldots + \varepsilon$, where a is the intercept corresponding to RT at the block coded as 0 (i.e., the block to which other block numbers were referenced; $X = 0$ for this block), b, c, and d are respectively linear, quadratic, and cubic slopes of the fitted regression line, and ε is the regression residual (the obtained RT minus the predicted RT by a block number) and is not of research interest in this study. The individual differences, especially the group differences in all these parameters (intercept and linear, quadratic, and cubic slopes), can be explicitly tested in the analysis. When a group difference (between SLI and NL) in any of the parameters is significant in the Pattern Phase but not in the Random Phase, this group difference may be regarded as evidence that individuals with SLI have a deficit specific to pattern learning.

Unlike many SRT methods, the SRT method used in this study provides an initial random phase of performance prior to the pattern learning phase. This initial random phase, as well as the random phase following the pattern blocks, can be used to test for the generalized response learning that is not specific to sequence learning and, in particular, whether this generalized response learning interacts with language group status. Thus, this method of growth curve analysis allows for separation of sequence specific and general response learning rates.

RESULTS

Response Accuracy and Language Status

We first examined the accuracy with which the participants pressed the correct buttons in response to each stimulus during the Random Phase 1, Pattern Phase 1, Pattern Phase 2, and Random Phase 2. Figure 2 shows mean response accuracy during the four phases in the SLI and NL groups. Since our dependent variable, proportion of trials that the participants responded correctly to, did not follow normal distribution, the data were transformed using a logit transformation prior to tests of the effects of Phase and Group. There was a significant effect of Phase Type, $F(2, 246) = 25.43$, $p < .0001$ and this analysis showed that

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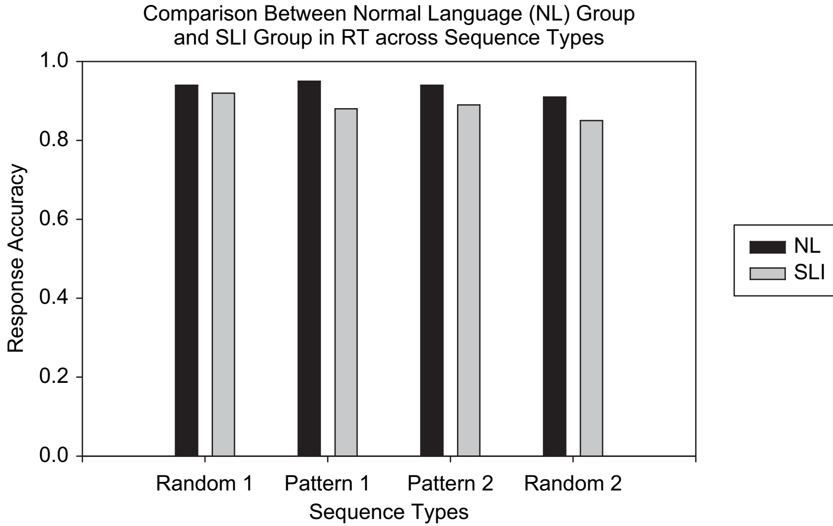

FIGURE 2 Response accuracy during Random Phase 1, Pattern Phase 1, Pattern Phase 2, and Random Phase 2 for the NL and SLI groups.

each of the Phases was different from the others. Random Phase 1 had the highest accuracy (*mean* 93.1%, *SD* = 6%) and Random Phase 2 had the lowest (*mean* 88.6%, *SD* = 11%), while the accuracy for the Pattern Phases (combining Patterns 1 and 2) was intermediate (*mean* 92%, *SD* = 10.2%). There was no difference in accuracy between Pattern 1 (90%) and Pattern 2 (91%) $F(1,79) = 0$, $p = .957$. This indicates that the accuracy differences between the phases were due to the order in which they were presented to the children. This decline in accuracy over time may have been due to fatigue or due to the inclusion and then removal of a pattern. The effect of Group also reached significance, $F(1, 246) = 7.02$, $p = .009$. The response accuracy in the NL group was 93.6% (*SD* = 5%) and 88.7% (*SD* = 13%) in the SLI group. The interaction between Phase type and Group did not reach significance, $F(2, 246) = 2.53$, $p = .08$., suggesting that the effect of order of presentation was not different in the SLI and NL groups.

Reaction Time and Language Status

We then examined changes in reaction times during random and pattern phases for the two groups of adolescents. We collapsed the trial-by-trial reaction times of each participant in the SRT task into the median response speed on correct trials across successive sets of 20 trials in each of the blocks. Medians were used

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because reaction time distributions are highly skewed; therefore medians are more representative of the distribution central tendencies. The block medians were submitted to a growth curve analysis using a mixture model (Proc Mixed in SAS). Figure 3 presents the median reaction times for the SLI and NL groups during the Random and Pattern Phases. Three separate models were run: one investigating reaction times during Random Phase 1, one investigating reaction times during combined Pattern Phases 1 and 2, and one investigating reaction times during Random Phase 2. The parameter values and standard deviations obtained from the three models are shown in Table 1. In each of the models, the response time median for a block was modeled as a function of block numbers. The blocks were numbered such that the zero point represented the third block[2]. This centered the time variable on the third block where the block number was coded as 0 on the new time variable and the RT corresponding to this block became the intercept for the regression line.

Each of these models computed four parameters for each participant: (1) intercept, (2) the instant linear slope, (3) the quadratic rate, and (4) cubic rate. Within the mixed model, these parameters served as random effects, which means they had error terms associated with them. The group identity (SLI vs. NL) was included in the model as a fixed-effects predictor of the four parameters. Non-significant interactions were trimmed out of the models. Since the blocks were measured from the same participant, the regression residual for different blocks was allowed to correlate by treating the regression intercept as a random coefficient.

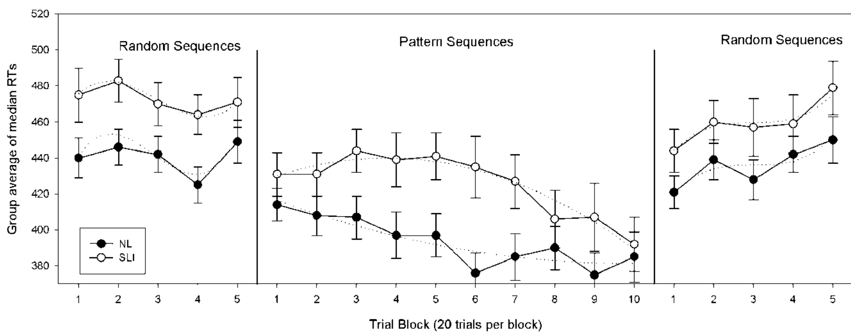

FIGURE 3 Change in reaction times over 20 trial blocks during Random Phase 1, Pattern Phases, and Random Phase 2 for the NL and SLI groups.

[2]The third block was used because it was the midpoint in the trial series for the two random conditions. This same block was used for the pattern condition to allow comparison of intercept and slope values at the same time point across the random and pattern conditions.

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TABLE 1
Parameter Estimates and SLI versus NL Group Differences for the Modeling

Sequence Type	*Effect Source*	*Estimate*	*SE*	*Type 3 Test* *DF*	*F*	*P with Bonnferoni correction*
Random 1	Intercept[a]	472.97	10.27	–	–	–
	Group difference in intercept	–32.75	13.74	(1, 257)	5.68	.06
	Slope	–13.69	4.11	(1, 257)	11.07	.003
	Cubic slope[a]	3.62	1.22	(1, 85)	8.73	.012
Pattern	Intercept[a]	439.30	10.83	–	–	–
	Group difference in intercept	–39.94	14.49	(1, 602)	7.59	.018
	Slope[a]	1.96	2.42	(1, 84)	1.56	.66
	Group difference in slope	–7.97	0.61	(1, 602)	6.03	.03
	Quadratic slope[a]	–1.30	0.46	(1, 84)	1.98	.48
	Group difference in quadratic slope	1.74	0.61	(1, 602)	8.04	.015
Random 2	Intercept[a]	459.74	11.26	–	–	–
	Group difference in intercept	–26.27	15.08	(1, 343)	3.04	.024
	Cubic Slope	1.92	0.46	(1, 343)	17.36	<.0005

Note. Separate models were run for Random Phase 1, Pattern Phases, and Random Phase 2. Non-significant interactions were removed from the models.
[a]Random parameter in the mixed model.

Random Phase 1. The best model fit for the Random Phase 1 included an intercept, a linear slope, a cubic term, and a group effect on the intercept. Even though the median reaction times at the third block in the SLI group was somewhat longer than the NL group, this difference did not reach significance [group difference in intercept = –32.75 (SD = 13.74), $F(1, 257) = 5.68$, p = .06]. The slight group difference may be due to differences in overall processing speed or speed of motor responses. Overall, the reaction times significantly

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decreased over time for both groups [linear slope = −13.69 (*SD* = 4.11), $F(1, 257) = 11.07$, $p = .003$]. This reduction in reaction times was not steady over blocks; the reaction times appeared to slightly increase first, then to significantly decrease, and finally to increase slightly again [cubic term = 3.62 (*SD* = 1.22), $F(1, 85) = 8.73$, $p = .012$]. The reduction in reaction times was similar for both groups and is likely to reflect factors like improved generalized response learning (e.g., left most box goes with left most button). Although this represents learning, it is not the type of sequence-specific learning that is the focus of the SRT task. Sequence-specific learning is revealed by decrease in reaction times during the pattern phases, when contrasted with the random phases.

Pattern Phases. For the pattern trial model, the best model fit included an intercept, a slope, a quadratic term, and group effects on the intercept, the slope and the quadratic term. This model showed that the SLI group was significantly slower than the NL group at the third trial block which represents the intercept [group difference in intercept = –39.94 (*SD* = 14.49), $F(1, 602) = 7.59$, $p = .018$], suggesting that during the pattern phases, adolescents with SLI exhibited longer reaction times when compared to NL peers. In order to investigate group differences in sequential learning of the pattern, rather than overall differences in reaction times, we need to consider group differences in the *shape* of the learning curve. The magnitude of the linear slopes at the third trial block was much greater for the NL group than the SLI group and this difference was significant [difference in slope = –7.97 (*SD* = .61), $F(1, 602) = 6.03$, $p = .03$], suggesting that the rate of learning in the NL group was faster than in the SLI group at the third trial block. The quadratic acceleration rate for each group was also different in that the NL group presented a positive quadratic function (concave shaped) whereas the SLI group fit a negative quadratic function (convex shape). This difference between groups in the nonlinear shape of the rate of change was significant [difference in quadratic acceleration = 1.74 (*SD* = 0.61), $F(1, 602) = 8.04$, $p = .015$.].

The significant difference in the quadratic parameter highlights a surprising pattern of performance by the SLI group. As shown in Figure 3, upon the introduction of the pattern, reaction time for the SLI group appeared to initially *increase* before shifting into a more rapid rate of decrease. This pattern of systematically slower responses during the early trials of the pattern was not found in either of the two pseudorandom blocks or in the NL group. It therefore appeared that the presence of the recurring pattern initially reduced the response efficiency of the SLI participants for a period of time. Overall, these results indicate that, while adolescents with SLI were able to learn sequence regularities, they required significantly more trials to do so. Furthermore, the shape of the learning curves for the two groups differed during the Pattern Phases but not

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during the Random Phase 1, suggesting that the group differences are directly related to learning the sequential elements in the pattern.

Random Phase 2. The best model fit for the Random Phase 2 included an intercept, a cubic term and a cubic term on the intercept. During the Random Phase 2, similar to Random Phase 1, the SLI group exhibited somewhat longer reaction times during the third block than the NL group, but this difference did not reach significance [group difference in intercept = −26.27 (*SD* = 15.08), $F(1, 343) = 3.04$, $p = .24$]. While there was no significant overall increase or decrease in reaction times in either group during the Random Phase 2, the reaction times appeared to fluctuate over time: a slight increase, followed by a plateau, and then another slight increase [cubic term = 1.92 (*SD* = .46), $F(1, 343) = 17.36$, $p < .0005$]. Again, similar to the Random Phase 1, the change patterns in reaction times were similar for both groups, indicating that group differences in learning rates were present only in learning the sequential elements during the Pattern Phases.

Reaction Time and Vocabulary or Grammar Status

Ullman (2001) has proposed that the acquisition of a rule system such as grammar is dependent upon procedural learning, whereas the arbitrary sound meaning pairing involved in lexical development relies on the declarative system. We therefore investigated if individual differences in SRT learning were more strongly associated with individual differences in grammar abilities than in vocabulary abilities. Using the composite scores from the kindergarten language measures, we reclassified the 85 children into groups based on their grammar and vocabulary abilities. The criterion for normal abilities was above −1.14 in *z*-score, and for below normal abilities the criterion was at or below 1.14 in *z*-scores (Tomblin et al., 1996; Tomblin & Zhang, 2006). Grammar diagnosis was based on the kindergarten measures of grammar composite score.

When the participants were recast into these two alternate systems (vocabulary and grammar) 20% of them in each case changed status. Additionally, 34% of the participants were assigned to different categories based on their vocabulary versus grammatical scores. Thus, the group status of the participants varied modestly depending upon the particular language measures used to categorize them. This recasting resulted in 44 children assigned to the poor grammar learner group and 41 children assigned to the normal grammar learner group.

We again used growth curve analysis to evaluate the association between grammar or vocabulary abilities and performance on the SRT task. Three separate

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models were run for both the grammar group comparison and vocabulary group comparison: one investigating reaction times during Random Phase 1, one investigating reaction times during Pattern Phases 1 and 2 combined, and one investigates reaction times during Random Phase 2. The parameter values and standard deviations obtained from the three models for the grammar group comparison are shown in Table 2. Figure 4 presents the median reaction times for the grammar impaired and normal grammar groups during the Random and Pattern Phases.

TABLE 2
Parameter Estimates and Grammar Impaired Vs. Grammar Normal Group Differences for the Modeling

				Type 3 Test		
Sequence Type	*Effect Source*	*Estimate*	*SE*	*DF*	*F*	*P with Bonnferoni correction*
Random 1	Intercept[a]	471.02	9.91	–	–	–
	Group difference in intercept	−31.22	13.70	(1, 257)	5.20	.06
	Slope	−13.69	4.11	(1, 257)	11.07	.003
	Cubic slope[a]	4.89	1.36	(1, 84)	9.09	.009
Pattern	Intercept[a]	436.60	10.48	–	–	–
	Group difference in intercept	−37.44	14.48	(1, 602)	6.68	.03
	Slope [a]	1.32	2.35	(1, 84)	2.04	.148
	Group difference in slope	−7.27	3.24	(1, 602)	5.01	.09
	Quadratic slope[a]	−1.27	0.44	(1, 84)	1.50	.66
	Group difference in quadratic slope	1.79	0.61	(1, 602)	8.72	.009
Random 2	Intercept[a]	461.17	10.77	–	–	–
	Group difference in intercept	−30.76	14.89	(1, 343)	4.27	.12
	Cubic slope	1.92	0.46	(1, 343)	17.36	< .0005

Note. Separate models were run for Random Phase 1, Pattern Phases, and Random Phase 2. Non-significant interactions were removed from the models.

[a]Random parameter in the mixed model.

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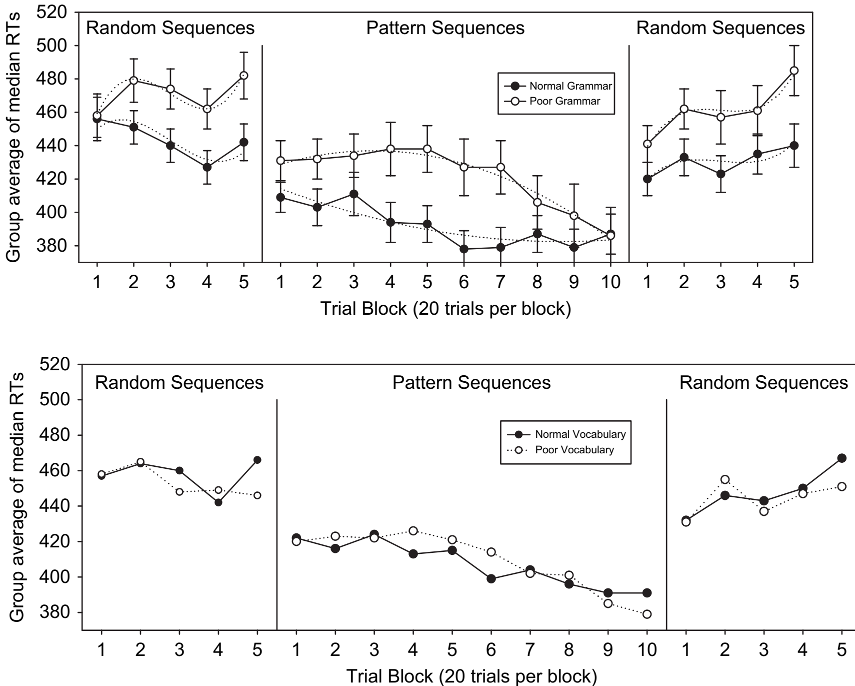

FIGURE 4 Change in reaction times over 20 trial blocks during Random Phase 1, Pattern Phases, and Random Phase 2 for the normal grammar and grammar impaired groups (top panel), and for the normal vocabulary and vocabulary impaired groups (bottom panel).

Grammar Status: Random Phase 1. The best model fit for the Random Phase 1 included an intercept, a linear slope, a cubic term, and a group effect on the intercept. The results for this model are very similar to the Random Phase 1 model for the original SLI vs. NL contrast above. The reaction times during the third block in the grammar impaired group were somewhat longer than the normal grammar group, but this difference did not reach significance [group difference in intercept = –33.22 (SD = 13.70), $F(1, 257) = 5.20$, $p = .06$]. Overall, the reaction times significantly decreased over time for both groups [linear slope = –13.69 (SD = 4.11), $F(1, 257) = 11.07$, $p = .003$]. This reduction in reaction times was not steady over time. The reaction times appeared to first slightly increase, then significantly decrease, and finally increase slightly [cubic term = 4.89 (SD = 1.38), $F(1, 84) = 9.09$, $p = .009$]. As was the case for the Random Phase 1 model

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contrasting SLI to NL performance, the patterns of change in reaction times were similar for the grammar impaired and normal grammar groups.

Grammar Status: Pattern Phases. For the pattern phases, the best model fit included an intercept, a slope, a quadratic term, and group effects on the intercept, the slope and the quadratic term. This model, almost identical to the Pattern Phase model for the SLI vs. NL contrast, showed that the grammar impaired group was significantly slower than the normal grammar group at the third trial block [group difference in intercept = –37.44 (SD = 14.48), F (1, 602) = 6.68, p = .03], indicating that during the pattern phases, adolescents with grammar impairments exhibited longer reaction times when compared to normal grammar peers. Similar to the SLI vs. NL model for the Pattern Phases, the shapes of the learning curves differed for the grammar impaired and normal grammar groups. There was a trend for the linear slopes at the third trial block to be significantly greater for the normal grammar group than the grammar impaired group [difference in slope = –7.27 (SD = 0.3.24), F(1, 602) = 5.01, p = .09]. Similar to what was found for the original SLI vs. NL comparison, the quadratic terms for the grammar impaired and normal grammar groups were also different in that the normal grammar group presented a positive quadratic function, whereas the grammar impaired group fit a negative quadratic function. This difference in the nonlinear shape of the rate of change was significant [group difference in quadratic acceleration = 1.79 (SD = 0.61), F(1, 602) = 8.72, p = .009]. These results indicate that adolescents with grammar impairments required significantly more trials to learn sequential elements in the Pattern Phases than the grammar normal peers. As was the case for the original SLI vs. NL comparison, the shape of the learning curves for the grammar impaired and the normal grammar groups differed during the Pattern Phases but not during the Random Phase 1, suggesting that the group differences were directly related to learning the sequential elements in the pattern rather than incidental learning of, for example, stimulus- response mappings and improved motor response agility.

Grammar Status: Random Phase 2. The best model fit for the Random Phase 2 included an intercept, a cubic term, and a group effect on the intercept. During the Random Phase 2, similar to Random Phase 1, and identical to the original SLI vs. NL modeling, the grammar impaired group exhibited somewhat longer reaction times during the third block than the grammar normal group, but this difference did not reach significance [group difference in intercept = –30.76 (SD = 14.89), F(1, 343) = 4.27, p = .12]. While there was no significant overall increase or decrease in reaction times in either group during the Random Phase 2, the reaction times appeared to fluctuate over time: a slight increase, followed by a plateau, and then another slight increase [cubic term = 1.92 (SD = .46), F(1, 343) = 17.36, $p < .0005$]. Again, similar to the Random Phase 1 and the original SLI vs.

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NL modeling, the change patterns in reaction times were similar for both groups, indicating that group differences were primarily associated with learning the sequential elements in the SRT task.

Vocabulary Status. In contrast with the grammar group comparisons, the estimates for the association of vocabulary impairment with SRT showed no significant differences between groups. Figure 4 presents the median reaction times for the vocabulary impaired and normal vocabulary groups during the Random and Pattern Phases. No differences were found between groups with regard to intercept, slope, quadratic acceleration, or cubic acceleration during any of the Phases.

Overall, the results indicate that low grammar abilities were directly associated with low performance on sequential pattern learning in a visual spatial task. Poor performance in vocabulary testing, however, was not directly linked to sequential pattern learning abilities.

DISCUSSION

This study set out to determine if adolescents with SLI diagnosed in kindergarten showed different learning characteristics in a SRT task than typically developing children. The data revealed a difference in the rate and form of reaction time declines in pattern learning between adolescents with normal language status and those identified with SLI. These group differences were not found in the random phases that preceded the pattern learning, suggesting that the differences in learning were primarily associated with the sequential elements of the task. The SRT task was a visual task requiring no overt use of language; there is therefore no a priori reason that the child's language status should have directly influenced performance on this task. Furthermore, the use of visual stimuli eliminated auditory processing and phonological information processing; as a result, the relatively poor pattern learning performance of the SLI group could not be due to an auditory perceptual limitation. Thus, despite the fact that, aside from having a sequential structure, this task shared very little with language stimuli, adolescents with long-term histories of poor language learning differed from normal language peers with regard to their learning of the patterns in the task. We can conclude that the association of individual differences in SRT learning and individual differences in language status is likely to be attributable to shared learning processes.

As noted in the results section, some learning in the SRT task involved the acquisition of generalized skill learning. This type of learning is most likely to occur during the initial random block. Although group differences approaching

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significance in intercept were found, no group differences in the slopes (linear or nonlinear) were shown. Therefore, there does not seem to be an association between language status and non-sequence-specific generalized skill learning. Thus, we conclude that the association between language and SRT learning in the pattern phases is very likely due to differences in sequence-specific learning skills in adolescents with SLI. This sequence-specific learning on the SRT task, along with pattern learning in other tasks, has been found to be impaired in patients with diseases affecting the corpus striatum (Parkinson's or Huntington's disease) but with preserved declarative learning abilities. This constellation of pattern learning deficits and common lesion sites (Butters, 1987; Pascual-Leone et al., 1993), along with support from functional imaging studies (Hazeltine & Ivry, 2003), has provided much of the evidence for the construct of procedural learning.

The sequence specific learning differences between the SLI and NL control group involved differences in the shape of the learning functions for the two groups. The NL control group demonstrated the expected pattern of a negative log function, where learning was initially rapid followed by a gradual approach toward an asymptote. The shape of the learning curve for the SLI group consisted of a period of largely stable and even possibly slowed responses prior to the onset rapid learning, with no evidence of an asymptote by the last trial block. Performance in last block of the pattern set for the SLI group did not differ from that of the NL group. Of particular interest is the stable or slowed period during the first half of the pattern trial blocks for the SLI group. This period of stability or even decline in RT actually followed a substantial drop in RT that occurred coincident with the onset of the pattern condition. Thus, it seems that the SLI group obtained some benefit from the pattern but then showed no more gain for several trial blocks. Recently, several investigators (Mainela-Arnold et al., 2005; Mainela-Arnold, 2005; McMurray et al., 2006; Norbury, 2005) have noted in studies of lexical and sentence processing that individuals with SLI show less suppression of competing lexical activations and sentence interpretations. This failure to suppress may be rooted in poor inhibitory or competitive processes. It is possible that during the initial period of stability, multiple candidate responses are vying with each other. This excess competition emerges only after the initial formation of candidate statistical representations, and is resolved with sufficient training. In contrast, the typical language learners were able to extract the pattern quickly, quickly developing the competitive processes that allow rapid response selection. At this point, the basis of the stability or even possibly decline in performance during the early learning phase in children with SLI is not known. However, it is quite possible that the explanation for this feature of learning may be important for understanding the basis of learning problems in children with SLI and individual differences in language abilities in general.

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Given the possible overlap between sequence-specific learning and language, we may ask what kind of knowledge is generated in such learning and what mechanisms are involved. The sequence used in this study and most other SRT tasks are deterministic in that a set pattern is established and repeated. In this regard, the SRT task does not present the kind of statistical and probabilistic challenge that language learning requires. Thus, in the SRT task, a simple way of learning the sequence would be to learn only pair-wise associations. Adjacency learning of this sort is well known as a mechanism for learning patterns of syllable transitions for word segmentation (Aslin et al., 1998; Saffran et al., 1997). However, both computational models (Cleeremans & McClelland, 1991) and behavioral studies (Curran & Keele, 1993; Stadler, 1995) of SRT learning demonstrate that this sequence-specific learning is likely to involve higher order relationships involving chunks or clusters of sequences or graded probabilistic relationships extending beyond the immediately adjacent pairs. Learning beyond adjacent pairs to more distant relations, including higher order structures, is the very thing currently being entertained as the kind of statistical information needed for language learning (see for instance: Gomez & Gerkin, 2001; Gomez, 2002). Therefore, it would appear that, although the SRT task appears to be a simple sequence learning problem, in fact, the sequential relationships learned may be similar to those involved in learning the structure of language.

What precisely is learned in sequence-specific learning during the SRT task? Keele and colleagues (Keele et al., 2003) have argued that the representations formed in the SRT task are multimodal representations that capture correlated temporal or sequential relationships across sensory-motor systems. These types of representations are likely to be useful in learning complex sequential information that is context dependent. The very same description can be given for language learning. Within the context of the Keele et al. model, we may assume that the sequence information learned by the participants in this study was multimodal and may have involved capturing multimodally correlated sequential information; it may be this type of multimodal information that is particularly problematic for the children with SLI. Recently, Just and colleagues (Just et al., 2004) have proposed that poor "integration and synchronization across the large-scale cortical network" accounts for the language problems of children with autism. It may be that children who exhibit difficulties restricted to language also have impairments in learning systems that integrate multimodal sequential information.

It can be seen from this brief summary of the literature on the SRT task that learning in the single task SRT procedure represents a learning process that results in memory representations that are likely to be embodied in the sensory-motor system and yet also abstract, both with respect to higher order sequential relationships and complex multimodal relations. When viewed from this perspective, it is not difficult to see that individual differences in a learning system that is

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capable of extracting structure in complex input might result in individual differences in language.

Sequence Learning and Grammar

The notion that a procedural learning system may contribute to language learning is certainly not new (see e.g., Reber, 1967). The past ten years have seen an increase in child language research exploring various hypotheses that in some way involve this learning system (e.g., Christiansen & Chater, 1999; Gupta & Cohen, 2002; Maye et al., 2002; Saffran, 2001; Ullman, 1998). A common theme throughout this work has been the belief that, with its emphasis on learning sequential structure, procedural learning may be well suited to the acquisition of structural aspects of language, such as phonology and grammar. Recently, Ullman (2001) has voiced the most explicit theory concerning the importance of procedural learning for the acquisition of grammar. The predictions of this theory were tested in this study by grouping children according to either their performance on tasks involving sentence comprehension and production, versus tasks that required only lexical knowledge. The results were in accord with Ullman's prediction in that individual differences in sentence use were associated with sequence learning, whereas individual differences in lexical use were not. It must be recognized that the grammar tasks in this study were not pure measures of grammatical abilities, as the children were required to use lexical information along with sentence structure. Bates and Goodman (1999) have noted that it is, in fact, not possible to examine grammatical proficiency without employing vocabulary. Factor analyses of the tests used for measurement of language in this study have been found to be largely unidimensional (Tomblin & Zhang, 2006). Thus, it is somewhat surprising that sentence use and vocabulary bore a differential relationship to SRT in our study. Despite there being a small amount of orthogonal variance in these measures for sentence use and vocabulary, there was a sufficient amount to allow for SRT to be associated with the composite grammar measures.

CONCLUSIONS

The direct implications of this study are that individual differences revealed in variations in language abilities may, in part, be explained by some very basic general purpose mechanisms involved in sequence learning. These mechanisms must be present in brain systems that are common to at least the visual and auditory system, as well as motor systems involving either manual or oral movements. The procedural memory system is a good candidate for such a brain system. Since a link between FOXP2 gene and brain areas associated with procedural learning has been established, future studies should evaluate the role

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FOXP2 gene may play in the development of procedural memory and grammatical skills.

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