Links Between Implicit Learning of Sequential Patterns and Spoken Language Processing

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Abstract

Spoken language consists of a complex, time-varying signal that contains sequential patterns that can be described in terms of statistical relations among language units. Previous research has suggested that a domain-general ability to learn structured sequential patterns may underlie language acquisition. To test this prediction, we examined the extent to which implicit sequence learning of probabilistically-structured patterns in normal-hearing adults is correlated with performance on a spoken sentence perception task under degraded listening conditions. Our data revealed that performance on the sentence perception task correlated with implicit sequence learning, but only when the sequences were composed of stimuli that were easy to encode verbally. The evidence is consistent with the hypothesis that implicit learning of phonological sequences is an important cognitive ability that contributes to spoken language processing abilities.

Keywords: Implicit learning, artificial grammar learning, sequence learning, speech perception, language.

Introduction

It has long been recognized that language comprehension involves the coding and manipulation of sequential patterns (Lashley, 1951; see also Conway & Christiansen, 2001). Spoken language can be thought of as patterns of sound symbols occurring in a sequential stream. Many of the sequential patterns of language are fixed, that is, they occur in a consistent, regular order (e.g., words are fixed sequences of phonemes). Thus, being able to encode and store in memory fixed sequences of sounds would appear to be a key aspect of language learning. Empirical work with normal-hearing adults and children supports this view, showing a strong link between sequence memory, word learning, and vocabulary development (for a review, see Baddeley, 2003).

Although short-term verbal memory is undoubtedly important for learning *fixed* sequences in language, such as words or idioms, the learning of more complex, highly variable patterns in language may require a different kind of cognitive mechanism altogether (Conway & Christiansen, 2001). For instance, in addition to fixed sequential patterns of sounds, spoken language also contains sequences that can be described in terms of complex statistical relations among language units. Rarely is a spoken utterance perfectly predictable; most often, the next word in a sentence can only be partially predicted based on the preceding context (Rubenstein, 1973). It is known that sensitivity to such probabilistic information in the speech stream can improve the perception of spoken materials in noise; the more predictable a sentence is, the easier it is to perceive it (Kalikow et al., 1977). Therefore, the ability to extract probabilistic or statistical patterns in the speech stream may be a factor that is important for language learning and spoken language processing: the better able one is at implicitly learning the sequential patterns in language, the better one should be at processing upcoming spoken materials in an utterance, especially under highly degraded listening conditions.

In this paper, we examine the hypothesis that a domain-general ability to implicitly encode complex sequential patterns underlies aspects of spoken language processing. This kind of incidental, probabilistic sequence learning has been investigated in some depth over the last few years under the rubrics of “implicit”, “procedural”, or “statistical” learning (Cleeremans, Destrebecqz, & Boyer, 1998; Conway & Christiansen, 2006; Saffran, Aslin, & Newport, 1996; Stadler & Frensch, 1998). To help elucidate the link between implicit learning and language processing, we used a new experimental methodology that was developed to assess sequence memory and learning based on Milton Bradley’s Simon memory game (e.g., Pisoni & Cleary, 2004). In this task, participants see sequences of colored lights and/or sounds and are required to simply reproduce each sequence by pressing colored response panels in correct order.

Not only can the Simon memory game task be used to assess learning and memory of fixed sequences, but it can also be used to measure implicit sequence learning of more complex rule-governed or probabilistic patterns (Karpicke & Pisoni, 2004). In the present experiment, we used a version of the Simon memory game that incorporates visual-only stimuli that contained structural regularities, and correlated participants’ performance on the implicit learning task with their ability to perceive spoken sentences that varied in terms of the final word’s predictability, under degraded listening conditions. Before describing the study in full, we first briefly review previous evidence related to implicit learning and language processing.

Implicit Sequence Learning and Language

Implicit learning involves automatic, unconscious learning mechanisms that extract regularities and patterns that are present across a set of exemplars, typically without direct awareness of what has been learned. Many researchers believe that implicit learning is one of the primary mechanisms through which children learn language (Cleeremans et al., 1998; Conway & Christiansen, 2001; Dominey, Hoen, Blanc, & Lelekov-Boissard, 2003; Ulman, 2004): language acquisition, like implicit learning, also involves the incidental, unconscious learning of complex sequential patterns. This perspective on language development is supported by recent findings showing that infants engage implicit learning processes to extract the underlying statistical patterns in language-like stimuli (Gómez & Gerken, 2000; Saffran et al., 1996).

Although it is a common assumption that implicit learning is important for language processing, the evidence directly linking the two processes is mixed. One approach is to assess language-impaired individuals on a putatively non-linguistic implicit learning task; if the group shows a deficit on the implicit learning task, this result is taken as support for a close link between the two cognitive processes. Using this approach, some researchers have found an implicit sequence learning deficit in dyslexics (Howard, Howard, Japikse, & Eden, 2006; Menghini, Hagberg, Caltagirone, Petrosini, & Vicari, 2006; Vicari, Marotta, Menghini, Molinari, & Petrosini, 2003) while others have found no connection between implicit learning, reading abilities, and dyslexia (Kelly, Griffiths, & Frith, 2002; Rüsseler, Gerth, & Münte, 2006; Waber et al., 2003). At least with regard to reading and dyslexia, the role of implicit learning is not clear (also see Grunow, Spaulding, Gómez, & Plante, 2006).

One complication with establishing an empirical link between implicit learning and language processing is that implicit learning itself may involve multiple subsystems that each handle different types of input (e.g., Conway & Christiansen, 2006; Goschke, Friederici, Kotz, & van Kampen, 2001). For instance, Conway and Christiansen (2006) used a novel modification of the artificial grammar learning paradigm (Reber, 1967), with participants exposed to sequential patterns from two grammars interleaved with one another. Participants learned both grammars well when the stimuli were in two different sense modalities (vision and audition) or were in two different perceptual dimensions within the same sense modality (colors and shapes or tones and nonsense words). However, when the grammars were instantiated using the same perceptual dimension (two sets of shapes or two sets of nonsense words), participants demonstrated much worse implicit learning performance. These results suggest the possible existence of multiple learning mechanisms that operate in parallel, each over a specific kind of input (tones, speech-like material, shapes, etc.).

A similar conclusion was reached by Goschke et al. (2001). They found that aphasics were impaired on the learning of phoneme sequences but not visual sequences, suggesting the involvement of dissociable domain-specific learning systems. The existence of multiple implicit learning systems may help explain why some studies have demonstrated a link between implicit learning and language and other studies have not: some implicit learning systems (e.g., perhaps those handling phonological patterns) may be more closely involved with language acquisition and processing than others.

The empirical study described below was designed to elucidate some of the complex issues regarding the nature of implicit sequence learning and its involvement in spoken language processing. In the present experiment, we used two versions of the Simon game task – one using color patterns and the other using non-color spatial patterns -- in order to examine possible differences in visual stimuli that can be easily or not easily encoded verbally. We also used a spoken language task under degraded listening conditions. In this way, we were able to assess whether implicit sequence learning that is or is not phonologically-mediated is correlated with spoken language perception under degraded listening conditions. Our hypothesis was that performance on the Simon implicit sequence learning task would be significantly and strongly correlated with performance on the spoken sentence perception task, but only when the Simon task uses stimuli that are easy to encode verbally.

Method

Participants

Twenty undergraduate students (age 18-36 years old) at Indiana University received either monetary compensation or course credit for their participation. All subjects were native speakers of English and reported no history of a hearing loss or speech impairment.

Apparatus

A *Magic Touch*® touch-sensitive monitor displayed visual sequences for the two implicit learning tasks and recorded participant responses.

Stimulus Materials

Spoken sentence perception task For the language perception task, we used English "SPIN" sentences created by Kalikow et al. (1977) and subsequently modified by Clopper and Pisoni (2006). The sentences varied in terms of the final word's predictability. Three types of sentences were used, 25 of each type: high-predictability (HP), low-predictability (LP), and anomalous (AN). All sentences were 5 to 8 words in length and were balanced in terms of phoneme frequency. HP sentences have a final target word that is predictable given the semantic context of the sentence (e.g., "*Her entry should win first prize*"); LP sentences have a target word that is not predictable given the semantic context of the sentence (e.g., "*The man spoke about the clue*"). On the other hand, AN sentences follow the same syntactic form and use the same carefully constructed set of phonetically balanced words as the HP and LP sentences, but the content words have been placed randomly (e.g., "*The coat is talking about six frogs*").

All 75 sentences were spoken by a single male speaker, a life-time resident of the "midland" region of the United States, whose spoken recordings were chosen from amongst a set of recordings taken from multiple speakers developed as part of the "Nationwide Speech Project" (see Clopper & Pisoni, 2006). The sentences were then degraded by processing them with a sinewave vocoder (www.tigerspeech.com) that simulates listening conditions for a user of a cochlear implant with 6 spectral channels. All sentences were leveled at 64 dB RMS.

Implicit sequence learning tasks For the sequence learning tasks, we used three different artificial grammars to generate the sequences. Grammar A was taken from Karpicke and Pisoni (2004) while Grammars B and C were from Knowlton and Squire (1996). An artificial grammar is a Markovian finite-state machine that consists of a series of nodes connected by various transitions (see Figure 1). The grammars can generate sequences of various lengths that obey certain rules that specify the order that sequence elements can occur. To use the grammar to generate a sequence, one begins at the arrow marked "start", and traverses through the various states to determine the elements of the sequence, until reaching the "end" arrow. For example, by passing through the nodes S1, S2, S5, S7, S10, Grammar A generates the sequence: 3-4-3-1.

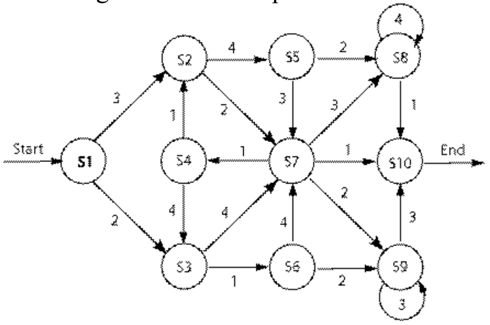

Figure 1: One of three artificial grammars used to generate sequences for the implicit learning tasks.

We used each grammar to generate 22 unique exemplars (2 exemplars of length 3, and 4 exemplars each of lengths 4-8) that were used for the Learning Phase of the task. Twenty additional exemplars were also generated by each grammar (4 exemplars each of lengths 4-8), for use in the Test Phase. Twenty ungrammatical sequences were also generated for the Test Phase. Ungrammatical sequences were created by taking each grammatical sequence and randomly shuffling the elements that comprise it. For example, the ungrammatical sequence 2-2-3-3 is a randomized version of the Grammar A grammatical sequence 3-2-2-3. Using this method, ungrammatical sequences differ from grammatical sequences only in terms of the *order* of elements within a sequence, not in terms of the actual elements themselves.

Procedure

All participants engaged in three tasks: a spoken sentence perception (SSP) task which occurred under degraded listening conditions; and two visual sequence learning tasks, "Colored-Sequence" (Color-Seq) and "Non-Colored-Sequence" (Non-Color-Seq). The order that participants engaged in each of these three tasks varied according to random assignment, but in all cases the SSP task always occurred as the middle of the three tasks.

Spoken sentence perception task In the SSP task, participants were told they would listen to sentences that were distorted by a computer, making them difficult to perceive. Their task was to identify the last word in each sentence and write the word down on a sheet of paper provided to them. Sentences were presented over headphones using a self-paced format. The 75 sentences described above were presented in a different random order for each subject. A written response was scored as correct if the written word matched the intended spoken target word; misspellings (e.g., "valt" instead of "vault") were counted as correct responses.

Implicit sequence learning tasks For the two sequence learning tasks, Color-Seq and Non-Color-Seq, we used a touchscreen version of the Simon game device. Participants were told that they would see visual sequences on the computer screen and then after each one, they were required to reproduce what they saw using the response panels on the touch screen. Unbeknownst to participants, the sequences were generated according to one of the three artificial grammars previously described. Each sequence learning task consisted of two parts, a Learning Phase and a Test Phase. The procedures for both phases were identical and in fact from the perspective of the subject, there was no indication of separate phases at all. The only difference between the two phases was which sequences were used. In the Learning Phase, the 22 Learning Sequences were presented randomly, two times each. After completing the sequence reproduction task for all of the learning sequences, the experiment seamlessly transitioned to the Test Phase, which used the 20 novel grammatical (G) and 20 ungrammatical (U) Test Sequences.

Sequence presentation consisted of colored (for Color-Seq) or black (for Non-Color-Seq) squares appearing one at a time, in one of four possible positions on the screen (upper left, upper right, lower left, lower right). Each square appeared on the screen for a duration of 700 msec, with a 500 msec ISI. For Color-Seq, the four elements (1-4) of each grammar were randomly mapped onto each of the four screen locations as well as four possible colors (red, blue, yellow, green). The assignment of grammar element to position/color was randomly determined for each subject; however, for each subject, the mapping remained consistent across all trials. Likewise, for Non-Color-Seq, the four elements of each grammar were mapped onto each of the four screen locations, randomly determined for each subject. The spatial mapping in this condition also remained invariant for a given subject.

After an element appeared for 700 msec, the screen was blank for 500 msec, and then the next element of the sequence appeared. After the entire sequence had been presented, there was a 2000 msec delay and then five panels appeared on the touch screen. Four of those panels were the same-sized and same-colored as the four locations that were used to display each sequence. The squares were appropriately colored (red, green, blue, and yellow for Color-Seq and all black for Non-Color-Seq). The fifth panel was a long horizontal bar placed at the bottom of the screen, which acted as the equivalent of the "Enter" button. The subject's task was to watch a sequence presentation and then to reproduce the sequence they saw by pressing the appropriate buttons in the correct order as dictated by the sequence. When they were finished with their response, they were instructed to press the long black bar at the bottom, and then the next sequence was presented after a 2-sec delay.

Participants were not told that there was an underlying grammar for any of the Learning or Test sequences, nor that there were two 2 types of sequences in the Test phase. From the standpoint of the participant, the task in Color-Seq and Non-Color-Seq was solely one of observing and then reproducing a series of unrelated sequences.

Finally, following the experiment, all participants filled out a debrief form that asked whether they used a verbal strategy when doing the Non-Color-Seq task, such as verbally coding the four different locations in terms of numbers "one", "two", etc.

Results

For the SSP task, subjects accurately perceived target words in HP sentences (*M*=18.2) significantly more often than LP or AN sentences (*M*=12.9 and 13.3, respectively): HP vs. LP, *t*(19) = 10.8, *p* < .001; HP vs. AN, *t*(19) = 7.1, *p* < .001.

For Color-Seq and Non-Color-Seq, a sequence was scored correct if the participant correctly reproduced the sequence in its entirety. Span scores were calculated using a weighted method, in which the total number of correct sequences at a given length was multiplied by the length, and then scores for all lengths added together. We calculated separate span scores for grammatical and ungrammatical test sequences for each subject. Performance on the two sequence learning tasks are shown in Table 1, which depicts weighted span scores for grammatical (G) and ungrammatical (U) sequences.

A 2x2 ANOVA contrasting Task (Color-Seq vs. Non-Color-Seq) and Sequence Type (grammatical vs. ungrammatical) revealed a main effect of Task [*F*(1, 76) = 4.4, *p* < .05] and a marginal main effect of Sequence Type [*F*(1, 76) = 3.6, *p* = .061] and no significant interaction. These results indicate that overall, participants span scores were better for the Color-Seq task, which is not surprising considering that the Color-Seq task has an extra cue (color) over and beyond the spatio-temporal cues available in the Non-Color-Seq task. The marginal effect of Sequence Type indicates that participants had higher span scores for the grammatical sequences and thus suggests that overall, participants showed implicit learning of the underlying grammatical regularities in the sequence patterns.

Table 1: Weighted span scores for grammatical (G) and ungrammatical (U) sequences, as well as the difference between the two (LRN)

	Sequence Type					
	G		U		LRN	
Sequence Task	*M*	*SE*	*M*	*SE*	*M*	*SE*
Color-Seq	64.9	5.13	56.4	5.77	8.55	4.62
Non-Color-Seq	55.3	5.70	43.9	4.35	11.5	3.08

For each subject, we also calculated the difference between G and U on each task, which served as a measure of sequence learning (LRN; see Table 1). To confirm that learning occurred in both tasks, we compared the LRN scores to chance levels using one-tailed t-tests. Both comparisons were statistically significant [Color-Seq: *t*(19) = 1.85, *p* < .05; Non-Color-Seq: *t*(19) = 3.72, *p* < .001], indicating that participants in both tasks on average showed implicit learning for the grammatical regularities of the sequences, demonstrated by having better memory spans for test sequences that were consistent with the grammars used during the learning phase. Finally, we compared the two LRN scores between tasks and found no differences between them, *t*(19) = .60, *p* = .56.

We next investigated the size of the learning effect for individual subjects. Although on average, subjects showed a learning effect, there was wide variation in LRN scores across these two tasks (Seq-Color: -18 to 71; Non-Color-Seq: -14 to 33). Because of the variability in the scores, it is possible to determine to what extent individual differences in implicit learning abilities for sequential patterns correlates with spoken sentence perception under degraded listening conditions.

To assess the relations between implicit sequence learning and spoken language perception, we computed correlations among the following dependent measures: HP, LP, AN, Color-Seq grammatical (C-G), Color-Seq ungrammatical (C-U), Color-Seq LRN (C-LRN), Non-Color-Seq grammatical (NC-G), Non-Color-Seq ungrammatical (NC-U), and Non-Color-Seq LRN (NC-LRN). If probabilistic sequence learning is an important underlying source of variance that contributes to spoken language perception, we would expect that the LRN scores will be strongly correlated with the spoken sentence perception scores.

The correlation analyses, shown in Table 2, revealed several interesting patterns. None of the G and U scores correlated significantly with the SSP scores. However, as expected, the LRN scores, which measure implicit learning of the underlying sequence patterns, revealed a different pattern altogether. The results showed that LRN for Color-Seq correlated significantly with HP (*r* = .48, *p* < .05) and LP (*r* = .56, *p* < .01) but not with AN (*r* = .36, *p* = .12), whereas LRN for Non-Color-Seq did not correlate significantly with any of the SSP measures (*r's* < .38).

Moreover, neither of the two LRN scores correlated significantly with one another ($r = .26, p = .28$)[1].

Additionally, we ran a principal component analysis (PCA) on all nine measures to reduce the data set to a smaller set of components. The results of the analysis revealed two components that explained 69% of the total variance. Interestingly, the second component (31.4% of total variance) includes HP, LP, and Color-Seq LRN, whereas the first component (37.6% of total variance) includes the six other DV's.

Table 2: Correlations between dependent measures for the sentence processing and implicit sequence learning tasks (see above text for abbreviations). Significant correlations at $p < .05$ are in bold; those at $p < .01$ are also underlined.

Measure	1	2	3	4	5	6	7	8	9
1.HP	--	**.83**	**.60**	.26	-.2	**.48**	.01	-.2	.33
2.LP		--	.39	.29	-.2	**.56**	.03	-.2	.28
3.AN			--	.37	.01	.36	.30	.13	.38
4.C-G				--	**.65**	.30	**.61**	.42	**.53**
5.C-U					--	**-.5**	**.52**	**.49**	.27
6.C-LRN						--	.03	-.1	.26
7.NC-G							--	**.85**	**.66**
8.NC-U								--	.15
9.NC-LRN									--

In sum, the results can be summarized as follows. First, participants on average showed implicit learning in both the Color-Seq and Non-Color-Seq task, as demonstrated by the LRN scores being statistically greater than zero. Second, only LRN for Color-Seq, but not Non-Color Seq, was significantly correlated with the high (HP) and low probability (LP) sentences in the SSP task; neither LRN socres were correlated with the anomalous (AN) sentences. Finally, a PCA analysis showed that HP, LP, and LRN for Color-Seq all loaded on a common component. These data suggest a strong link between visual implicit sequence learning and spoken language processing abilities.

Discussion

Our hypothesis was that participants' abilities on a visual, implicit sequence learning task, especially one that incorporated stimuli that could be easily encoded verbally, would be correlated with their performance on a spoken sentence perception task under degraded listening conditions. Building on previous empirical and theoretical work suggesting that spoken language processing depends upon domain-general implicit sequential learning skills, our results provide the first empirical demonstration of individual variability in implicit learning performance correlating with language processing in typically-developing subjects. The results are particularly striking given that the sequence learning and language tasks involved stimuli in two different sensory modalities (vision and audition, respectively).

A few observations are important to highlight. First, performance on the SSP task was not correlated with span scores for G or U sequences. That is, the contribution to language processing that we have demonstrated is not due merely to serial recall abilities. It was only when we assessed how much memory span *improved* for grammatically-consistent sequences did we find a significant correlation. Thus, it is the ability to extract knowledge about structured sequential patterns over a set of sequences that is important, not just the ability to encode and recall a sequence of items from memory.

A second point to make is that the Color-Seq task correlated much more strongly with the high (HP) and low (LP) predictable sentences compared to the anomalous (AN) sentences. To do the HP (and to a lesser extent, LP) sentence perception tasks successfully, the listener needs to use the context of the preceding material in the sentences to help predict and identify the final target word. This sequential context is not available for the AN sentences because they were semantically anomalous. In turn, successful performance on the Color-Seq task also requires sensitivity to sequential, probabilistic context. That is, the greater one's sensitivity to sequential structure in the grammatical sequences, the better chance one has of correctly recalling a novel grammatical sequence that contains the same kind of probabilistic structure. Thus, we believe we have identified a key link between implicit sequence learning and spoken language perception: *both require the ability to acquire and use probabilistic information distributed across temporal patterns*.

Third, we note that only the Color-Seq task, not the Non-Color-Seq task, was correlated with SSP. From a procedural standpoint, the only difference between Color-Seq and Non-Color-Seq was that the Color-Seq task included not only spatiotemporal information, but also the presence of color cues. One account of these differences is that the sequences from the Color-Seq task are very readily verbalizable and codable into phonological form (e.g., "Red-Blue-Yellow-Red") whereas those from the Non-Color-Seq task are not. Thus, Color-Seq but not Non-Color-Seq might involve implicit learning of phonological representations, and it could be this basic learning ability that contributes to success on the SSP task.

To examine this prediction further, we used the post-experiment debriefing questionnaire to identify 12 participants ("phonological coders") who attempted to encode sequences in the Non-Color-Seq task using some kind of verbal code, such as labeling each of the four spatial positions with a digit (1-4). The remaining 8 subjects ("non-phonological-coders") indicated they did not use a verbal code during the task. We assessed correlations between these two groups' LRN scores and SSP measures and found that although none of the correlations quite reached statistical significance (presumably due to a lack of

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[1] With a sample size of n=20, there is only enough power to identify "large" correlation/effect sizes (Cohen, 1988); thus, a non-significant correlation in this data may not signify no correlation at all, but it does suggest that if a correlation exists, it is substantially weaker than the significant effects reported here.

statistical power), the difference in the correlations between the two groups was quite striking: phonological coders' performance on the sequence task correlated with HP (r = .43), LP (r = .28), and AN (r = .44) whereas the correlations for non-coders were r = -.31 for HP, r = -.17 for LP, and r = .14 for AN.

Thus, for those participants who explicitly used a phonological-coding strategy on the Non-Color-Seq task, their performance was positively correlated with SSP task performance, whereas for participants who did not use such a strategy, their performance was much less or even negatively correlated with SSP task performance. Although statistically non-significant at this time, this pattern of results for the Non-Color-Seq task may suggest that a crucial aspect of implicit sequence learning that contributes to spoken language processing is the learning of structured patterns from sequences that can be easily represented using a verbal code.

To summarize, we believe the evidence points to an important factor underlying spoken language processing: the ability to implicitly learn complex sequential patterns, and perhaps especially those that can be represented phonologically. Using a visual implicit sequence learning task, we found that sequence learning performance correlated with performance on a spoken sentence perception task requiring one to capitalize on sequential context. These results suggest a strong link between implicit sequence learning and spoken language processing and not only provide important new theoretical insights, but also have practical implications regarding the nature of language processing in both typical and clinical populations.

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References

Baddeley, A.D. (2003). Working memory and language: An overview. *Journal of Communication Disorders, 36*, 189-208.

Cleeremans, A., Destrebecqz, A., & Boyer, M. (1998). Implicit learning: News from the front. *Trends in Cognitive Sciences, 2*, 406-416.

Clopper, C.G. & Pisoni, D.B. (2006). The Nationwide Speech Project: A new corpus of American English dialects. *Speech Communication, 48*, 633-644.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences*. Hillsdale, NJ: Erlbaum.

Conway, C.M. & Christiansen, M.H. (2006). Statistical learning within and between modalities: Pitting abstract against stimulus-specific representations. *Psychological Science*, *17*, 905-912.

Conway, C.M., & Christiansen, M.H. (2001). Sequential learning in non-human primates. *Trends in Cognitive Sciences*, 5, 529-546.

Dominey, P.F., Hoen, M., Blanc, J.-M., & Lelekov-Boissard, T. (2003). Neurological basis of language and sequential cognition: Evidence from simulation, aphasia, and ERP studies. *Brain and Language, 86*, 207-225.

Gómez, R.L. & Gerken, L.A. (2000). Infant artificial language learning and language acquisition. *Trends in Cognitive Sciences, 4*, 178-186.

Goschke, T., Friederici, A. D., Kotz, S. A., & van Kampen, A. (2001). Procedural learning in broca's aphasia: Dissociation between the implicit acquisition of spatio-motor and phoneme sequences. *Journal of Cognitive Neuroscience, 13*(3), 370-388.

Grunow, H., Spaulding, T.J., Gómez, R.L., & Plante, E. (2006). The effects of variation on learning word order rules by adults with and without language-based learning disabilities. *Journal of Communication Disorders, 39*, 158-170.

Howard, J.H., Jr., Howard, D.V., Japikse, K.C., & Eden, G.F. (2006). Dyslexics are impaired on implicit higher-order sequence learning, but not on implicit spatial context learning. *Neuropsychologia, 44*, 1131-1144.

Kalikow, D.N., Stevens, K.N., & Elliott, L.L. (1977). Development of a test of speech intelligibility in noise using sentence materials with controlled word predictability. *Journal of the Acoustical Society of America*, *61*, 1337-1351.

Karpicke, J. D., & Pisoni, D. B. (2004). Using immediate memory span to measure implicit learning. *Memory & Cognition, 32(6)*, 956-964.

Kelly, S.W., Griffiths, S., & Frith, U. (2002). Evidence for implicit sequence learning in dyslexia. *Dyslexia, 8*, 43-52.

Knowlton, B.J. & Squire, L.R. (1996). Artificial grammar learning depends on implicit acquisition of both abstract and exemplar-specific information. *Journal of Experimental Psychology: Learning, Memory, & Cognition, 22*, 169-181.

Lashley, K.S. (1951). The problem of serial order in behavior. In L.A. Jeffress (Ed.), *Cerebral mechanisms in behavior* (pp. 112-146). New York: Wiley.

Menghini, D., Hagberg, G.E., Caltagirone, C., Petrosini, L., & Vicari, S. (2006). Implicit learning deficits in dyslexic adults: An fMRI study. *Neuroimage, 33,* 1218-1226.

Pisoni, D.B. & Cleary, M. (2004). Learning, memory, and cognitive processes in deaf children following cochlear implantation. In F.G. Zeng, A.N. Popper & R.R. Fay (Eds.), *Springer handbook of auditory research: Auditory prosthesis*, SHAR Volume X (pp. 377-426).

Reber, A.S. (1967). Implicit learning of artificial grammars. *Journal of Verbal Learning and Behavior, 6*, 855-863.

Rubenstein, H. (1973). Language and probability. In G.A. Miller (Ed.), *Communication, language, and meaning: Psychological perspectives* (pp. 185-195). New York: Basic Books, Inc.

Rüsseler, J., Gerth, I., & Münte, T.F. (2006). Implicit learning is instact in developmental dyslexic readers: Evidence from the serial reaction time task and artificial grammar learning. *Journal of Clinical and Experimental Neuropsychology, 28*, 808-827.

Saffran, J.R., Aslin, R.N., & Newport, E.L. (1996). Statistical learning by 8-month-old infants. *Science, 274*, 1926-1928.

Stadler, M.A. & Frensch, P.A. (Eds.) (1998). *The handbook of implicit learning*. London: Sage Publications.

Ullman, M. T. (2004). Contributions of memory circuits to language: The declarative/procedural model. *Cognition, 92*, 231-270.

Vicari, , S., Marotta, , L., Menghini, D., Molinari, M., & Petrosini, L. (2003). Implicit learning deficit in children with developmental dyslexia. *Neuropsychologia, 41*, 108-114.

Waber, D. P., Marcus, D. J., Forbes, P. W., Bellinger, D. C., Weiler, M. D., Sorensen, L. G., et al. (2003). Motor sequence learning and reading ability: Is poor reading associated with sequencing deficits? *Journal of Experimental Child Psychology, 84*, 338-354.