Published in final edited form as:

Lang Learn Dev. 2015 July 1; 11(3): 215–236. doi:10.1080/15475441.2014.904168.

Procedural Learning and Individual Differences in Language

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Abstract

The aim of the current study was to examine different aspects of procedural memory in young adults who varied with regard to their language abilities. We selected a sample of procedural memory tasks, each of which represented a unique type of procedural learning, and has been linked, at least partially, to the functionality of the corticostriatal system. The findings showed that variance in language abilities is associated with performance on different domains of procedural memory, including the motor domain (as shown in the pursuit rotor task), the cognitive domain (as shown in the weather prediction task), and the linguistic domain (as shown in the nonword repetition priming task). These results implicate the corticostriatal system in individual differences in language.

Introduction

Role of Corticostriatal System in Language

It has been widely viewed that language learning and processing are served by neural circuits within the cortex, particularly in the left hemisphere of most right-handed individuals. The evidence comes from more than a century of lesion studies (e.g., Broca, 1865), and more recently, functional brain imaging research leaves little doubt regarding cortical language regions (e.g., Price, 2000). In recent years, however, the possibility that subcortical structures play a role in language has received increased support. Crosson (1985) reviewed several studies of individuals with basal ganglia lesions who presented language impairments, and then proposed a brain system linking traditional language areas of the cortex via thalamic with other subcortical pathways. In his language model, the basal ganglia receive a large amount of language input from cerebral cortex, and after processing and integration, they send it back to cerebral cortex via inhibitory control of the thalamus. This model explains why aphasia can occur after subcortical lesions. Crosson (1992) contended that understanding the role of the subcortical mechanisms in language would lead to a better understanding of how the brain produces language.

Further evidence of basal ganglia involvement in language has come from research on individuals with basal ganglia disease. Lieberman et al. (1992) examined language ability in individuals with Parkinson's disease, and suggested that the neural pathways connecting the basal ganglia with the cortex contributed to speech production and syntactic comprehension

via attentional mechanisms. Lieberman et al.'s account was tested further by Dominey and his colleagues (1995, 1997), who proposed that the corticostriatal system was well suited for acquiring and processing syntax due to its capability to deal with sequential learning. These researchers developed a recurrent connectionist model that emulated the corticostriatal system to learn mappings of syntactic strings to thematic roles (e.g., agent, patient...etc.), and results consistently showed that this model of the corticostriatal system was a powerful learning mechanism, capable of generalizing temporal sequences of form-to-meaning mappings (Dominey et al., 2006; Dominey & Inui, 2009).

In parallel with these proposals, Ullman et al. (1997) demonstrated that individuals with Parkinson's disease had greater difficulty with the production of regular morphological rules (e.g., walk-walked) than irregular rules (e.g., run-ran). These findings led to Ullman's declarative-procedural model of language processing, in which the corticostriatal system contributes to the procedural learning of grammatically regular rules, whereas the hippocampal system contributes to the declarative learning of lexicon and irregular forms (Ullman, 2004). This distinction between procedural and declarative memory initially came from research on amnesia that showed selective sparing of memory involving gradual, feedback-guided learning (a.k.a. non-declarative or procedural memory) as opposed to impaired memory for rapid learning of arbitrary associations (a.k.a. declarative memory). Therefore, it has been proposed that the procedural system was served by the corticostriatal system, whereas the declarative system was served by the cortico-hippocampal system (Squire, 1992). Ullman took this dichotomous model of memory and argued for specific contributions of different memory circuits to different aspects of language.

Soon after Ullman, the procedural and declarative memory systems were also incorporated in a computational model of word learning by Gupta (Gupta, 2012; Gupta & Cohen, 2002; Gupta & Dell, 1999; Gupta & Tisdale, 2009). This model employed a recurrent connectionist architecture that provided a role for the corticostriatal system (i.e., the procedural memory system) in learning the serial order structure of phonological elements within words, as well as a role for the hippocampal system (i.e., the declarative memory system) in mapping word forms to meanings. In other words, Gupta proposed that both procedural and declarative memory systems engage in word learning processes, which was contrasted with Ullman's model where word learning was supported by the declarative memory system only.

In recent years, these initial hypotheses regarding the involvement of the corticostriatal system in language have been supported by studies on adults with neurodegenerative basal ganglia disease (Grossman, 1999; Longworth et al., 2005; Teichmann et al., 2005), as well as by brain imaging studies on typical language users (Crosson et al., 2003; Kotz et al., 2003). These findings lead to a general consensus that certain language functions, especially that of rule- or pattern-based learning and processing, are supported by the procedural memory system.

Specific Language Impairment (SLI): Variation at the Extremes of the Normal Range

The view that the procedural memory system is important to morphosyntactic development was clearly expressed by Ullman and Pierpont (2005). They proposed that a substantial

portion of the problems in children with SLI¹, morphosyntactic difficulty in particular, is linked to abnormalities of the brain structures and/or functions that underlie procedural memory. Ullman and Pierpont further hypothesized that the declarative system may be intact in these children, and therefore plays a compensatory role in grammatical learning. To date, research regarding the role of the procedural memory system in language development has been primarily concerned with its role in SLI.

We contend, however, that individual differences in procedural learning abilities would be expected to also underlie some of the variation found in language ability in the general population. In this respect, we argue that individuals with SLI do not represent a qualitatively distinct group; instead, they simply represent the low end of a continuous distribution of language skills. In other words, we suggest that the same factors that contribute to individual differences in language development among children with normal levels of language development will also contribute to SLI. This position is consistent with Leonard (1987, 1991, 1998), Tomblin (Tomblin & Zhang, 1999), and Dollaghan (2011). Within this perspective, findings of the research concerning the contribution of procedural learning to SLI should generalize to individual differences in language learning and use regardless of language ability. The advantage of studying individuals with SLI comes largely from the exclusions of well-known contributions to individual differences in language learning, such as hearing loss or other neurodevelopmental disorders.

Procedural Learning and SLI

Motivated by Ullman and Pierpont (2005), several studies have shown the association between procedural learning abilities and proficiency in language by contrasting individuals with SLI and typical language users. In all but one case, these studies have used the serial reaction time (SRT) task (Nissen & Bullemer, 1987). The SRT task is one of the most well studied procedural memory tasks, measuring performance of sequential learning. In a typical SRT task, participants learn to respond as quickly and accurately as possible to successively presented visual cues without knowing about the structured presentation of the stimulus sequence. With practice, reaction times for the repeating sequence will progressively decrease. After several blocks of exposure to the repeating sequence, an unannounced switch is made from the repeating sequence to a random stimulus sequence. The discrepancy in reaction times due to introduction of the random sequence is generally considered as an indirect measure of procedural learning.

Tomblin, Mainela-Arnold, and Zhang (2007) used the SRT task to investigate procedural memory in adolescents with SLI. They found a positive correlation between grammatical abilities and procedural learning, and the SLI group showed slower learning rates than the comparison group. Lum et al. (2010, 2012) reported similar SRT findings, revealing a significant reaction time advantage (i.e., evidence of procedural learning) between children with and without SLI (see also Hedenius et al., 2011; Sengottuvel & Rao, 2013, in press). Hedenius et al. (2011) did not find significantly different performance on the SRT task between children with and without SLI in the first place; however, they showed that children

¹Specific Language Impairment (SLI) is a neurodevelopmental disorder that primarily involves persistent limitations in the acquisition and use of language in the context of grossly normal sensory, cognitive, and neurological status (Leonard, 1998).

without SLI revealed signs of sequential knowledge consolidation after an average of three days, whereas children with SLI did not. Thus, they concluded that there was a difference in learned procedural knowledge between individuals with and without SLI. However, the same results regarding poor procedural learning in SLI have not been found in other studies (Gabriel et al., 2011, 2012; Lum & Bleses, 2012; Mayor-Dubois et al., 2012). Gabriel and her colleagues (2013) recently showed that their initial negative findings could have been due to the level of complexity of the sequences used in the studies. When more complex sequences were used in the SRT task, group effects did emerge (Gabriel et al., 2013). In summary, although findings concerning depressed learning in the SRT task in individuals with SLI are not uniform at this point, the collective evidence is supportive of poor learning on this task being associated with SLI.

Procedural learning abilities in SLI have also been examined by Kemeny and Lukacs (2009) using the weather prediction (WP) task. The WP task is another classic procedural learning task, assessing the cognitive aspect of procedural memory (e.g., Knowlton et al., 1994). In this categorization learning task, participants learn to predict a binary outcome (i.e., rain or sunshine) on the basis of probabilistic combinations of four visual cues. Kemeny and Lukacs found that children with SLI showed significantly lower accuracy rate on the WP task than their age-matched peers, which suggested impaired cognitive aspect of procedural memory.

The studies above provide support for a relationship between procedural learning and individual differences in language, although most of the work has contrasted groups of people with typical language abilities and those with SLI. However, this supporting evidence mainly comes from the use of the SRT task along with one study employing the WP task. In the literature on procedural learning, there are several behavioral paradigms other than the SRT and the WP tasks that have been widely used to assess procedural memory, such as the pursuit rotor task and priming tasks. Given that procedural memory is a complex construct reflected in a variety of different behavioral tasks, it is not possible to find a single task that stands alone as the “gold standard” for procedural memory testing. Therefore, in the current study, we chose a sample of procedural learning tasks to examine different aspects of procedural memory in young adults who were selected to have different levels of language ability.

Using Procedural Memory Tasks as a Way to Examine Functionality of Corticostriatal System

Several procedural learning behaviors reflect the functionality of the corticostriatal loops (Gabrieli, 1998; Seger, 2006). The corticostriatal loops refer to multiple segregated and interactive neural pathways connecting the basal ganglia with cerebral cortex via the thalamus (Alexander & Crutcher, 1990). While different loops contribute to different learning processes, the basal ganglia serve as a gating mechanism regulating information flow to the cortex within the corticostriatal loops, and thus play a pivotal role in mediating a broad range of procedural learning processes.

The use of an array of procedural learning tasks is, in part, motivated by the fact that different procedural learning tasks tap into different structures of the corticostriatal loops (Seger, 2006). In the literature, the SRT task has been shown to involve the corticostriatal

loops, particularly the anterior putamen and the head of the caudate nucleus (Kim et al., 2004; Rauch et al., 1997). Learning during the WP task, on the other hand, primarily relies upon the caudate nucleus in the corticostriatal system, as well as its interactions with the cortico-hippocampal system (see Shohamy et al., 2008, for a review).

There are two commonly used procedural learning tasks that have not been used to examine the association between procedural learning and individual differences in language. One is the pursuit rotor task, which assesses motor-based procedural learning. Imaging studies showed a positive correlation between progressive performance on the pursuit rotor task and activity in the putamen, implicating the role of the motor corticostriatal loop in procedural memory (Grafton et al., 1993). The other is repetition priming. Repetition priming refers to a gradual change in the processing of a stimulus (e.g., words, nonwords, or pictures) due to prior exposure to the same stimulus, unbeknownst to participants (Gabrieli, 1998). Despite its frequent use in memory literature, the neural systems that support repetition priming remain unclear due to the variety of tasks, and the corticostriatal loops have been implicated as one of the possible underlying mechanisms in several priming studies (Gupta & Cohen, 2002; Poldrack & Gabrieli, 2001; Poldrack et al., 1999). In the current study, we used the nonword repetition priming task as a means to assess the linguistic domain of procedural memory.

In sum, substantial research has shown that procedural memory is supported by multiple segregated and interactive corticostriatal loops, and this brain-behavior relationship can be reflected via performance on various procedural learning tasks. Our current understanding of the contribution of procedural learning to individual differences in language is largely limited to performance on the SRT task, and therefore only a limited range of corticostriatal functions has been assessed. Given that the SRT findings in individuals with SLI support an involvement of procedural memory in individual differences in language development, it is important to examine whether this association can be observed in other procedural learning tasks that rely on different components of the corticostriatal system.

The Current Study

The aim of the current study was to examine different aspects of procedural memory in young adults who were selected to have different levels of language ability. To achieve this aim and therefore bridge the gap in the literature, we selected a sample of procedural memory tasks based on the following criteria. First, in these tasks, participants do not have direct access to language representations in order to reduce the confounding effect of language on procedural memory performance. Second, each task represents a unique aspect of procedural memory, including motor skill learning, sequential learning, categorization learning, and repetition priming. Third, performance on these tasks is supported by the corticostriatal system, or at least implicated in the literature. By doing so, we ended up having four procedural memory tasks. We hope that performance to complete these tasks might shed light on the role and the integrity of the corticostriatal system in individual differences in language.

Methods

Participants

We recruited two groups of young adults from our longitudinal cohort, one with persistent poor language abilities ($n = 25$) and the other with typical language abilities ($n = 23$). These participants were originally assessed in kindergarten and diagnosed as having either typical language development or language impairments by using the diagnostic standards and measurement tools (Tomblin, Records, & Zhang, 1996). They have been followed up longitudinally since then. Their language and nonverbal IQ composite scores assessed in kindergarten were reported in Table 1. At the time being tested, these participants were within the age range of 19 to 25 years. None of them has ever reported a history of attention deficit hyperactivity disorder (ADHD) or autism spectrum disorders (ASD).

To assess their current nonverbal IQ and language skills, these participants completed two performance IQ measures and three language tasks respectively. The two nonverbal IQ measures included the Block Design and Matrix Reasoning subtests from Wechsler Abbreviated Scale of Intelligence (WASI, Wechsler, 1999). And the three language tasks were: 1) Word Derivations, a subtest from The Test of Adolescent and Adult Language, Fourth Edition (TOAL-4; Hammill et al., 2007) to assess knowledge of derivational morphology, 2) Peabody Picture Vocabulary Test, Fourth Edition (PPVT-4; Dunn & Dunn, 2007) to assess receptive vocabulary, and 3) a modified version of the Token Test (de Renzi & Faglioni, 1978; Morice & McNicol, 1985) to assess sentence comprehension. All the test scores were reported in standard scores with a mean of 100 and SD of 15. These scores were converted from z scores based on local norms (the Token Test) or national norms (PPVT-4, Word Derivations, Nonverbal IQ). The language composite scores were the average of the standard scores of the Token Test, PPVT-4, and Word Derivations. The nonverbal IQ composite was derived from Block Design and Matrix Reasoning.

Individuals who have a history of language impairment and whose current language composite scores were at least 1.25 standard deviations (SD) below the mean were considered as having poor language abilities; otherwise, they were assigned to the typical language group. Participant characteristics are summarized in Table 1.

Materials and Procedure

Four procedural memory tasks, namely the pursuit rotor task, the SRT task, the WP task, and the nonword repetition priming (NRP) task, were selected to provide a sampling of implicit learning paradigms that assesses disparate processing aspects of procedural memory.

Pursuit Rotor Task—We used a computerized version of the pursuit rotor task from the Psychology Experiment Building Language (PEBL) battery (Mueller, 2010), and changed the original mouse-driven interface into a stylus-driven/touch screen interface to resemble the traditional pursuit rotor apparatus as close as possible.

In the task, participants were asked to maintain contact between a stylus and a small circular target on a touch screen. If the stylus is on top of the circular target, the target will turn bright red. Otherwise, the target will remain dark red. To control for differences in motor

ability between groups, the rotation speed was first adjusted for each participant on four practice trials so that he/she could maintain contact with the touch screen for at least 25% of the time (i.e., 5 of 20 seconds). Each participant completed four practice trials followed by six blocks of four experimental trials. Each trial lasted twenty seconds, and there was a twenty-second rest period between two consecutive trials. In addition, two blocks were separated by approximately 10-15 minutes, during which other testing took place.

The computer software automatically generated percentage TOT for each trial, and then we calculated the mean percentage TOT for each block of four trials. In the pursuit rotor task, procedural learning was defined as significant improvement of percentage TOT across the six successive blocks.

SRT Task—We used an interleaved version of the SRT task, followed by a sequence generation task to assess the learned knowledge of sequential patterns (see Rauch et al., 1997, for details of the experimental design). Four boxes were arranged horizontally on a computer screen. For each trial, a neutral visual stimulus appeared in one of the four boxes for two seconds, followed by a fixed period (i.e., 0.4 second) with no visual stimulus appeared.

Unlike the traditional SRT task wherein one random block followed a series of pattern blocks (Nissen & Bullemer, 1987), this interleaved version comprised of the pattern block and the random block alternating along the experiment. In the pattern block, a visual stimulus followed a 12-item sequence (i.e., 1-2-1-4-2-3-4-1-3-2-4-3), which repeated six times for a total of 72 trials. In contrast, in the random block, a visual stimulus was pseudo-randomly presented for a total of 24 trials, with the constraint that no location was immediately repeated. Four random blocks (R) and three pattern blocks (P) were arranged in the following order: R-P-R-P-R-P-R. For data analysis, the median reaction time (RT) of an individual's performance on each block was calculated to minimize the impact of skewness of the RT distribution and outlier RTs. In the SRT task, procedural learning was defined as significant discrepancy in RTs between random and pattern blocks.

After completion of the task, a sequence generation task was conducted. Examiners encouraged participants to “guess” what the sequence was by making a series of 15 key presses. This follow-up task was scored based on the longest consecutive string of correct responses. Participants' performance was then compared with a chance distribution as an index of significant learned knowledge of sequence regularities. Chance performance was estimated by randomly generating 16,000 recall series, and the chance recall length was 3.80.

WP Task—The procedure and the stimuli of the WP task were taken from Knowlton et al. (1994). More details of the task could be found in the paper cited above. To summarize, participants learned the probabilistic association between two equally occurring outcome variables (i.e., RAIN or SUN) and combinations of four cue cards. Each cue card has its own predictive value. Cue 1 predicts SUN in 75% of all cases (i.e., RAIN in 25% of all cases), Cue 2 in 57%, Cue 3 in 43%, and Cue 4 in 25%. On each trial, participants saw four distinct cue cards presented either individually or in combinations of up to three cards on the

computer screen, with fourteen possible cue combinations. Participants were expected to first learn the response to those cues that have the best predictive value (e.g., the cues with 75% and 25% predictive values), and then implicitly integrate this information into a whole pattern across multiple trials in order to make the best prediction in response to different cue combinations.

For data analysis, the total fifty trials were split into five blocks of ten trials. Percentage of correct answers was measured for each block. In the WP task, procedural learning was defined as significant improvement of response accuracy across blocks (i.e., learning trajectory from the first to the last block). In addition, we also examined when this learning effect emerged by comparing the percent response accuracy in each block to the chance level.

NRP Task—The NRP task was designed in the Language and Memory Lab in the Department of Psychology at the University of Iowa. All auditory stimuli were five-syllable nonwords obtained from a nonword corpus developed by Gupta et al. (2004). The task included one practice block of eight trials, and nine experimental blocks of twenty nonword trials. In each experimental block, ten nonwords were primed across the nine blocks, whereas the other ten were unprimed (i.e., they only occurred once throughout the task). Production of unprimed nonwords served as the baseline performance in comparison with that of primed nonwords.

Before the task started, participants were instructed that they would hear a number of nonwords one at a time through the speakers, and their job was to repeat the nonword aloud as quickly and as accurately as possible. In each trial, participants were given approximately 2500 ms for immediate repetition before the next nonword was presented.

The following two steps were taken to check response accuracy. First, the examiner scored each trial as “correct” or “incorrect” during the task, and was encouraged to circle incorrect phonemes/syllables on the performance record sheet, if time permitted. Then, after the completion of the task, the corresponding author listened to all of the digitally recorded experimental sessions again to assure response accuracy. The scoring procedure was binary, such that for a trial to be scored as correct, it must contain all of the correct phonemes in the correct sequence, without any omission, substitution, addition of sound, hesitation, pause, or self-correction. In the NRP task, procedural learning, also known as priming effects in this case, was defined as significantly improved repetition accuracy of primed nonwords in comparison with that of unprimed nonwords across blocks.

General Procedure

Participants were tested individually either on campus at the University of Iowa, or in the Child Language Research Center mobile office (i.e., a van converted for testing) at their home. The total time to complete the entire experiment was approximately two hours, and participants were compensated for their time. The E-Prime 2.0 software package (Psychology Software Tools, Inc., Pittsburgh, PA) was used to control stimulus presentation

and recording of response times and accuracy in all of the tasks except for the pursuit rotor task. The order of task presentation was counterbalanced across participants.

Statistical Analysis

Two primary analyses were completed for the current study. The aim of the first analysis was to determine whether the poor language group and the typical language group had equivalent performance on the four procedural memory tasks. These analyses were conducted using mixed design analyses of variance (ANOVAs) to test for group difference based on language ability. When chance levels of performance could be established, we also tested whether participants' learning performance exceeded chance within each group. Our principal hypotheses concerned relationships between language status and each procedural learning task, and therefore the alpha levels ($\alpha = .05$) applied to each hypothesis. These analyses did not incorporate nonverbal IQ as a covariate, and this practice followed the arguments made recently by Dennis and his colleagues (2009). A second analysis was performed to examine whether performance on each procedural learning task provided unique contributions to the prediction of language ability. Standard multiple regressions were carried out, with language composite scores as the dependent variable and performance on the multiple procedural memory tasks as a set of independent variables. Statistical analyses were performed using SPSS software, Version 19 (SPSS Inc., Chicago IL). Effect size was automatically calculated in partial eta squared (η_p^2) in SPSS.

Results

Pursuit Rotor Task

Data from one of the participants with poor language abilities were missing due to technical problems. Two analyses were conducted to determine: 1) whether the poor language group and the typical language group were equivalent with respect to the individually adjusted rotation speed, and 2) whether the two groups showed different curves of procedural learning across blocks.

The rotation speed was measured in revolutions per minute (rpm). The rotation speed was individually adjusted at the beginning of the task to equate performance between groups (i.e., all participants could maintain contact with the touch screen for at least 25% of the time). An independent-samples *t*-test revealed that the rotation speed was not significantly different between the poor language group ($M = 36.38$, $SD = 15.50$) and the typical language group ($M = 40.04$, $SD = 12.55$), $t(45) = 1.13$, $p = .26$.

In the pursuit rotor task, procedural learning was reflected by changes in mean percentage target on time (TOT) across the six blocks. A 6 (Block: 1-6) $\times$ 2 (Group: Poor Language, Typical Language) ANOVA revealed a significant main effect of Block, $F(5, 225) = 34.49$, $p < .001$, $\eta_p^2 = .43$, and a significant Group by Block interaction, $F(5, 225) = 3.34$, $p < .001$, $\eta_p^2 = .07$. The Group main effect was not significant, $F(1, 45) = .089$, $p = .77$, $\eta_p^2 = .002$. Figure 1(a) demonstrates changes in mean percentage TOT across the six blocks by group. Post-hoc analyses for the interaction effect showed that participants with poor language abilities did not reveal reliable change across the six blocks, $F(5, 140) = .76$, $p = .58$,

whereas participants with typical language abilities revealed a significant increase in percentage TOT from Block 1 to Block 6, $F(5, 132) = 2.60, p = .03$.

SRT Task

Three statistical analyses were conducted to determine whether the poor language group and the typical language group were equivalent with respect to 1) RT patterns of procedural learning across blocks, 2) percentage error rates, and 3) performance on the follow-up sequence generation task.

In the SRT task, median RTs for correct responses were computed for each condition (i.e., the random condition and the pattern condition). In the typical language group, the median RTs were 329.48 ms ($SD = 40.99$) in the random condition, and 309.70 ($SD = 40.48$) in the pattern condition. The poor language group was slower than the comparison group in general, with RTs 410.52 ms ($SD = 66.41$) in the random condition, and 395.12 ($SD = 72.26$) in the pattern condition. A 2 (Condition: Pattern, Random) $\times$ 2 (Group: Poor Language, Typical Language) ANOVA revealed a significant main effect of Condition, $F(1, 46) = 25.10, p < .001, \eta_p^2 = .35$, and of Group, $F(1, 46) = 26.28, p < .001, \eta_p^2 = .36$. However, the interaction effect was not significant, $F(1, 46) = .39, p = .54, \eta_p^2 = .01$. Results are shown in Figure 1(b).

Given that the poor language group was globally slower than the typical language group in performing the SRT task, percentage error was further examined to see if there was a speed-accuracy tradeoff. An independent samples t -test showed that the percentage error rates did not reach significance between the poor language ($M = 3.98, SD = 3.35$) and the typical language ($M = 2.63, SD = 1.97$) groups, $t(46) = 1.67, p = .10$. This finding indicated that the poor language group might sacrifice speed for accuracy.

In terms of the follow-up sequence generation task, the results showed that the mean maximum consecutive correct responses was 3.80 ($SD = .82$) in the poor language group, and 4.48 ($SD = .95$) in the typical language group. The computer generated random performance on maximum consecutive correct responses was 3.84 ($SD = .89$). One-sample t -tests revealed significant learned knowledge of sequence in the typical language group, $t(22) = 3.23, p = .004$, but not in the poor language group, $t(24) = .25, p = .81$. Figure 1(c) illustrates the results of the sequence generation task.

WP Task

Two statistical analyses were carried out to determine 1) whether the poor language group and the typical language group were equivalent in overall response accuracy, and 2) at which block procedural learning occurred in each group.

In the WP task, a 5 (Block: 1-5) $\times$ 2 (Group: Poor Language, Typical Language) ANOVA was performed to see whether there was a significant difference in response accuracy between the poor language and the typical language group. Figure 1(d) shows the results of a significant main effect of Group, $F(1, 46) = 6.72, p = .01, \eta_p^2 = .13$, and of Block, $F(4, 184) = 3.87, p = .005, \eta_p^2 = .08$. The interaction effect was not significant, $F(4, 184) = .75, p = .56, \eta_p^2 = .02$.

One-sample *t*-tests were employed to examine at which block procedural learning began (i.e., performance on response accuracy above chance levels). Participants with typical language abilities showed significant learning effect starting from the first block ($ps < .005$). In contrast, participants with poor language abilities did not show above-chance learning in the first block, $t(24) = 1.67, p = .11$, or in the second block, $t(24) = 1.96, p = .06$; the learning effect emerged from the third block ($ps < .05$). An independent *t*-test revealed that the performance in the last block did not significantly differ between the poor language group and the typical language group, $t(46) = 1.42, p = .16$.

NRP Task

Figure 1(e) illustrated procedural learning by the two groups across blocks. Two statistical analyses were performed to determine 1) whether the poor language group and the typical language group have equivalent performance across blocks, and 2) at which block procedural learning (i.e., priming effect) occurred in each group.

In the NRP task, priming effects served as the dependent variable. A 9 (Block: 1-9) $\times$ 2 (Group: Poor Language, Typical Language) ANOVA revealed a significant main effect of Block, $F(8, 368) = 8.24, p < .001, \eta_p^2 = .15$, and a significant main effect of Group, $F(1, 46) = 12.82, p < .001, \eta_p^2 = .22$. The interaction effect was not significant, $F(8, 368) = .65, p = .73, \eta_p^2 = .01$.

An inspection of the data in Figure 1(e) suggested that participants with poor language abilities remained within chance levels over more training blocks than those with typical language abilities. In order to determine in which block priming effects began to exceed chance levels, one-sample *t*-tests were carried out. Results showed that participants with typical language abilities exhibited significant priming effects starting from the second block ($ps < .01$). In contrast, participants with poor language abilities did not show significant priming effects until the fifth block, and priming effects disappeared in the last block, $t(24) = 1.27, p = .22$.

Multivariate Analyses of Procedural Learning and Language

In the prior analyses, we examined the relationship between procedural learning and language for each task separately. These tasks were selected because they reflected functions of different corticostriatal loops according to the literature. Table 3 showed that the correlations among the task measures were either negligible or weak (see Table 2 for definitions of variables), indicating that these measures could contribute independent information regarding language variation. Therefore, we computed a standard multiple regression, with language composite scores as the dependent variable and performance on the procedural memory tasks (i.e., the pursuit rotor task, the SRT task, the WP task, and the NRP task) as a set of independent variables. Summary indices of learning in each task were described in Table 2. In addition, we also examined if the procedural learning measures were a significant predictor of nonverbal IQ.

Results showed that the linear combination of the four procedural learning measures significantly predicted language performance, $F(4, 42) = 6.17, p = .001, R^2 = .37$. Table 4

illustrated the first order correlations between each of the procedural learning indices. The results of these first order correlations between the procedural learning tasks and individual differences in language parallel the findings wherein language abilities were dichotomized (i.e., the poor language group and the typical language group). Table 4 also showed the partial correlations for each learning measure with language after entering the other variables, and only the NRP task contained unique variance associated with language. Thus, the variances in the pursuit rotor task and in the WP task, which were significantly associated with language in the first order correlations, were likely to be common with variance in the NRP task.

Our examination of the association between nonverbal IQ and the procedural learning tasks showed that nonverbal IQ was not significantly correlated with any of the procedural learning indices ($ps > .07$). Additionally, nonverbal IQ was not associated with the linear combination of these measures within a multivariate model, $F(4, 42) = 1.30, p = .29, R^2 = .11$.

General Discussion

The aim of the current study was to examine different aspects of procedural memory in young adults who varied with regard to their language abilities. To achieve this aim, a sample of procedural memory tasks was selected, including the pursuit rotor task, the SRT task, the WP task, and the NRP task. Learning processes during these tasks have been tapped, at least partially, into the functionality of the corticostriatal system. It is important to note that the corticostriatal loops refer to the neural pathways connecting the cortex with the basal ganglia via the thalamus, and therefore it is difficult to tease apart the unique contributions of the cortex and the subcortex to procedural learning by using behavioral tasks. In addition, we acknowledge that the corticostriatal loops are not the only neural networks involved in these tasks; the corticocerebellar loops have been implicated in some of the tasks as well (e.g., the pursuit rotor task and the SRT task). Nevertheless, given our recent work showing structural abnormalities in the basal ganglia and the thalamus but not in the cerebellum of individuals with persistent poor language abilities (Lee, 2012; Lee, Nopoulos, & Tomblin, 2013), the discussion will focus on the possible role of the corticostriatal loops in individual differences in language.

Summary and Discussion of Results

Pursuit Rotor Task—Participants with poor language abilities did not show significant motor-based procedural learning assessed by the pursuit rotor task, whereas participants with typical language abilities demonstrated significant change on performance across blocks. This contrast could not be explained by group difference in motor control ability, because the rotation speed was individually adjusted for each participant and was not significantly different between groups. These results indicated that participants with poor language abilities were poor at motor-based procedural learning, providing tentative evidence for the association between the motor corticostriatal loop and individual differences in language.

SRT Task—The poor language group and the typical language group demonstrated similar RT advantage in this interleaved version of the SRT task, indicating an equivalent degree of perceptual-based procedural learning. These findings were in contrast to those from recent studies exploring procedural learning in SLI with the SRT task (Hedenius et al., 2011; Lum et al., 2010, 2012; Sengottuvel & Rao, 2013, in press; Tomblin et al., 2007; but see Gabriel et al., 2011, 2012; Lum & Bleses, 2012; Mayor-Dubois et al., 2012). Recently, Gabriel et al. (2013) noted that poor learning of the SRT task in individuals with SLI might be dependent upon the length or complexity of the sequence used in the SRT paradigm. These authors found that twelve-item sequences were needed to show an association of procedural learning with language status. The sequence used in the current study contained twelve items; however, it remains possible that the material to be learned was not sufficiently challenging to reveal significant differences between the two groups.

Although a significant difference was not found in the training phase of the SRT task, results from the follow-up sequence generation task did reveal group differences. To interpret these disparate findings, we must consider how the two tasks differ with respect to learning and memory systems. Most of the research with regard to this issue has centered on the degree to which learning and performance is unconscious (i.e., implicit) or conscious (i.e., explicit). There is general agreement that during the training phase of the SRT task, learning is likely to be predominantly implicit, particularly during the early trials (Fu, Fu, & Dienes, 2008); however, with sufficient training, the learned knowledge can be accessed explicitly (Willingham, Nissen, & Bullemer, 1989). In contrast, the evidence generally shows that the sequence generation task entails explicit recollection of the representations of implicitly acquired sequence information (Destrebecqz et al., 2005). Fu and colleagues (2008) proposed that performance differences in the sequence generation task are affected by the quality of the representations built during the sequence learning process. Moreover, recollection of sequence information in the sequence generation task demands more robust representations than performance in the sequence learning task does. Therefore, within this framework, it is possible that the typical language group achieved a better level of knowledge of the sequence pattern than the poor language group in the current study; however, the representations formed by the poor language group were sufficient to yield similar effects in the learning phase of the SRT task. In this regard, our current findings are in line with those of Hedenius et al. (2011). In their study, group differences on the SRT task did not emerge until three days later, indicating that the knowledge acquired by individuals with poor language abilities was in a relatively fragile state, and therefore led to difficulty with long-term storage and retrieval.

WP Task—Individuals with poor language abilities demonstrated poor cognitive-based procedural learning, which was reflective of poor overall performance on response accuracy in the WP task. This finding replicates that of an earlier study by Kemeny & Lukacs (2010). With respect to the time when procedural learning began, the typical language group showed consistent above-chance learning starting from the first block. However, the poor language group did not show above-chance learning until the third block, but appeared to catch up in the last block.

These results indicated that individuals with poor language abilities were able to learn probabilistic categorization rules to some degree (i.e., similar learning effects in the last block), despite poor overall performance on response accuracy in comparison to those with typical language abilities. Nevertheless, they had a different learning trajectory in comparison to the typical language group, as shown in one-sample *t*-tests. The poor language group required a long period of time to evaluate useful information from the environment (e.g., probability of stimulus association in this task) prior to the rapid onset of learning. This may indicate that individuals with poor language abilities take a disparate path to build up memory representations in the brain, which will affect how they store that information over a long time, and how they use that information on later occasions.

NRP Task—When compared with participants with typical language abilities, those with poor language abilities demonstrated relatively poor procedural learning in the linguistic domain, as shown by less robust repetition priming effects in the NRP task. In terms of a learning trajectory, one-sample *t*-tests revealed that the typical language group showed consistent above-chance learning starting from the second block, where priming started. In contrast, the poor language group did not show above-chance learning until the fifth block, and the learned knowledge seemed vulnerable—priming effects disappeared in the last block.

These results resemble those obtained in the WP task, indicating that individuals with poor language abilities were able to detect the primed stimuli to some degree, despite poor overall performance on repetition accuracy. However, they demonstrated a different learning trajectory in comparison to participants with typical language abilities, as shown in one-sample *t*-tests. The poor language group required additional stimulus exposure before significant onset of learning; however, the learned procedural knowledge seemed fragile and prone to error.

Repetition priming has been widely viewed as a type of procedural memory (a.k.a. non-declarative memory) (Gabrieli, 1998). While some accounts state a clear distinction between repetition priming and other types of procedural learning (e.g., habit learning) (e.g., Squire, 1992), others are proposed to have a common incremental learning system underlying both skill learning and repetition priming (Gupta & Cohen, 2002; Poldrack & Gabrieli, 2001; Poldrack et al., 1999). Results concerning the neural correlates of repetition priming have shown evidence of cortical suppression as a signature of priming. However, results are mixed regarding the role of subcortical regions in repetition priming. For example, Heindel et al. (1989) reported relatively normal priming effects in individuals with Huntington's disease, suggesting that the degenerated striatum does not seem affect priming abilities. However, in the same work, they also showed impaired priming effects in individuals with Parkinson's disease, implicating a role of the basal ganglia in repetition priming.

Given the mixed results in the literature, we will not be surprised but expect to see cortical involvement in the NRP task. It is less clear whether the current findings can be viewed as direct evidence of inefficient/impaired function of the basal ganglia, given the limited and mixed findings in the literature. However, a respective contribution of the cortex and the basal ganglia to the NRP task should not be a concern for the purpose of the current study

because the NRP task was only selected as an index of the linguistic domain of procedural learning supported by the corticostriatal system. Future brain imaging studies are necessary to investigate the close interactions between cortical and subcortical regions in repetition priming.

What do These Results Tell us about the Nature of Language Development?

Several characteristics have been addressed with regard to the nature of language development. For example, language development is an implicit and incremental process, wherein repetitive exposures to the same stimuli are important for learners to catch regularities (Saffran, Aslin, & Newport, 1996). In addition, language processing is sequential in nature, and requires learners' ability to categorize linguistic elements, such as morphosyntactic or phonological components (Lieberman, 2002). Furthermore, developmental changes in young children's motor learning skills can influence developmental changes in linguistic and cognitive aspects of language acquisition (Iverson, 2010). These characteristics of language development (i.e., implicit and incremental process, repetitive exposure, sequential learning, categorization learning, and motor skill learning) have been found strongly associated with the corticostriatal system, the basal ganglia in particular (Kozioł & Budding, 2009).

In the current study, we selected a sampling of tasks that tap into different types of procedural learning, including motor skill learning (as shown in the pursuit rotor task), sequential learning (as shown in the SRT task), categorization learning (as shown in the WP task), and priming with repetitive exposures to the same stimuli (as shown in the NRP task). We found that performance on these tasks, except that on the SRT task, was associated with individual differences in language. These results implicate the multiple facets of language development. Given that language development is cumulative, having problems with either of the facets may end up developing language difficulty in the long run.

Relationship between Procedural Learning and Individual Differences in Language: Is It Due to General Cognitive Deficits?

Concerns might be raised regarding the significant discrepancy of nonverbal IQ between the two groups in the current study, which is likely to contribute to general learning difficulties in the poor language group. We recognize this possibility; however, we did not match our participants on nonverbal IQ scores because by doing so, we may end up having two unrepresentative samples: either the poor language group will have higher nonverbal IQs than the population of poor language abilities, or the typical language group will have nonverbal IQs below normative expectations (Dennis et al., 2009). To assure those who might not agree with this position, we did examine whether performance on the different procedural learning tasks was associated with non-verbal IQ scores. This analysis showed that despite a strong correlation between nonverbal IQ and language scores, nonverbal IQ was not significantly associated with any of these tasks nor was it associated with the combination of these tasks. This lack of an association between nonverbal IQ and procedural learning greatly reduces the possibility that nonverbal IQ could serve as a confounder in the current study.

Possible Role of Corticostriatal System in Individual Differences in Language

Over the past decades, there has been a growing interest in the contributions of the interactions between cortical and subcortical structures to language, and the corticostriatal system in particular receives lots of attention. Much classic evidence of the basal ganglia mediation in language comes from studies of patients with striatal damage. For example, individuals with Huntington's disease showed difficulty learning a simplified artificial language, wherein novel words followed artificial grammatical rules and no semantic representations were accessible (De Diego-Balaguer et al., 2008). In addition, they demonstrated inefficient use of purely syntactic operations during sentence comprehension (Teichmann et al., 2005). Language learning difficulties in Parkinson's disease are similar to those reported in Huntington's disease (Lieberman et al., 1992). These findings implicate the basal ganglia in language processing pertaining to regularity extractions.

While patient studies shed light on the role of the corticostriatal system in language processing, findings should be interpreted with caution because degenerative disease processes tend to affect multiple brain systems, and are usually confounded with aging. Imaging techniques, on the other hand, are promising tools for providing new insight into this question. Recent imaging research has shown that the basal ganglia support various aspects of language, including phonological processing (Tettamanti et al., 2005), syntactic processing (Friederici & Kotz, 2003), and semantic processing (Crosson, Benjamin, & Levy, 2007). These findings implicate the basal ganglia in rule- or pattern-based computational processes that cut across a wide variety of linguistic domains.

In addition to patient and imaging studies, neurochemical research also reveals a possible connection between the basal ganglia and language. Wong et al. (2012) proposed an association between dopamine-related genetic variation and individual differences in language, and the frontostriatal pathway and the procedural memory system are considered as the endophenotypes of individual differences in language. In addition, it was found that levodopa (L-dopa), a drug frequently used to increase dopamine levels in patients with striatal diseases (e.g., Parkinson's disease), has the potential to enhance language learning in healthy human brains (Breitenstein et al., 2006; Knecht et al., 2004). Breitenstein and her colleagues designed an implicit word learning paradigm, wherein participants learned to extract statistical probabilities of word-object mappings from repetitive exposure to nonwords without conscious awareness (see Breitenstein & Knecht, 2002, for details). Knecht et al. (2004) showed that compared to those receiving a placebo, healthy participants who took L-dopa for five consecutive days performed better on learning speed, overall accuracy rate, and long-term retention of newly learned words. These results indicate that activities of dopamine neurons in the basal ganglia are associated with probabilistic associative learning with high-frequency repetition, which is an important feature of language acquisition.

It should be noted that we are neither trying to ignore the significant contribution of the cortex to language, nor suggesting an isolated influence of the basal ganglia on language. Instead, we propose that the cortico-centric view on language is not sufficient to reflect the complex and integrated neural basis of language. It is the reciprocal interconnection between cortical and subcortical structures that contributes to the higher functions of the brain.

Conclusion

In the current study, we selected a sample of procedural learning tasks to assess disparate processing aspects of procedural memory. The results showed that individuals with poor language abilities demonstrated relatively poor performance on these procedural memory tasks. This study is significant in two ways: 1) it contributes to our understanding of the association between procedural memory and individual differences in language in a wide range of domains, and 2) the behavioral findings implicate the corticostriatal loops as part of the neural basis of individual differences in language. Future research is suggested to use imaging techniques to examine how corticostriatal connectivity supports language learning and processing.

Acknowledgments

The research was supported by R01-DC007643-05 from the National Institutes of Health awarded to Dr. Bruce Tomblin. We would like to thank Rick Arenas, Connie Ferguson, Wendy Fick, Marlea O'Brien, and Marcia St. Clair (last name listed alphabetically) from the Child Language Research Center at the University of Iowa for research assistance and data collection, Trace Poll at Elmhurst College for developing the WP task on E-Prime software, and the anonymous reviewers for their invaluable comments to strengthen the manuscript. We are also grateful to the participants for agreeing to take part in this research.

References

- Alexander GE, Crutcher MD. Functional architecture of basal ganglia circuits: Neural substrates of parallel processing. *Trends in Neurosciences*. 1990; 13:266–271. [PubMed: 1695401]
- Breitenstein C, Knecht S. Development and validation of a language learning model for behavioral and functional-imaging studies. *Journal of Neuroscience Methods*. 2002; 114:173–179. [PubMed: 11856568]
- Breitenstein C, Floel A, Korsukewitz C, Wailke S, Bushuven S, Knecht S. A shift of paradigm: From noradrenergic to dopaminergic modulation of learning? *Journal of the Neurological Sciences*. 2006; 248:42–47. [PubMed: 16815467]
- Broca P. Remarques sur le siège de la faculté de langage articulé. *Bulletin de la Societe d'anthropologie*. 1865; 5:377–393.
- Crosson B. Subcortical functions in language: A working model. *Brain and Language*. 1985; 25(2): 257–292. [PubMed: 3904918]
- Crosson, B. Subcortical functions in language and memory. NY: the Guilford Press; 1992.
- Crosson BA, Benefield H, Cato MA, Sadek JR, Moore AB, Wierenga CE, et al. Left and right basal ganglia and frontal activity during language generation: Contributions to lexical, semantic, and phonological processes. *Journal of the International Neuropsychological Society*. 2003; 9:1066–1077.
- Crosson, BA.; Benjamin, M.; Levy, I. Role of the basal ganglia in language and semantics: Supporting cast. In: Hart, J.; Kraut, MA., editors. *Neural basis of semantic memory*. Cambridge University Press; Cambridge: 2007. p. 219–243.
- De Diego-Balaguer R, Couette M, Dolbeau G, Durr A, Youssov K, Bachoud-Levi AC. Striatal degeneration impairs language learning: Evidence from Huntington's disease. *Brain*. 2008; 131(11): 2870–2881. [PubMed: 18842608]
- Dennis M, Francis DJ, Cirino PT, Schachar R, Barnes MA, Fletcher JM. Why IQ is not a covariate in cognitive studies of neurodevelopmental disorders. *Journal of International Neuropsychological Society*. 2009; 15:331–343.
- De Renzi E, Faglioni P. Normative data and screening power of a shortened version of the Token Test. *Cortex*. 1978; 14:41–49. [PubMed: 16295108]

- Destrebecqz A, Peigneux P, Laureys S, Degueldre C, Del Fiore G, Aerts J, et al. The neural correlates of implicit and explicit sequence learning: interacting networks revealed by the process dissociation procedure. *Learning and Memory*. 2005; 12:480–490. [PubMed: 16166397]
- Dollaghan CA. Taxometric analyses of specific language impairment in 6-year-old Children. *Journal of Speech, Language, and Hearing Research*. 2011; 54:1361–1371.
- Dominey PF, Arbib MA, Joseph JP. A model of cortico-striatal plasticity for learning oculomotor associations and sequences. *Journal of Cognitive Neuroscience*. 1995; 7:311–336. [PubMed: 23961864]
- Dominey PF. An anatomically structured sensory-motor sequence learning system displays some general linguistic capacities. *Brain and Language*. 1997; 59(1):50–75. [PubMed: 9262851]
- Dominey PF, Hoen M, Inui T. A neurolinguistic model of grammatical construction processing. *Journal of Cognitive Neuroscience*. 2006; 18:2088–2107. [PubMed: 17129193]
- Dominey PF, Inui T. Cortico-striatal function in sentence comprehension: Insights from neurophysiology and modeling. *Cortex*. 2009; 45(8):1012–1018. [PubMed: 19446801]
- Dunn, LM.; Dunn, DM. Peabody picture vocabulary test-fourth edition (PPVT-4). MN: Pearson; 2007.
- Friederici A, Kotz SA. The brain basis of syntactic processes: Functional imaging and lesion studies. *NeuroImage*. 2003; 20:8–17.
- Fu Q, Fu X, Dienes Z. Implicit sequence learning and conscious awareness. *Consciousness and Cognition*. 2008; 17(1):185–202. [PubMed: 17383202]
- Gabriel A, Maillart C, Guillaume M, Stefaniak N, Meulemans T. Exploration of serial structure procedural learning in children with language impairment. *Journal of the International Neuropsychological Society*. 2011; 17:1–8. [PubMed: 21083962]
- Gabriel A, Maillart C, Stefaniak N, Lejeune C, Desmottes L, Meulemans T. Procedural learning in specific language impairment: Effects of sequence complexity. *Journal of International Neuropsychological Society*. 2013; 19:264–271.
- Gabriel A, Stefaniak N, Maillart C, Schmitz X, Meulemans T. Procedural visual learning in children with specific language impairment. *American Journal of Speech-Language Pathology*. 2012; 21:329–341. [PubMed: 22846879]
- Gabrieli JDE. Cognitive neuroscience of human memory. *Annual Review of Psychology*. 1998; 49:87–115.
- Grafton ST, Woods RP, Tyska M. Functional imaging of procedural motor learning: Relating cerebral blood flow with individual subject performance. *Human Brain Mapping*. 1993; 1(3):221–234. [PubMed: 24578042]
- Grossman M. Sentence processing in Parkinson's disease. *Brain and Cognition*. 1999; 40(2):387–413. [PubMed: 10413567]
- Gupta, P. Word learning as the confluence of memory mechanisms: Computational and neural evidence. In: Faust, M., editor. *The handbook of the neuropsychology of language*. Vol. 2. West Sussex, UK: Blackwell Publishing Ltd; 2012.
- Gupta P, Cohen NJ. Theoretical and computational analysis of skill learning, repetition priming, and procedural memory. *Psychological Review*. 2002; 109(2):401–448. [PubMed: 11990324]
- Gupta, P.; Dell, GS. The emergence of language from serial order and procedural memory. In: MacWhinney, B., editor. *The Emergence of Language*. Hillsdale, NJ: Lawrence Erlbaum; 1999. p. 447–482.
- Gupta P, Lipinski J, Abbs B, Lin P, Aktunc E, Ludden D, et al. Space aliens and nonwords: Stimuli for investigating the learning of novel word-meaning pairs. *Behavior Research Methods, Instruments, & Computers*. 2004; 36:599–603.
- Gupta P, Tisdale J. Word learning, phonological short-term memory, phonotactic probability and long-term memory: towards an integrated framework. *Philosophical Transactions of the Royal Society B: Biological Sciences*. 2009; 364(1536):3755–3771.
- Hammill, DD.; Brown, VL.; Larsen, SC.; Wiederholt, JL. *Test of adolescent and adult language*. Austin, TX: Pro-Ed; 2007.
- Hedenius M, Persson J, Tremblay A, Adi-Japha E, Verissimo J, Dye CD, et al. Grammar predicts procedural learning and consolidation deficits in children with specific language impairment. *Research in Developmental Disabilities*. 2011; 32(6):2362–2375. [PubMed: 21840165]

- Heindel WC, Salmon DP, Shults CW, Walicke PA, Butters N. Neuropsychological evidence for multiple implicit memory systems: a comparison of Alzheimer's, Huntington's and Parkinson's disease patients. *Journal of Neuroscience*. 1989; 9:582–587. [PubMed: 2521896]
- Iverson JM. Developing language in a developing body: the relationship between motor development and language development. *Journal of Child Language*. 2010; 37:229–261. [PubMed: 20096145]
- Kemeny F, Lukacs A. Impaired procedural learning in language impairment: Results from probabilistic categorization. *Journal of Clinical and Experimental Neuropsychology*, iFirst. 2009:1–12.
- Kim J, Reading SAJ, Brashers-Krug T, Calhoun VD, Ross CA, Parlson GD. Functional MRI study of a serial reaction time task in Huntington's disease. *Psychiatry Research: Neuroimaging*. 2004; 131:23–30. [PubMed: 15246452]
- Knecht S, Breitenstein C, Bushuven S, Wailke S, Kamping S, Floel A, et al. Levodopa: Faster and better word learning in normal humans. *Annals of Neurology*. 2004; 56:20–26. [PubMed: 15236398]
- Knowlton BJ, Squire LR, Gluck MA. Probabilistic classification learning in amnesia. *Learning and Memory*. 1994; 1(2):106–120. [PubMed: 10467589]
- Kotz SA, Frisch S, von Cramon DY, Friederici AD. Syntactic language processing: ERP lesion data on the role of the basal ganglia. *Journal of the International Neuropsychological Society*. 2003; 9(7): 1053–1060. [PubMed: 14738286]
- Kozioł, LF.; Budding, D. Subcortical structures and cognition: Implications for neuropsychological assessment. Springer Publications; New York, N.Y: 2009.
- Lee, JC. Unpublished doctoral dissertation. University of Iowa; Iowa, USA: 2012. Are individual differences in language associated with differences in the corticostriatal system? A behavioral and imaging study.
- Lee JC, Nopoulos PC, Tomblin JB. Abnormal subcortical components of the corticostriatal system in young adults with SLI: A combined structural MRI and DTI Study. *Neuropsychologia*. 2013; 51(11):2154–2161. [PubMed: 23896446]
- Leonard, L. Is specific language impairment a useful construct?. In: Rosenberg, S., editor. *Advances in applied psycholinguistics (Vol 1) Disorders of first language development*. New York, NY: Cambridge University Press; 1987. p. 1-39.
- Leonard L. Specific language impairment as a clinical category. *Language, Speech, and Hearing Services in Schools*. 1991; 22:66–68.
- Leonard, L. *Children with specific language impairment*. Cambridge, MA: The MIT Press; 1998.
- Lieberman P. On the nature and evolution of the neural bases of human language. *American Journal of Physical Anthropology*. 2002; 119(35):36–62. [PubMed: 12653308]
- Lieberman P, Kako E, Friedman J, Tajchman G, Feldman LS, Jiminez EB. Speech production, syntax comprehension, and cognitive deficits in Parkinson's disease. *Brain and Language*. 1992; 43:169–189. [PubMed: 1393519]
- Longworth CE, Keenan SE, Barker RA, Marslen-Wilson WD, Tyler LK. The basal ganglia and rule-governed language use: evidence from vascular and degenerative conditions. *Brain*. 2005; 128(3): 584–596. [PubMed: 15659423]
- Lum JAG, Bleses D. Declarative and procedural memory in Danish speaking children with specific language impairment. *Journal of Communication Disorders*. 2012; 45:46–58. [PubMed: 22000901]
- Lum JAG, Conti-Ramsden G, Page D, Ullman M. Working, declarative, and procedural memory in specific language impairment. *Cortex*. 2012; 48:1138–1154. [PubMed: 21774923]
- Lum JAG, Gelgec C, Conti-Ramsden G. Procedural and declarative memory in children with and without specific language impairment. *International Journal of Language and Communication Disorders*. 2010; 45(1):96–107. [PubMed: 19900077]
- Mayor-Dubois C, Zesiger P, van der Linden M, Roulet-Perez E. Nondeclarative learning in children with specific language impairment: Predicting regularities in the visuomotor, phonological, and cognitive domains. *Child Neuropsychology*, iFirst. 2012:1–9.
- Morice R, McNicol D. The comprehension and production of complex syntax in schizophrenia. *Cortex*. 1985; 21:567–580. [PubMed: 4092484]

- Mueller, ST. Programming and usage guide for the psychology experiment building language PEBL version 0.11. 2010. Available at: <http://pebl.sourceforge.net>
- Nissen MJ, Bullemer P. Attentional requirements of learning: Evidence from performance measures. *Cognitive Psychology*. 1987; 19:1–32.
- Poldrack RA, Gabrieli JDE. Characterizing the neural mechanisms of skill learning and repetition priming: Evidence from mirror reading. *Brain*. 2001; 124:67–82. [PubMed: 11133788]
- Poldrack RA, Selco SL, Field JE, Cohen NJ. The relationship between skill learning and repetition priming: Experimental and computational analyses. *Journal of Experimental Psychology: Learning, Memory, and Cognition*. 1999; 25(1):208–235.
- Price CJ. The anatomy of language: contributions from functional neuroimaging. *Journal of anatomy*. 2000; 197(3):335–359. [PubMed: 11117622]
- Rauch SL, Whalen PJ, Savage CR, Curran T, Kendrick A, Brown HD, et al. Striatal recruitment during an implicit sequence learning task as measured by functional magnetic resonance imaging. *Human Brain Mapping*. 1997; 5:124–132. [PubMed: 10096417]
- Saffran JR, Aslin RN, Newport EL. Statistical learning by 8-month-old infants. *Science*. 1996; 274(5294):1926–1928. [PubMed: 8943209]
- Seger CA. The basal ganglia in human learning. *The Neuroscientist*. 2006; 12(4):285–290. [PubMed: 16840704]
- Sengottuvel K, Rao PK. Aspects of grammar sensitive to procedural memory deficits in children with specific language impairment. *Research in Developmental Disabilities*. 2013; 34(10):3317–3331. [PubMed: 23911642]
- Sengottuvel K, Rao PK. Sequence learning pattern in children with specific language impairment. *International Journal on Disability and Human Development*. in press.
- Shohamy D, Myers CE, Kalanithi J, Gluck MA. Basal ganglia and dopamine contributions to probabilistic category learning. *Neuroscience and Biobehavioral Reviews*. 2008; 32:219–236. [PubMed: 18061261]
- Squire LR. Declarative and nondeclarative memory: Multiple brain systems supporting learning and memory. *Journal of Cognitive Neuroscience*. 1992; 4(3):232–243. [PubMed: 23964880]
- Teichmann M, Dupoux E, Kouider S, Brugieres P, Boisse M, Baudic S, et al. The role of the striatum in rule application: The model of Huntington's disease at early stage. *Brain*. 2005; 128:1155–1167. [PubMed: 15788544]
- Tettamanti M, Moro A, Messa C, Moresco RM, Rizzo G, Carpinelli A, et al. Basal ganglia and language: Phonology modulates dopaminergic release. *Neuroreport*. 2005; 16:397–401. [PubMed: 15729145]
- Tomblin JB, Mainela-Arnold E, Zhang X. Procedural learning in adolescents with and without specific language impairment. *Language Learning and Development*. 2007; 3:269–293.
- Tomblin JB, Records NL, Zhang X. A system for the diagnosis of specific language impairment in kindergarten children. *Journal of Speech & Hearing Research*. 1996; 39:1284–1294. [PubMed: 8959613]
- Tomblin, JB.; Zhang, X. Are children with SLI a unique group of language learners?. In: Tager-Flusberg, H., editor. *Neurodevelopmental disorders: contributions to a new framework from the cognitive neurosciences*. Cambridge, MA: MIT Press; 1999. p. 361–382.
- Ullman MT. Contributions of memory circuits to language: The declarative/procedural model. *Cognition*. 2004; 92:231–270. [PubMed: 15037131]
- Ullman MT, Corkin S, Coppola M, Hickok G, Growdon JH, Koroshetz WJ, et al. A neural dissociation within language: Evidence that the mental dictionary is part of declarative memory, and that grammatical rules are processed by the procedural system. *Journal of Cognitive Neuroscience*. 1997; 9(2):266–276. [PubMed: 23962016]
- Ullman MT, Pierpont EI. Specific language impairment is not specific to language: The procedural deficit hypothesis. *Cortex*. 2005; 41:399–433. [PubMed: 15871604]
- Wechsler, D. Wechsler abbreviated scale of intelligence (WASI). San Antonio, TX: The Psychological Corporation; 1999.
- Willingham DB, Nissen MJ, Bullemer P. On the development of procedural knowledge. *Journal of Experimental Psychology: Learning, Memory and Cognition*. 1989; 15:1047–1060.

Wong PCM, Morgan-Short K, Ettlinger M, Zheng J. Linking neurogenetics and individual differences in language learning: The dopamine hypothesis. *Cortex*. 2012; 48(9):1091–1102. [PubMed: 22565204]

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Figure 1.

Abbreviations for the poor language group and the typical language group were Poor and Typical respectively. (a) Mean percentage TOT (%) for the six blocks of the pursuit rotor task (four trials per block) by group. (b) Results of the SRT task. Procedural learning was reflected by RT difference between random blocks and pattern blocks. (c) Results of the follow-up sequence generation task. **: significant difference at the .01 level. (d) Results of the WP task. Procedural learning was defined as significant improvement of response accuracy across blocks. (e) Results of the NRP task. Priming effects (i.e., procedural learning) was defined as significantly improved repetition accuracy of primed nonwords in comparison with that of unprimed nonwords across blocks.

Table 1

Summary of participant characteristics.

Sex Ratio (Female : Male)	Poor Language Group (<i>n</i> = 25)		Typical Language Group (<i>n</i> = 23)		<i>p</i>
	<i>M</i>	(<i>SD</i>)	<i>M</i>	(<i>SD</i>)	
Age (Years)	22.14	1.31	22.23	.54	n.s.
PPVT-4	84.40	7.27	101.09	13.24	< .001
Token Test	52.32	32.55	101.30	13.86	< .001
Word Derivations	72.00	7.91	93.48	13.27	< .001
Nonverbal IQ composite	89.68	12.41	110.52	9.89	< .001
Language Composite					
Scores Assessed in Kindergarten	74.56	8.49	107.59	16.12	< .001
Nonverbal IQ Composite					
Scores Assessed in Kindergarten	87.52	12.39	106.69	13.53	< .001

Table 2

Definitions of variables used in correlation and multiple regression analyses.

Variable	Definition
Language composite	Average standard scores of PPVT-4, Word Derivation, and Token Test
Nonverbal IQ composite	Standard scores derived from the nonverbal subtests of the WASI (i.e., Block Design and Matrix Reasoning)
Pursuit rotor task	Difference of average TOT between the last block and the first block
SRT task	Difference of median RTs between random blocks and pattern blocks
WP task	Average percent accuracy across five blocks
NRP task	Difference of average percent accuracy in repetition between primed nonwords and unprimed nonwords

Table 3

Correlations among procedural learning tasks. SRT: Serial reaction time task; WP: Weather prediction task; NRP: Nonword repetition priming Task.

	1	2	3	4
1 Pursuit Rotor Task	-			
2 SRT Task	.17 (<i>p</i> = .27)	-		
3 WP Task	.05 (<i>p</i> = .73)	-.12 (<i>p</i> = .42)	-	
4 NRP Task	.26 (<i>p</i> = .07)	-.01 (<i>p</i> = .94)	.35* (<i>p</i> = .01)	-

Table 4

First order and partial correlations between procedural learning tasks and language composite scores. SRT: Serial reaction time task; WP: Weather prediction task; NRP: Nonword repetition priming Task.

Predictors	First Order correlation with language composite scores	Standardized coefficient with language composite after controlling for all other predictors
Pursuit Rotor	0.30* ($p = .04$)	0.16 ($p = .22$)
WP	0.38* ($p < 0.01$)	0.20 ($p = .12$)
SRT	0.06 ($p = .68$)	0.09 ($p = .49$)
NRP	0.57* ($p < 0.01$)	0.44* ($p < .01$)