The Roles of Nonlinguistic Statistical Learning and Memory in Language Skill

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Background & Objectives: Statistical learning of transitional probabilities is a basic mechanism that may influence language performance. This study investigated whether nonlinguistic statistical learning can predict language performance as well as the role of memory as a potential mediating link between statistical learning and language performance. ***Methods:*** Participants included 20 typically achieving, school-aged children and 20 adults who completed auditory and visual statistical learning tasks and related memory tasks. Participants also completed tasks that assessed acquired language knowledge (grammatical judgment and a standardized language test) and language processing efficiency (rapid naming and non-word repetition). ***Results:*** Nonlinguistic statistical learning ability significantly contributed to language performance, illustrating the general learning mechanism underlying both linguistic and nonlinguistic domains. Statistical learning contributed no significant variance after memory to performance in the language processing tasks. Conversely, statistical learning but not memory performance was a significant predictor of performance in the language knowledge tasks. The results illustrate the important roles of both memory and statistical learning in language performance. ***Discussion & Conclusion:*** The results indicate that statistical learning appears to be more directly associated with language tasks that emphasize complex semantic and grammatical knowledge learned over time rather than language tasks that emphasize access and retrieval of less complex linguistic information. Additionally, statistical learning operates similarly across modalities, and memory is an important component of real time learning. (***Korean Journal of Communication Disorders*** 2010;15;381-396)

Key Words: nonlinguistic statistical learning, language knowledge, language processing, nonlinguistic memory

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Ⅰ. Introduction

As opposed to a theoretical view in which language is considered autonomous, general interactive information-processing approaches support the idea that basic cognitive mechanisms need to be integrated in order to efficiently learn and use language (Elman et al., 1996). One basic mechanism that has been proposed to underlie both language and nonlinguistic performance is statistical learning, the ability to incidentally learn distributional regularities of complex input (Fiser & Aslin, 2002; Saffran, Aslin & Newport, 1996). Statistical learning typically takes place incidentally or without explicit instruction. Thus, research in this area has overlapped with work on implicit learning (Thomas et al., 2004), procedural learning (Ullman & Pierpont, 2005), and artificial grammar learning (Gomez & Gerken, 2000).

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Of key interest in statistical learning has been how distributional regularities in the input facilitate language acquisition. In particular, the transitional probability with which one spoken element co-occurs sequentially with an adjacent element may be a critical mechanism by which infants are able to chunk the speech stream into meaningful units. Co-occurring syllables with high transitional probability presumably help to identify within-word information and co-occurring syllables with low transitional probability mark between-word boundaries (Saffran, Aslin & Newport 1996).

If statistical learning of transitional probabilities is a fundamental learning mechanism that is responsible for learning both linguistic and nonlinguistic information (Fiser & Aslin, 2002), then individuals' language performance would be expected to correlate with statistical learning of linguistic stimuli (Evans, Saffran & Robe-Torres, 2009). It also would be expected that a close link would be found between nonlinguistic statistical learning and language performance. However, there has been no study which directly examines the link between different aspects of language performance and statistical learning of nonlinguistic inputs. The first purpose of this study is to examine the close relation between nonlinguistic statistical learning and children's and adults' language ability.

Statistical learning of transitional probabilities of adjacent segments is not the only mechanism at play in learning. Learning in real time builds on other more basic mechanisms, including memory. Speech and other auditory stimuli used in statistical learning paradigms are inherently temporal in that one sound/visual shape that is presented fades away before the following sound/shape. Thus, to associate stimuli to discover distributional regularities, the first stimulus must be held temporarily in short-term memory or activated and made available for other cognitive processing in some way. As Ludden & Gupta (2000) suggested, statistical learning is better when there is greater memory capacity and/or attentional resources available. However, few studies have examined the relation between memory and nonlinguistic statistical learning. The second purpose of this study is to examine the role of memory as a potential mediating link between statistical learning and language performance.

The following sections provide an overview of key research on linguistic and nonlinguistic (auditory and visual) statistical learning, followed by a discussion of the influence of memory, and language task demands.

1. Linguistic Statistical Learning

The typical experimental paradigm that has been used to examine statistical learning of transitional probabilities in the language domain involves exposing learners during a training session to strings of letters or speech sounds in which different syllable transitional probabilities are embedded. In a test session, the participants decide which of two stimulus strings is more familiar based on the training exposure (Aslin, Saffran & Newport, 1998; Saffran et al., 1996; 1997). In a classic study, Saffran et al. (1996) created 2 minutes of a continuous nonsense speech stream, *bidakupadotigolabubidaku* in which three-syllable words were embedded (e.g., *bidaku*). After a group of 8-month-olds listened to the brief speech stream, a head turn preference procedure was used to assess whether the infants could differentiate these words from nonsense strings comprised of the same syllables presented during the exposure session but in a different consecutive order (e.g., *tilado*). The infants listened significantly longer to the nonsense strings than to the familiar words, thus showing sensitivity to the patterned stimuli. In a similar paradigm in which frequency of occurrence was controlled, Aslin, Saffran & Newport (1998) demonstrated that the 8-month-olds' learning was related to distributional analysis of the transitional probability of syllables in the stimuli rather than the frequency of syllable co-occurrence.

More recent work on linguistic statistical learning has examined the link between learning spoken transitional probabilities and learning object labels by both infants and adults (Graf Estes et al., 2007; Mirman et al., 2008; Yu & Smith, 2007). The link with children's receptive and expressive vocabulary skills also recently have been examined (Evans, Saffran & Robe-Torres, 2009).

Evans, Saffran & Robe-Torres (2009) used speech sounds to examine whether children with and without Specific Language Impairment (SLI) can track statistical probabilities among complex input and how this ability is related to their vocabulary knowledge. The children heard a 21-minute nonsense speech stream, similar to the ones in Saffran, Aslin & Newport (1996), and were asked to pay attention and answer questions later. After this training session, children were tested for their knowledge of word boundaries (e.g., children had to decide between words vs. nonwords based on what they have been exposed to). Results showed that the typically developing group performed above chance (58%) while the group with SLI was at chance level (52%). Additionally, there was a significant correlation between children's receptive and expressive vocabularies and their statistical learning accuracy. There was no significant relationship for the group with SLI.

2. Nonlinguistic statistical learning

In the nonlinguistic domain, there have been several studies which have addressed transitional probabilities, using auditory stimuli such as tones and visual stimuli such as shapes. For example, in the auditory domain, Saffran et al. (1999) examined adult statistical learning with non-speech sounds, using continuous tone streams instead of the speech streams used by Saffran, Aslin & Newport (1996) and Saffran et al. (1997). An experimental paradigm similar to the previous studies was used. There were two different types of tone sequences. The same tones were used to create these two different tone sequences but the order of the tones was different in each sequence. Half of the adult participants were exposed to one type of tone sequence and the other half were exposed to the other tone sequence. The adults performed significantly above chance in identifying the tone sequences. Saffran et al. (1999) suggested that the pattern learning ability used for linguistic information can also be used to detect patterns in nonlinguistic information.

In addition to their examination of linguistic statistical learning, Evans, Saffran & Robe-Torres (2009) investigated the children's nonlinguistic statistical learning using a parallel paradigm with a 42-minute tone sequences. As for the linguistic stimuli; the group of typically developing children, but not the group with SLI, were able to track statistical probabilities at a level above chance. The authors concluded that children with SLI have deficits in domain-general implicit learning because they showed poor performance with both speech and tone inputs. However, the relation between nonlinguistic statistical learning and the children's vocabulary was not examined.

Nonlinguistic statistical learning has been examined not only in the auditory domain but also in the visual domain. For example, Kirkham, Slemmer & Johnson (2002) studied infants' visual statistical learning at 2, 5, and 8 months of age. The training stimuli were colored shapes presented in a continuous stream as long as the infant paid attention. There were three shape pairs with each pair composed of two different shapes. The probability of co-occurrence for two shapes was greater within pairs than between pairs; thus infants could implicitly learn the sequential pattern in the shape stream based on these probabilities. The testing showed that the infants at all ages looked longer at novel shape sequences than at the familiar sequences indicating that they had automatically learned the visual pattern.

Fiser & Aslin (2002) examined adults' ability to learn a pattern among temporal sequences of visual shapes. There were 12 basic shapes grouped into four triplets and presented one at a time in a continuous 6-minute sequence on a computer screen. After this exposure to the shape sequence, the adults indicated which sequences were more familiar, with the sequences composed of one of the four possible triplets and one of four impossible triplets (which had never occurred in training). The participants chose the possible triplets in a mean of 95% of test trials, significantly better than chance performance. The overall finding that nonlinguistic transitional probabilities provide a way to access the structure of complex stimuli mimics findings in the linguistic domain and suggest that there may be a single underlying mechanism that enables individuals to learn linguistic and nonlinguistic information. To our knowledge this study is the first study to investigate the close relationship between auditory and visual statistical learning and language skills. Thus, we have included adults to validate our experiments to see whether adults can perform statistical learning with the new experimental stimuli created from our study.

3. Statistical Learning, Memory, and Language

Language is a highly complex, multi-level behavior; and other cognitive processes beyond statistical learning are at play in language ability. As mentioned previously, memory is considered a critical cognitive mechanism for tracking statistical probabilities among complex inputs especially when information is presented temporally. Whether addressing nonlinguistic or linguistic statistical learning, the possible role of memory has been raised; however, there has been little direct investigation of the link between these two constructs. Adults' speed in implicit learning and problem solving have been found to be affected by memory load (Reber & Kotovsky, 1997), although this relation may hold only at memory capacity limits (Frensch & Miner, 1994).

More recently, Ludden & Gupta (2000) suggested that reduced working memory and attention resources may affect statistical word learning performance negatively. In this study, adults participated in a conventional statistical learning paradigm which was implemented in two different conditions, load and no load conditions. In the no-load condition, participants were exposed to artificial language stimuli and asked to pay attention during the exposure session (i.e., similar to Saffran, Aslin & Newport, 1996). In the load condition, participants were asked to color a picture while listening to the stimuli (similar to Saffran et al., 1997). The results showed that performance in the no load condition was significantly better than in the load condition. Ludden & Gupta (2000) concluded that the learning outcome was better in the no load condition, because greater working memory resources were available. Similarly, Evans, Saffran & Robe-Torres (2009) suggested that attention and/or working memory played a role in the poorer statistical learning performance by children with SLI compared to their typically developing peers.

In the current study, we examine short term memory using nonlinguistic stimuli as a basic cognitive process that contributes to overall statistical learning, and which may help explain some of the relation between statistical learning and language performance.

A final issue to be raised in examining whether there is a link between nonlinguistic statistical learning and language is to determine the facets of language performance in which statistical learning of transitional probabilities may be most evident. Rather than assume a finer distinction between different aspects of acquired language knowledge (e.g., vocabulary and grammar), we have taken an information processing approach in which language performance may be considered broadly to be more dependent or less dependent on accumulated linguistic knowledge and experience. Thus, in this study we selected two linguistic tasks, Rapid Naming and Nonword Repetition tasks, designed to reduce the role of prior language experience and accumulated knowledge (Campbell et al., 1997) and emphasize efficiency. Two other linguistic tasks were chosen; *Grammaticality Judgment and Clinical Evaluation of Language Fundamentals* (CELF; Semel, Wiig & Secord, 1995) that are more dependent on previous world knowledge. These four language tasks will allow us to look at a broader aspect of language performance and also enable us to examine the link between statistical learning ability and language performance above and beyond memory.

4. Summary

First, the current study examined whether nonlinguistic statistical learning is associated with language performance. If statistical learning of transitional probabilities is a key mechanism that operates across linguistic and nonlinguistic information, then individuals' various language skills should be in some way associated with their nonlinguistic statistical learning. Second, this study investigated whether statistical learning interacts with memory when predicting language performance. It is expected that basic cognitive processes such as memory interact with statistical learning. In particular, given that memory is an important factor when learning occurs in real time, it is anticipated that memory will be correlated with statistical learning, and that memory may mediate associations between statistical learning and language performance.

Ⅱ. Methods

1. Pilot Testing

To ensure robust experimental methods, pilot testing was carried out with 8 children and 8 adults who did not participate in the larger study. The pilot testing was used to identify target participant ages and task design, including stimulus numbers and presentation rates. Pilot findings are mentioned as relevant throughout the Method.

2. Participants

Twenty children with no medical concerns who were aged 8;1 to 13;11 completed the experimental tasks (*M* = 10;4, *SD* = 1;7). Seventeen children were Caucasian and three were Asian American. Twenty adults aged 19;0 to 28;2 also participated (*M* = 23;1, *SD* = 2;11). Eighteen adults were Caucasian and two were Asian American. All five Asian Americans had lived in the United Stated since the age of 1year. All participants spoke English as a native language, passed hearing screening (pure tones presented at 25dB at 1, 2, and 4KHz) and vision screening (letters and numbers with acuity of 20/25 or better), and showed a nonverbal intelligence test score within the normal range on the Leiter International Performance Scale-Revised (Roid & Miller, 2002). Children had a mean Leiter standard score of 111 (*SD* = 14). The adults had a mean Leiter score of 103 (*SD* = 14).

3. Experimental Tasks

In order to examine different aspects of statistical learning ability, four experimental tasks were developed. In each of Auditory statistical learning and Visual statistical learning there was a training session and a test session. In the training session, participants were exposed to sequences of patterned stimuli for several minutes. This was followed by a test session in which participants were tested on whether they had learned the pattern. These tasks required implicit learning of shape/tone patterns, and thus were dependent on maintaining previously-presented shape images/tones in short-term memory. The other two tasks, Auditory memory and Visual memory had the same memory demands as Auditory and Visual statistical learning but did not entail a temporal component that required learning in real time.

The stimuli and procedures for each of the four experimental tasks are described below. Stimulus preparation is described in the Appendix.

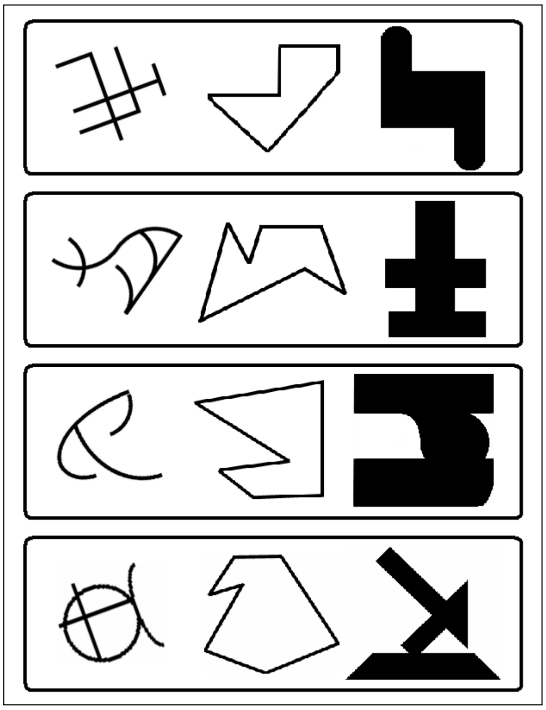
Visual and Auditory statistical learning and Visual memory were presented on a laptop computer with MATLAB using the Psychophysical Toolbox (Brainard, 1997; Pelli, 1997). E-Prime (Psychology Software Tools, 2000) was used for Auditory memory. All tasks were administered in a counterbalanced order on the same day, but with the language and nonverbal IQ tasks separating the four learning and memory tasks.

3.1 Visual Statistical Learning

The training procedure followed Fiser & Aslin (2002) in which participants looked at a series of visual stimuli. For adults, a continuous 6-minute 'movie' of sequenced non-namable shapes was presented on the laptop computer. Pilot testing showed that a 6-minute movie was too long to sustain children's attention, and a 4.5 min movie was used for children. A black vertical bar was positioned in the middle of the computer monitor.

There was a predictable sequence of shape presentation, using four sets of triplets for adults and three of these triplet sets for children <Figure - 1>. For example, for the A-B-C triplet, whenever shape A appeared on the screen, shape B immediately followed, followed immediately by shape C. After C, the first shape from one of the three other triplets (chosen at random) appeared next followed by other members of that base pair. The same base triplet never appeared twice consecutively, and the same sequence of two base triplets also never appeared twice consecutively.

For the shorter task version for children, there were 72 base triplets, each triplet appearing 24 times. Here, the within-triplet transitional probability was 1.0; the between-triplet probability was 0.50. The shape presentation rate for adults was 1.0 sec following Fiser & Aslin (2002). Pilot testing was used to find an optimal presentation rate for children so that confounding factors, such as memory load, would not influence performance (Fazio, 1998). A 1.3 sec presentation rate was used in the experimental task.



<Figure - 1> Visual statistical learning base triplets

3.1.2 Experimental Session

After the training session, participants were shown two shape triplet sets consecutively (presented in random order), and asked to press a response button to indicate the triplet set that looked familiar based on what they had seen during training. Twenty-four test pairs were used, presented in the same format as in the training session. In each, one of the pairs was a base triplet and one was an impossible triplet (i.e., a triplet that had never occurred in the training movie). The dependent variable was percentage accuracy in identifying the 24 base triplets.

3.2 Auditory Statistical Learning

3.2.1 Training Session

This training was adapted from Saffran et al. (1997) in which there were 3.4 min of continuously streaming sounds in a semi-random order for adults, following the same pattern rule as in Visual statistical learning. Pilot testing indicated that a shorter task version was needed for children to be able to sustain attention, and a 2.4 min sound stream was used. Auditory stimuli were presented to participants under headphones. Participants were asked to listen to sounds while coloring a picture to maintain the attention while performing the task as in the study of Saffran et al. (1997). The presentation rate of each sound for both children and adults was 250 ms, with pilot testing indicating this was appropriate for both age groups.

3.2.2 Experimental Session

After the training session, participants listened to pairs of triplet sounds and were asked to press a response button to indicate the triplet sounds that sounded familiar based on what they had heard in training. Twenty-four test pairs were used, each with one possible and one impossible triplet. The dependent variable was percentage accuracy in identifying the 24 base triplets.

3.3 Visual Memory

In this task, participants were asked to remember sequences of shapes. There were four randomly presented conditions with a total of 53 items. The first condition required participants to recall 2-shape sequences (8 items). The second condition was composed of 15 items in which 3-shape sequences had to be recalled. Four-shape sequences were recalled in the third condition and 5-shape sequences in the fourth condition (15 items in each condition). Each shape appeared on the screen one at a time for 1.0 sec for adults and 1.3 sec for children, the same presentation rates as in Visual statistical learning. Following this shape presentation two shape sequence options were displayed simultaneously; one option was presented randomly in the top half of the computer screen and the other in the lower half of the screen. Participants decided which option displayed the correct sequence of shapes. For each condition, participants were told the number of items to be recalled. There was one practice item for each task condition before the experimental task began. During the practice session, feedback was given about response accuracy and correct finger placement on the response buttons. There was no time limit in responding to these test items.

3.4 Auditory Memory

Parallel to the Visual memory task, there were 2-, 3-, 4-, and 5-tone sequences to be recalled in Auditory memory. Participants listened to a sequence of 250 ms long tones; then a second tone sequence was presented after 500ms. Participants decided whether this sequence was the same/different as the first sequence by pressing response buttons. For each condition, participants were told how the number of items to be recalled. The dependent variable was percent accuracy. There were 15 items in each condition, with a total of 32 ‘same’ and 28 ‘different’ items. As in Visual memory, there was one practice item for each of the four task conditions prior to the experimental task.

3.5 Language Tasks

There were four language tasks, two which emphasized proficiency in recalling/using linguistic stimuli and two which assessed acquired language knowledge. The two proficiency measures included the Rapid Naming task from the Comprehensive Test of Phonological Processing (Wagner, Torgesen & Rashotte, 1999) and Dollaghan & Campbell’s (1998) Nonword Repetition task, Rapid Naming relies on the accurate retrieval of phonological representations under speeded constraints (Manis, Seidenberg & Doi, 1999). In this task, participants named digits, colors, and objects as quickly and as accurately as they could. There were three visual stimulus presentations: 72 one-syllable digits, 72 colors, and 72 common objects. A standard score based on response time (measured online with a stop watch) was calculated for each of the three stimulus categories. A Cronbach’s alpha reliability coefficient of .74 was obtained, with this coefficient considered acceptable to indicate a single underlying construct. Thus, the average of all three standard scores was used as the dependent variable for this language task.

Nonword Repetition conventionally is used as a measure of phonological working memory, although arguably also assesses other aspects of phonological encoding and processing (Graf Estes, Evans & Else-Quest, 2007). Participants listened under headphones to 16 nonsense words varying in length from 1 to 4 syllables, and repeated each word. The 16 nonsense words provided a total of 96 target phonemes to be imitated, with the dependent variable of percentage phoneme accuracy.

To assess acquired language knowledge, we used a standardized test, the CELF. The CELF assesses spoken semantic and syntactic knowledge, with the total standard score reflecting both receptive and expressive language skills. Some CELF subtests use auditory stimuli (e.g., imitating spoken sentences). Other subtests require visual processing (e.g., looking at written words and arranging them in grammatical sentences). Other subtests involve both modalities (e.g., listening and then pointing to pictures).

We also administered a Grammaticality Judgment task, which assessed grammatical understanding in real time. In this task, children judged sentences as grammatically correct/incorrect when the sentences were presented at a speech signal compressed to 75% of the normal rate. There were 43 target sentences: 19 grammatical sentences and 24 ungrammatical sentences. Errors in the ungrammatical sentences were verb inflection, noun inflection, and article omission or substitution errors (e.g., *Her brother helping her* and *The woman cheering*). Sentences were presented under headphones using E-Prime on a laptop computer. The dependent variable was percentage accuracy in identifying grammatical sentences.

4. Analyses

Participants' performance on Auditory statistical learning and Visual statistical learning was examined using single-sample two-tailed *t* tests to determine differences from chance performance. A correlation analysis was used to determine whether statistical learning was associated across auditory and visual modalities and to identify the link with short-term memory. A stepwise regression was used to find out how much of the variance was explained for language performance by statistical learning and memory above and beyond age and nonverbal IQ. For each of the four language measures, either the Visual or Auditory statistical learning tasks were used as predictors of performance. To reduce the total number of correlations, predictions were made within the modality of task presentation. That is, Visual memory and Visual statistical learning were used to predict Rapid Naming performance because this language task uses stimuli that are presented visually. Auditory memory and Auditory statistical learning were used to predict Grammaticality Judgment and Nonword Repetition, with both of these language tasks using auditory stimuli. For the CELF, both Visual memory/Visual statistical learning and Auditory memory/Auditory statistical learning were used to predict language performance given that both auditory and visual stimuli are presented in the CELF. Finally, memory was entered before statistical learning in each of the step-wise regressions, with memory considered the more basic process. Age and IQ were entered first in the analyses as control variables. Both children and adults showed the same patterns in the regression analysis, and the groups were combined to increase statistical power.

Ⅲ. Results

1. Group Performance

The children's and adults' performance on the four experimental tasks is summarized in Table 1. When performance was significantly better than chance (above 50%), it was considered that participants had learned the pattern. Children's mean accuracy was significantly better than chance for Auditory statistical learning, $t(19) = 7.57$, $p < .001$, and Visual statistical learning, $t(19) = 8.69$, $p < .001$.Adults also performed significantly better than chance on Auditory statistical learning, $t(19) = 8.36$, $p < .001$, and Visual statistical learning, $t(19) = 40.0$, $p < .001$. As shown in Table1, both groups showed that they were able to learn the patterns with high accuracy but below ceiling levels. For the memory tasks, children's mean accuracy was significantly better than chance for Auditory memory, $t(19) = 38.37$, $p < .001$, and Visual memory, $t(19) = 25.24$, $p < .001$. Adults performed similarly, with accuracy significantly better than chance in both tasks (Auditory memory: $t(19) = 48.9$, $p < .001$, Visual memory: $t(19) = 51.21$, $p < .001$). The Memory and Learning tasks had different demands, and it was not a central goal to compare group accuracy across these tasks. However, it is worth noting that both children and adults showed equivalently lower Auditory statistical learning accuracy than Auditory memory accuracy. Although adults had higher accuracy than children for Visual statistical learning and Visual memory, within each group there was the same level of accuracy on these two visual tasks <Table - 1>.

<Table 1> Mean Percent Accuracy on Visual memory, Visual statistical learning, Auditory memory, and Auditory statistical learning in Children and Adults

	Visual		Auditory	
	Memory	Learning	Memory	Learning
Children (N = 20)	86.1(6.1)	86.0(14.7)	90 (5.0)	76.1(12.2)
Adults (N = 20)	94.8(3.9)	97.3(5.3)	94.8(4.0)	75.2(13.5)

Note. Standard deviations are given in parentheses.

The auditory and visual versions of the learning and memory tasks were not directly analogous. Moreover, only one child and two adults reported that they thought the tasks assessed pattern learning (these participants had average task accuracy). However, to address the concern of potential practice effects across modalities, accuracy was calculated separately for Visual statistical learning and Auditory statistical learning, depending on the order of presentation. Participants who took part in Visual statistical learning first had equivalent accuracy in Visual statistical learning to those who first took part in Auditory statistical learning (adult *M*: 97.1% vs. 97.5%; child *M*: 85.9% vs. 86.1%). There also was no order disadvantage for Auditory statistical learning in taking part in this task without having first completed Visual statistical learning (adult *M*: 79.6% vs. 70.8%; child *M*: 76.6% vs. 75.5%).

2. Correlations among Experimental Tasks

As noted earlier, the children and adults showed similar patterns of performance across tasks and the two groups were combined in the results presented here. <Table - 2> shows the partial Pearson correlation matrix (adjusting for the contributions of chronological age and non-verbal IQ) for the four experimental tasks. Indicating that statistical learning was related across modalities, there was a moderate partial correlation between Visual statistical learning and Auditory statistical learning ($N = 40$, $r = .53$, $p < .05$ after controlling for age and non verbal IQ).There also was a systematic relation between the Memory and Learning tasks in each modality. Visual memory and Visual statistical learning were significantly correlated ($r = .52$) as were Auditory memory and Auditory statistical learning ($r = .37$). However, Visual memory and Auditory memory were not significantly correlated (for either the combined group or for children or adults separately).

<Table-2> Task Partial Correlation Matrix Covarying for Age and Nonverbal IQ

	Visual Memory	Auditory Memory	Visual Learning	Auditory statistical learning
Visual memory	1.00			
Auditory memory	.14	1.00		
Visual statistical learning	.52*	.19	1.00	
Auditory statistical learning	.42*	.37*	.53*	1.00

* N = 40, $p < .05$ (two-tailed, with Bonferroni correction).

3. Predicting Language Performance

Partial correlations (adjusted for age and nonverbal IQ) also were performed between Visual statistical learning and the two language tasks relying either solely or in part on visual information, Rapid Naming and the CELF. Visual statistical learning was significantly correlated with Rapid Naming ($r = .39$, $p < .05$) but not the CELF ($r = -.26$, $p = .113$). There were significant correlations between Auditory statistical learning and all three language tasks relying on auditory information (Nonword Repetition: $r = .37$, $p < .05$; Grammaticality Judgment: $r = .51$, $p < .05$; CELF: $r = .37$, $p < .05$).

Separate stepwise regressions were used to determine how much of the variance in language performance could be explained by Visual or Auditory statistical learning beyond the contribution of memory in addition to age and nonverbal IQ. Visual memory and Visual statistical learning were entered as predictor variables for Rapid Naming and the CELF. Auditory memory and Auditory statistical learning were used as predictor variables for Nonword Repetition, Grammaticality Judgment, and the CELF.

Rapid Naming. Table 3 shows the proportion of variance contributed by predictors in each regression. The full regression model accounted for 44.1% of the variance in Rapid Naming. Age and IQ accounted for 30.2% of the variance, with age contributing most of this variance. Visual memory accounted for an additional 11.5% of the variance. However, Visual statistical learning did not contribute any significant variance beyond that contributed by the other predictors.

Nonword Repetition. A separate regression model accounted for 40.5% of the variance in Nonword Repetition. Age and IQ accounted for 26.4% of the variance, with IQ contributing most of this variance. Auditory memory added an additional 10% of the variance but Auditory statistical learning added no significant variance. As for Rapid Naming, it was the memory task that significantly contributed to the model with statistical learning accuracy contributing no additional significant variance.

Grammaticality Judgment. A total of 28.6% of the variance was accounted for in this regression.

<Table-3> Results of Stepwise Regression Predicting Language Scores

Step	R^2	Cumulative R^2	p level
Rapid Naming			
Age and IQ	.302	.302	.001
Visual memory	.115	.417	.011
Visual statistical learning	.024	.441	.229
Nonword Repetition			
Age and IQ	.264	.264	.001
Auditory memory	.102	.366	.012
Auditory statistical learning	.039	.405	.078
Grammaticality Judgment			
Age and IQ	.080	.080	.081
Auditory memory	.028	.108	.149
Auditory statistical learning	.178	.286	.003
CELF (with visual predictors)			
Age and IQ	.153	.153	.046
Visual memory	.015	.168	.421
Visual statistical learning	.146	.314	.028
CELF (with auditory predictors)			
Age and IQ	.153	.153	.046
Auditory memory	.025	.182	.268
Auditory statistical learning	.095	.277	.039

Note. N = 40 in each regression; p level refers to the significance levels for the point at which the predictor variable was entered into the regression.

The only significant predictor, accounting for 17.8% of the variance, was Auditory statistical learning. Thus, it was not memory but statistical learning ability that contributed to Grammaticality Judgment.

CELF. Results of the two stepwise regressions for the CELF are shown in <Table - 3>, one regression including Auditory memory and Auditory statistical learning and a separate regression including Visual memory and Visual statistical learning. Age and IQ contributed 15.3% of the total variance in each regression. Neither Auditory memory nor Visual memory contributed significantly to the regressions. However, Auditory statistical learning did contribute significantly to the regression model (9.5%) as did Visual statistical learning (14.6%).

4. Summary

Both adults and children performed above chance in each of the four experimental tasks. Performance on the Learning and Memory tasks were correlated within each modality. However, Auditory and Visual memory performance was not correlated significantly. Learning task performance significantly predicted performance on the language tasks assessing accumulated language knowledge. Conversely, Memory task performance predicted language tasks emphasizing processing efficiency.

Ⅳ. Discussion and Conclusion

The present study examined the performance of children and adults on tasks that required statistical learning of transitional probabilities in the visual and auditory modalities. Two primary questions were investigated. The first question was how different aspects of language performance were associated with nonlinguistic statistical learning. The second question was whether memory was associated with statistical learning performance. Our findings suggest that nonlinguistic statistical learning significantly predicts language performance and that memory is closely related when learning occurs in real time. Memory performance was more closely associated with language tasks which emphasized processing efficiency or recall (i.e., nonword repetition and rapid naming). Statistical learning performance was the better predictor for performance on tasks assessing more complex language knowledge learned over time (i.e., grammaticality judgment and CELF scores).

It previously has been found that statistical probabilities among speech sounds and non-speech sounds can be learned in the auditory modality (Saffran, Aslin & Newport, 1996; Saffran et al., 1997; Saffran et al., 1999; Evans, Saffran & Robe-Torres, 2009). It also has been found that patterns can be learned among shapes in the visual modality (Fiser & Aslin, 2001; 2002; Kirkham, Slemmer & Johnson, 2002). Although these studies did not investigate the same individuals' performance on both auditory and visual tasks, the findings suggest that the same statistical learning mechanism may exist across auditory and visual modalities. The moderately high partial correlation between Auditory and Visual statistical learning found in this study is in line with the idea that there is a single or general mechanism underlying the two modalities which enables us to learn complex information effectively. This is consistent with the recent work (Evans, Saffran & Robe-Torres, 2009) suggesting that statistical learning ability is a domain-general ability. In order to address this question more directly, a test of generalization of learning across modalities would be informative. Moreover, although our analyses accounted for the possible covarying influences of age and nonverbal IQ, it remains possible that the correlation is driven by other underlying shared factors, such as attention and motivation (Ludden & Gupta, 2000).

An important contribution of this study is to demonstrate that memory, specifically participants' ability to recall a previous auditory/visual stimulus and relate it to the following stimulus in real time, was highly correlated with statistical learning ability within the same modality. This result does not weaken the relative importance of statistical learning as a cognitive mechanism, but does indicate that the interaction between memory and learning should not be overlooked.

This study also is the first to examine the link between nonlinguistic statistical learning of transitional probabilities and individuals' language performance. The study also adds to the minimal information on the contribution of memory to statistical learning. The Memory and Statistical learning tasks were developed so that linguistic processing would not be triggered when performing the tasks. Language tasks emphasized both acquired linguistic knowledge and linguistic processing efficiency. The step-wise regressions revealed that a significant proportion of the variance in linguistic skills was predicted by performance on the nonlinguistic tasks after controlling for the developmental covariants of age and IQ. Language learning skills are not isolated from learning in other fundamental aspects of cognition, such as memory and statistical learning. The results are more in line with theoretical debate on domain-general cognitive resource theories in which basic cognitive mechanisms need to be integrated for language learning than domain-specific cognitive resource theories.

The specific pattern of results is intriguing. If we had explored only statistical learning performance, our conclusion would have been that statistical learning contributed robustly to language skills. However, investigation of memory tasks enabled us to make more fine-grained observations. Performance on the Rapid Naming task was not predicted directly by statistical learning performance. Rather, memory performance (recall of visual sequences of increasing length) was the more important predictor. Rapid Naming is a real-time task that emphasizes automated processing, and it is believed to tap the ability to rapidly retrieve information that has been stored for a long time (Manis, Seidenberg & Doi, 1999). The results suggest that the ability to hold real-time nonlinguistic information in memory was indeed associated with Rapid Naming performance. Similarly, much of the variance in the other language processing task, Nonword Repetition was explained by Auditory memory (recall of auditory sequences of increasing length) rather than by statistical learning performance. Nonword Repetition also assesses the ability to access and recall linguistic units in real time. Again, it makes intuitive sense that memory performance should be closely related with this measure of language processing efficiency.

On the other hand, each of the two language tasks that were designed to assess mainly acquired language knowledge was associated more closely with statistical learning than memory ability. Performance on both Grammaticality Judgment and the CELF relies on complex grammatical and semantic patterns that are acquired over time. Performance on these two tasks was predicted by statistical learning ability. We anticipated that the CELF would be predicted by both the auditory and visual experimental tasks because of the auditory-visual format of this standardized test. It was not possible to tease apart the modality of stimuli on this standardized test. Some CELF subtests use only auditory stimuli, others use only visual stimuli, and still others use both. It would be informative in future research to determine more specific modality associations using a different measure of acquired language knowledge. However, these results indicate overall that if individuals are good learners of nonlinguistic regularities, they also may be good learners of linguistic regularities.

This study was not designed to compare the two statistical learning tasks directly. However, it is important to note that there is increasing understanding that task demands and the units over which learning operates affects performance (Ludden & Gupta, 2000; Turk-Browne et al., 2008). Task differences between Auditory statistical learning and Visual statistical learning may have influenced task performance. Recent findings from Yim (2009) suggest that when visual statistical learning is manipulated with attentional load, individuals show lower performance. Learning in the Auditory statistical learning task presumably occurred more incidentally because both children and adults were engaged in coloring during the training session. Also, attention and/or working memory resources may have been divided in this task between the coloring and listening to the auditory stimuli which was a similar situation in Ludden & Gupta (2000). Learning in the Visual statistical learning training session presumably occurred with greater participant engagement/intention and with more focused attention because participants were looking continuously at the visual stimuli without any other task at hand. It also is possible that participants changed attention allocation or strategies throughout the training sessions. It remains debatable in the literature whether implicit learning occurs with or without attention. Some researchers have argued that attention to the stimuli is necessary for learning (Nissen & Bullemer, 1987) while others have stated that some stimulus sequence types can be learned without attention (Cohen, Ivry & Keelf, 1990; Frensch, Buchner & Lin, 1994). Notably et al. (2005) found poorer accuracy in a linguistic statistical learning task when there was a concurrent visual task. It may be this type of inherent task difference in attention demands rather than the difference in modality that helps to explain, for example, why participants had lower accuracy in Auditory statistical learning than in Visual statistical learning. We did not assess participants' attention or engagement directly, and it will be important in future studies to determine the role that these interrelated variables play.

In summary, this study suggests that some aspects of language and nonlinguistic cognitive processing are related for individuals who have typical language and cognitive skills. The study also demonstrates that memory is an important factor when statistical learning happens in real time.

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Appendix

Stimulus Preparation for Visual Tasks

Stimulus Selection. For Visual statistical learning and Visual memory, a total of 33 simple, non-namable shapes were used. These included 9 closed shapes adapted from Fiser & Aslin (2002), 10 line-drawn shapes from Gauthier et al. (2003); 8 multi-angle shapes from a mental rotation task (Windsor et al., 2008); and 6 Japanese Hiragana and Hindi characters. All shapes were the same size, 6.85° × 6.85°, and shown in black on a white background. To identify these 33 shapes, pilot testing was carried out with 40 undergraduate students who viewed a larger set of 63 shapes. These participants were asked to name shapes if they were able to do so. Each shape was presented for 6 sec with a 3-sec interval between shapes. The 40 shapes that were named by fewer than four participants were selected as the experimental stimuli, with the 7 Hindi shapes also removed because participants reported that these characters seemed like line drawings rather than shapes.

Base Triplets. The visual base triplets were composed from one shape from each of the shape sets of Fiser & Aslin (2002), Windsor et al. (2008), and Gauthier et al. (2003). Using the three different categories of shapes was important so that each shape was not easily confusable with any other shape within its triplet. Shapes that were used in base triplets in Visual statistical learning were not used in Visual memory. Participants saw 12 different shapes in Visual statistical learning and 21 shapes in Visual memory.

Stimulus Preparation for Auditory Tasks

Stimulus Selection. For Auditory statistical learning and Auditory memory, it also was important to control for the possibility of linguistic mediation. Novel auditory stimuli which contained no phonetic content were used. For Auditory statistical learning, 12 sounds were generated by Cool-Edit Pro (Syntrillium Inc., 1998): 4 steady-state tones, 4 glide tones, and 4 noises. Each sound was 250 ms long. Three of the steady-state tones were combinations of 4 pure tones, with base tone frequencies of 110, 3000, and 5000 Hz. The fourth stimulus was composed of three harmonics at 4000, 6000, and 8000 Hz. The 4 glide tones were composed of only one frequency component, which changed linearly throughout the stimulus (from 250 to 880 Hz; 800 to 100 Hz; 1000 to 100 Hz; and from 100 to 500 Hz for the first 125 ms of the stimulus and then from 500 to 100 Hz for the second 125 ms). The noises were created by applying three filters to white noise. The low-pass filter removed all acoustic information above 600 Hz. The high-pass filter removed information below 2000 Hz. The band-pass filter removed information below 300 Hz and above 2500 Hz. All sound files were digitized at 22.05 kHz with 16-bit quantization. To ensure that sounds were perceptually distinct; two untrained listeners were presented with sound pairs and identified whether the two sounds were the same or different. All 12 sounds were reported to be different from one another. For Auditory memory, stimuli included sequences of 100 ms tones. Tone sequences ranged from 2 to 5 tones, presented at 500, 1000, 2000, or 3000 Hz.

언어능력에서 비언어정보 통계적 학습과 기억력 역할

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배경 및 목적: 통계적 학습(statistical learning)은 언어수행능력에 있어서 매우 중요한 기제이다. 본 연구는 언어능력과 비언어정보의 통계적 학습 및 기억력간의 관계를 청각과 시각 영역에서 연구하였다. 첫번째 연구목표는 비언어정보의 통계적 학습이 언어능력을 설명할 수 있는지를 살펴보았다. 두번째 연구목표는 언어수행능력에 있어서 통계적 학습과 기억력의 역할이 어떠한 상관관계를 맺고 있는지에 대해 살펴보았다. **방법:** 정상학령기 아동 20명과 정상 성인 20명이 연구에 참여하였으며, 언어능력은 크게 두가지 영역으로, 습득된 언어지식(문법판단과제와 표준화된 검사도구를 통해 측정된 언어능력)과 언어처리과정의 효율성(빠르게 이름대기 과제와 무의미 단어반복과제를 통해 측정된 언어능력)을 검사하였다. **결과:** 첫째, 비언어정보의 통계적 학습능력은 언어능력에 통계적으로 유의미한 영향을 미쳤다. 이 결과는 언어와 비언어영역간에 하나의 근본적인 학습체계가 밑바탕에 내재되어 있음을 제시하였다. 둘째, 통계적 학습능력과 기억력은 서로 다른 양상으로 언어능력에 영향을 미쳤다. 통계적 학습능력은 습득된 언어지식에 통계적으로 유의미하게 영향을 미쳤고, 기억력은 언어처리과정의 효율성에 통계적으로 유의미하게 영향을 미쳤다. **논의 및 결론:** 본 연구결과 언어능력에 있어서 비언어정보의 통계적 학습과 기억력 두가지의 중요성을 보여주었다. 『**언어청각장애연구**』, 2010; 15;381-396.

핵심어: 비언어정보, 통계적 학습, 언어지식, 언어처리과정, 기억력

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