Learning a Center-Embeddding Rule in an Artificial Grammar Learning Task

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Abstract

Beginning with Fitch and Hauser (2004), a number of studies have used the Artificial Grammar Learning task to investigate learning rules generating hierarchical structural relations among sequences of elements that are characteristic of the grammar of human languages. Studies that have examined the learning of a center-embedding rule (A^nB^n rule) exemplified by the sentence, *The dogs the girl the boys like feeds bark incessantly* have provided mixed results. We present the results of three experiments that demonstrate learning when training occurs incrementally (e.g., Lai & Poletiek, 2011) and requires feedback when testing with a grammaticality judgment task. We also use a novel completion task, which demonstrated learning both with and without feedback. In all cases, not all participants learned the rule.

Keywords: Artificial grammar learning task, center-embedding

Introduction

Over the past decades, the Artificial Grammar Learning (AGL) paradigm has been an important methodology for investigating children and adults' ability to learn grammatical rules that underlie the hierarchical embedding of natural language. The AGL paradigm uses a set of rules to generate meaningless sequences of letters, syllables, or other elements. The sequences are presented to participants during a training phase, and, then learning is tested typically with novel sequences presented for grammaticality judgments. The participants' ability to both accept grammatical sequences and reject ungrammatical ones is considered evidence of learning the underlying rule.

Following several previous AGL studies the, the current experiments examined adults' learning a recursive center-embedding rule with the notation A^nB^n. It creates hierarchical dependencies like in the sentence, *The dogs the girl the boys like feeds bark incessantly*. AGL studies have yielded mixed findings concerning adults' ability to learn the A^nB^n rule when it requires what we refer to as subcategory dependencies. That is, A and B refer to two different categories and the superscripted numbers refer to dependent A and B subcategories (e.g., the occurrence of an element from subcategory A^1 requires the occurrence of an element from subcategory B^1).

Fitch and Hauser (2004) were among the first to test learning of the A^nB^n rule by humans as well as primates. Their A and B categories were recordings of 16 different CV syllables, with 8 A category syllables recorded in a female voice and 8 B category syllables recorded in a male voice. Grammatical sequences simply had an equal number of A and B syllables (n = 2 or 3) and no repetitions of token syllables. Participants listened to a recording of 30 grammatical sequences without any explicit learning instructions. Afterwards, they performed a same-different judgment task (without feedback) consisting of novel grammatical sequences with n = 2, 3, or 4 (the latter testing generalization). The ungrammatical sequences reversed the order of the AB categories or had alternating AB syllables. The human participants (but not the primates) readily distinguished the grammatical and ungrammatical sequences (89% correct) as well as judged 84% of grammatical sequences with n = 4 as being "same".

However, a study by Perruchet and Rey (2005) failed to find evidence that humans learn the A^nB^n rule when it creates sequences with non-adjacent dependencies thereby reflecting a hierarchical structure. Like Fitch and Hauser, their A and B categories consisted of synthesized recordings of 16 different CV syllables, with the 8 A category recordings having higher pitch than the 8 B category recordings. Unlike Fitch and Hauser, each A category syllable was matched to a B category syllable creating AB item dependencies. Thus, given a dependency between *ba* (A category) and *lo* (B category), if *ba* occurred first in a sequence then *lo* occurred last. The sequences had 1- or 2-embeddings (n = 2 or 3), with no repetitions of token syllables. Participants listened to 32 sequences during an exposure period without explicit learning instructions. Afterwards, they were given a same-different judgment task (with no feedback) consisting of novel grammatical sequences and ungrammatical sequences created by scrambling the order of the B syllables (thereby violating AB item dependencies). In addition, half of both the grammatical and ungrammatical sequences had alternating high-low pitch thereby violating the pitch pattern. The results showed that the participants' same-different responses were based on whether the test sequences' pitch pattern was consistent with the exposure sequences and not on whether the order of the B category syllables reflected the center-embedded dependency.

A number of subsequent AGL studies with only human participants have provided mixed evidence of learning the A^nB^n rule (Bahlmann, Gunter, & Friederici, 2006; Bahlmann, Schubotz, & Friederici, 2008; de Vries, Monaghan, Knecht, & Zwitserlood, 2008; Lai & Poletiek, 2011). Most studies used the syllables shown in Table 1 in which the A and B categories were distinguished by the syllables' vowels and the three AB dependent subcategories were based on the initial consonants.

Unlike Perruchet and Rey (2005) the subsequent studies presented the A^nB^n sequences visually, with each syllable presented one at a time for a duration ranging from 300 ms to 800 ms across studies and with an interstimulus interval ranging from 0 ms to 200 ms. The studies also differ from Perruchet and Rey (2005) in several other important ways: (1) Participants were explicitly instructed to try to learn the rule underlying the grammatical sequences, (2) the training sequences were presented in a series of blocks each ending with a grammaticality judgment test, and (3) participants received feedback on their grammaticality judgments.

Although the subsequent studies differ from each other in a number of ways, the mixed findings appear to be due to two differences: the nature of the ungrammatical test sequences and whether training was incremental. In the case of the ungrammatical test sequences, as shown in Table 2, the violation involved a subcategory dependency, in which a B-category syllable was replaced with a syllable from another subcategory (Bahlmann et al. 2006; Bahlmann et al., 2008; Lai & Poletiek, 2011) and/or it involved scrambling the order of the of the dependent B category syllables (de Vries, et al., 2008; Perruchet & Rey, 2005). de Vries et al. argued that scrambled sequences are necessary to test participants' learning of the hierarchical center-embedding structure because they contrast with grammatical sequences specifically with respect to that structure. Ungrammatical sequences with a subcategory dependency violation can be rejected using a counting strategy, namely, for every syllable in the first half of a sequence that begins with *b*-, *d*-, or *g*-, there must be a syllable in the second half that begins with *p*-, *t*-, or *k*- respectively. This strategy would correctly reject the ungrammatical sequence bedegiko**po**pu because the *de* requires either *to* or *tu* in the last three syllables. However, the strategy would incorrectly accept the scrambled sequence bedegiko**potu**.

Table 1: Syllables representing the A and B categories and subcategory dependencies in de Vries et al. (2008 Experiment 2), Bahlman et al. (2008), Lai & Poletiek (2011), and Experiments 1-3.

A Category (-e, -i)	B Category (-o, -u)
A-B Dependent Subcategories	
A^1 be, bi	B^1 po, pu
A^2 de, di	B^2 to, tu
A^3 ge, gi	B^3 ko, ku

Of the subsequent studies using the same or similar materials shown in Table 1, only de Vries et al. (2008) used scrambled test sequences, and doing so showed no evidence of learning the A^nB^n rule. Bahlman et al. (2008) as well as Lai and Poletiek (2011) used test sequences with a subcategory violation which were reliably distinguished from grammatical sequences. In addition, unlike de Vries et al., both Bahlman et al. (2008) and Lai and Poletiek (2011) employed incremental training that began with 0-embedding sequences. In fact, Lai and Poletiek found no evidence of learning the A^nB^n rule with random training or with incremental training that began with 1-embedding sequences. Thus, learning the A^nB^n rule appears to require first learning the subcategory dependencies, which is facilitated by exclusive initial training with the 0-embedding sequences. Once the subcategory dependencies are learned, they provide a scaffolding for learning the structural dependency (e.g., Elman, 1993). Learning the subcategory dependencies is more difficult with random training, especially if it does not include 0-embedding sequences, as in the case of de Vries et al. (2008). The aim of Experiment 1 was to verify the importance of incremental training and presented scrambled ungrammatical test sequences.

Table 2: Examples of grammatical & ungrammatical test sequences with 0-, 1-, or 2-embedding levels (LVL) presented in various studies. Ungrammatical sequences with a subcategory violation were used in Bahlmann et al. (2008) and Lai & Poletiek (2001). Scrambled sequences were used in de Vries et al. (2008) and Experiment 1. Violations are indicated by bold.

LVL	Grammatical	Ungrammatical Subcategory Violation	
0	A^1B^1 bepo	$A^1\mathbf{B^3}$ be**ko**	
		Subcategory Violation	Scrambled
1	$A^1A^3B^3B^1$ begekupu	$A^1A^3B^3\mathbf{B^2}$ bigiko**tu**	$A^1A^3\mathbf{B^1B^3}$ bigi**puko**
2	$A^1A^2A^3B^3B^2B^1$ bedigikotopu	$A^1A^2A^3B^3\mathbf{B^1}B^1$ bedegiko**po**pu	$A^1A^2A^3B^3\mathbf{B^1B^2}$ bedegiko**potu**

Experiment 1

Experiment 1 was a replication of Lai and Poletiek's (2011) incremental and random training conditions, each consisting of 12 blocks. For both training conditions, the grammaticality judgment task at the end of each block included either Lai and Poletiek's ungrammatical test sequences with a subcategory violation or scrambled ungrammatical test sequences. If learning occurs in the Incremental condition with scrambled test sequences then it would provide evidence that participants learned the A^nB^n rule rather than a counting strategy. A final test block with 3- and 4-embedding sequences also was presented to assess participants' ability to generalize the rule (e.g., Fitch & Friederici, 2012). Incremental training that begins exclusively with the 0-embedding level should facilitate learning the AB subcategory dependencies, which, in turn, should enable learning the A^nB^n rule. Once the rule is learned, there should be consistently high accuracy on the grammaticality judgment task at the end of each block. Therefore, we examined the individual participants' performance on the grammaticality judgment task across the blocks to assess whether those who learned the AB subcategory dependencies also subsequently learned the A^nB^n rule. We also had participants provide written descriptions of the rule at the end of the experiment.

Method

Participants Sixty-four undergraduate students enrolled in Psychology courses participated and received course credit. All were native English speakers.

Materials and Design The materials consisted of the six A Category and six B Category syllables, and subcategory dependencies shown in Table 1. The 144 training sequences created from the syllables by Lai and Poletiek (2011) were used and consisted of an equal number of 0-, 1-, and 2-embedding sequences, with two, four, and six syllables, respectively. Across the entire training set, each syllable occurred with an equal frequency.

The training sequences were presented in 12 blocks with 12 sequences per block. In the Incremental training condition, the 0-, 1-, and 2-embedding sequences were presented in three stages each with four blocks. In the Random training condition, each block had an equal number of 0-, 1-, and 2-embedding sequences in a random order.

In both the Incremental and Random training conditions, each block ended with a test block. The test blocks consisted of 12 sequences, four for each level of embedding (two grammatical and two ungrammatical). The grammatical sequences were novel except for the 0-embedding sequences because all possible combinations were presented during training. The type of training condition was crossed with type of ungrammatical test sequence (subcategory violation or scrambled) yielding four conditions. The same grammatical test sequences were presented in all four conditions. The ungrammatical sequences in the subcategory violation condition were the same as Lai and Poletiek's (2011). Their 0-embedding ungrammatical sequences with a B subcategory violation were also presented in the Scrambled test condition. However, the ungrammatical 1- and 2-embedding test sequences were created by correcting the subcategory dependency violation in Lai and Poletiek's ungrammatical sequences and then reversing the order of the last two B category syllables (see Table 2).

The final generalization test block, consisted of 12 3-embedding and 12 4-embedding sequences, half of which were ungrammatical. The longer sequences necessitated having two A-category syllables from the same subcategory; however, there were no repetitions of the same token. The ungrammatical test sequences representing the Subcategory Violation and the Scrambled conditions were created in the same manner as the shorter ungrammatical test sequences representing these conditions.

Procedure Participants were randomly assigned to one of the four experimental conditions and tested individually in a small room. They sat in front of a monitor and a keyboard with two keys labeled "Y" and "N". They were told that they would see sequences of syllables that were generated by a rule and that their task was to try to learn the rule. They were informed that the sequences would be presented in 12 training blocks each ending with a test block presenting sequences that were generated by the rule and sequences that were not. They were instructed to press the "Y" or "N" key after each test sequence to indicate whether it was generated by the rule.

As in Lai and Poletiek's (2011) experiment, each training sequence was preceded by a fixation cross displayed for 500 ms in the center of the computer screen. Then each syllable of a sequence was displayed one at a time in the center of the screen for 800 ms with no delay between syllables. The last syllable was immediately followed by the fixation cross.

Each training block ended with a message instructing the participant to press the spacebar to begin the test block. The test sequences were presented in the same manner as the training sequences, except that the last syllable of a sequence was followed by the question "Does the sequence conform to the rule that generated the training sequences?" Following the participants' "Y" or "N" key response, feedback was presented in the form of "Correct" or "Incorrect" displayed for 500 ms.

The test blocks ended with a message instructing the participant to press the spacebar to begin the next training block, or in the case of the last test block, a message instructing the participant to press the spacebar to begin a final test block (the generalization test). After the experiment, the participants completed a survey that asked them to describe the rule that generated the training sequences. The survey also included 10-point rating scales for indicating their level of effort and questions about handedness and left-familial handedness. The entire experimental session lasted about 30 minutes.

Results and Discussion

The accuracy of each participant's responses to the grammatical and ungrammatical test sequences was measured by calculating A' using Stanislaw and Todorov's (1999) equation. A' is a nonparametric version of d' that is calculated from the hit and false alarm rates to take into account a "yes" or "no" response bias. Unlike d', A' can be calculated when a participant's hit or false alarm rates are 1 or 0. An A' value of 1.0 corresponds to perfect accuracy and a value of 0.5 corresponds to chance.

Mean A' values in the four conditions were calculated from the participants' responses to all 168 test and generalization sequences. The mean A' values in the two Incremental training conditions were .66 (Subcategory Violation) and .67 (Scrambled) and were higher than the mean A' in the two Random training conditions, which were .56 (Subcategory Violation) and .55 (Scrambled). The mean A' values were submitted to a 2X2 randomized ANOVA with type of ungrammatical sequences (Subcategory Violation or Scrambled) and type of Training (Incremental or Random) as between-subjects variables. Only the main effect of Training was significant ($F(1,60)= 10.98$), reflecting higher accuracy in the Incremental condition than in the Random condition. One-sample t-tests comparing the participants' overall A' against the chance value of 0.50 were significant in all conditions for the 0-embedding sequences but the overall *A′* values for the 1- and 2-embedding sequences were significantly greater than chance only in the Incremental conditions (*A′* range .61 - .65), consistent with Lai and Poletiek's original findings.

The similar results in the two Incremental conditions provides evidence that participants learned the A^nB^n rule rather than a counting strategy. Additional evidence comes from the Incremental conditions' higher *A′* for the 3- and 4-embedding sequences in the final generalization test. Both *A′* values in the Scrambled condition were significantly greater than chance (*A′*= .72, *t*(15)= 3.94 for 3-embedding and *A′*= .65, *t*(15)= 2.23 for 4-embedding). Only the *A′* for the 3-embedding sequences was above chance in the Subcategory Violation condition (*A′*= .74, *t*(15)= 4.92, and A'= .54, *t*< 1 for 4-embedding). The mean *A′* for the generalization sequences in the two Random conditions ranged from .55 to .58 and were not greater than chance.

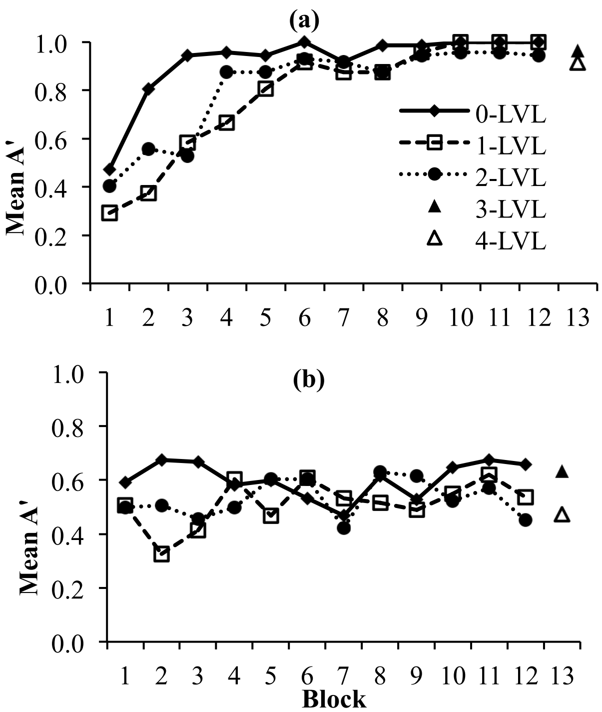

Figure 1: Mean *A′* for each level of embedding (LVL) in each test block averaged over participants in the Incremental condition in Experiment 1. Figure (a) means of the 9 participants who achieved a *A′*=1.00 for the 0-embedding items by block 6, and (b) the other 23 participants' means.

None of the participants in the Random conditions accurately described the rule. Six participants in the Incremental conditions accurately described the rule and tthree others provided the correct AB subcategory dependencies, though they did not elaborate on the embedding relation. Four of these participants were in the Incremental-Subcategory Violation condition and five were in the Incremental-Scrambled condition. All nine had an *A′* greater than .90 for the 24 test sequences in the last three blocks, and all had an *A′* greater than .80 for the 24 generalization sequences. Figure 1a shows the mean *A*' for these nine participants for each test block and for each level of embedding. These participants' had a mean *A′* = 1.00 for the 0-embedding sequences by the 6^{th} block and mean A' = .95 for the 1- and 2-embedding sequence by the 9th block, providing evidence that learning the AB subcategory dependencies facilitated learning the A^nB^n rule. For comparison, Figure 1b shows the mean *A′* values for the other 23 participants in the Incremental conditions. There mean *A′* for the 0-embedding test sequences peaked at .67 in block 3.

Experiment 2

A limitation of the AGL paradigm for investigating the learning of the A^nB^n rule is that much of the learning may occur in the test blocks when both positive and negative examples of the rule are presented with feedback on the participants' judgment. In addition, the sequential presentation of individual syllables of the test sequences required participants to retain them in working memory to make judgments. Thus, inaccurate judgments may be due in part to memory errors. Experiments 2 and 3 addressed these limitations by replacing the grammaticality judgment test with a production test that required participants to provide completions to sequences consisting of just the A-category syllables. Specifically, test sequences consisting of one, two, or three A-category syllables representing the first half of sequences with 0-, 1-, or 2-embeddings, respectively, were displayed with underscores indicating the number of B-category syllables that were to be entered for a completion response. Participants entered their completions by pressing keys that were labeled with the complete set of A- and B-category syllables, even though correct responses required only B-category syllables. The A-category syllables in the 1- and 2-embedding test items were from different subcategories. Thus, correct completions required providing B syllables from the dependent subcategories and in the correct order. Like Experiment 1, the final test block included 3- and 4-embedding items to assess generalization of the rule. Each test sequence was displayed until the participant finished entering a completion for it, thereby eliminating the need to maintain the sequence in memory. The participants also were asked to describe the rule at the end of the experiment. The training blocks were identical to the Incremental conditions in Experiment 1.

Method

Participants Sixteen undergraduate students enrolled in Psychology courses participated and received course credit in exchange. All were native English speakers.

Materials and Design The training materials were identical to Experiment 1. However, the testing materials were different. Each test block had 12 sequences, four with one, two, and three A category syllables, corresponding to the first half of 0-, 1-, and 2-embedding sequences, respectively. The final test block had 24 additional sequences, 12 with four A category syllables and 12 with five A category syllables, testing generalization to 3- and 4-embeddings, respectively. The test sequences representing 1- and 2-embeddings contained A-category syllables from different subcategories (e.g., gibide). The test sequences in the final block representing the 3- and 4-embeddings consisted of at least one A syllable from each subcategory, but no more than two from the same subcategory, which were different tokens (e.g., bedegegibi). Each A-category syllable occurred equally frequently across the entire set of test sequences. The organization and order of presentation of the training and testing materials were identical to Experiment 1's Incremental-Scrambled condition.

Procedure The same procedure as Experiment 1 was used except for the test at the end of each block. Participants were told that it was a sequence-completion task in which the first half of syllable sequences would be presented, and they were to type the second half by selecting from the labeled keys on the keyboard. On each test trial, a whole test sequence was displayed in the center of the screen with underscores indicating the number of syllables that were to be typed for a completion (e.g., de __, bidige __ __ __). The test sequence remained visible until the participant typed the required number of syllables by pressing labeled keys on the keyboard and the return key after the last syllable. Then, feedback was displayed for 500 ms. The same survey as Experiment 1 was given at the end of the experiment, which asked participants to describe the rule.

Scoring Completions to 0-embedding test items were scored as *Match* if they had a correct B subcategory syllable. Completions to the 1-, 2-, 3-, and 4-embedding items were scored as *Correct* if both the dependent B subcategory syllables and their order were correct. They were scored as *Match* if only the dependent B subcategory syllables were correct.

Results and Discussion

For each participant, the proportion of Match and Correct completions were calculated for the 0- 1-, and 2-embedding sequences over the four test blocks corresponding to the three incremental training stages. A 3X2 repeated measures ANOVA on the Correct proportions with Stage and Embedding (1 or 2) as factors yielded a significant main effect of Stage ($F(2,30)= 10.50$, $p< .001$), reflecting an increase in the Correct proportions across each stage (.10, .30, and .45). Neither the main effect of Embedding nor the interaction was significant ($Fs< 1.00$).

Consistent with Experiment 1, the individual participants' performance (Figure 2) showed that learning the A^nB^n rule depended on learning the AB subcategory dependencies. Six participants' Correct proportions for 1- and 2-embedding items in the last three test blocks was above .80 as well as their Correct proportions for the 3- and 4-embedding generalization items. Five accurately described the A^nB^n rule. Figure 2a shows that these 6 participants' mean Match proportion for the 0-embedding items was .92 by the 3rd block and 1.00 by the 7th block. The decrease in their Match proportions for the 1- and 2-embedding items coincides with an increase in their Correct proportions, reflecting their learning the correct ordering of the B syllables. In contrast, Figure 2b shows that the other 10 participants' mean Match proportion for 0-embedding items peaked at .67 in the 4th block (the last 0-embedding training block) and no increase in their mean Correct proportions for the 1- and 2-embeddings across any blocks.

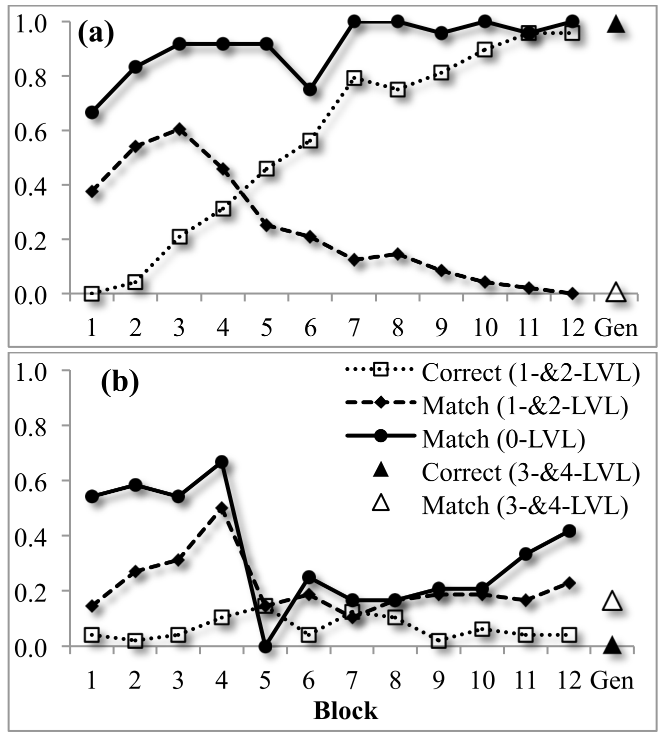

Figure 2: Mean proportions of Correct completions (correct B syllable dependency & order) and Match completions (correct B syllable dependency only) in each test block and for each embedding level (LVL) in Experiment 2. Figure (a) mean proportions of the 6 participants who achieved a 0-LVL Match proportion of 1.00, and (b) mean proportions for the other 10 participants.

Experiment 3

Experiment 3 investigated the effect of feedback in the test blocks on learning the A^nB^n rule by eliminating it. There were two conditions that contrasted the type of test: grammaticality judgment (identical to Experiment 1's Incremental-Scrambled condition) or completion (identical to Experiment 2).

Method

Participants The participants were 32 students enrolled in Psychology courses who received a course credit. All were native speakers of English.

Materials and Design The training and test sequences for the Grammaticality Judgment condition were the same as in

Experiment 1's Incremental-Scrambled condition. The training and test sequences for the Completion condition was the same as in Experiment 2.

Procedure The procedure for the Grammaticality Judgment condition was the same as Experiment 1's Incremental-Scrambled condition, except that participants' response to the test sequences was followed by a 500 ms blank screen instead of feedback. Likewise, the procedure for the Completion condition was the same as Experiment 2 except there was a 500 ms delay after the participant pressed the return/enter key.

Results and Discussion

Grammaticality Judgment Condition In contrast to Experiment 1, no learning of the A^nB^n rule occurred. The overall mean *A′* for 0-embedding test sequences was greater than chance ($t(15) = 2.41$, $p< .05$, two-tailed), but not the mean *A′* for the 1- and 2-embedding test sequences nor the 3- and 4- embedding generalization sequences ($t < 1.0$). The highest mean *A′* (.64) was for the 0-embedding test sequences in the first training stage, which decreased to chance level in the subsequent two stages. One participant had an $A' > .80$ for the 1- and 2-embedding test sequences in the last 3 blocks and for the generalization sequences, but did not accurately describe the rule.

Completion Task Condition The participants' Correct proportions were analyzed with a 3X2 repeated measures ANOVA with Stage and Embedding (1 or 2) as within-subject factors. There was a main effect of Stage ($F(2,30)= 5.70$, $p= .008$), with higher proportions in stage 3 (.29) than stages 1 and 2 (.03 and .23, respectively). Neither the main effect of Embedding nor the interaction was significant ($Fs< 1$). Four participants (25%) showed evidence of learning the A^nB^n rule, with a mean Correct proportion of .97 for the 1- and 2-embedding items in the last three blocks and for the 3- and 4-embedding generalization items. They also accurately described the rule. Similar to the 6 participants in Experiment 2, their average Match proportion for the 0-embedding items was 1.00 by the 7^{th} block at which point there mean Correct proportion for the 1- and 2-embeddings was .96.

General Discussion

The current set of experiments provides additional support for Lai and Poletiek's (2011) finding that learning the A^nB^n rule in AGL studies is facilitated by incremental training that begins with 0-embedding sequences, which support learning the AB subcategory dependencies. This learning, in turn, allows individuals to determine the center-embedding structure. The current study also eliminated the use of a counting strategy by presenting scrambled sequences as ungrammatical items.

Presenting a grammaticality judgment task at the end of each training block allows one to track the course of learning, but it also is a primary source of the learning when feedback is provided. When feedback is eliminated, as in Experiment 3, no learning of the A^nB^n rule occurred despite incremental training.

Experiment 2 and 3's completion tasks revealed that once the AB subcategory dependencies were learned, individuals hypothesized a symmetrical structural rule (i.e., cross-dependency, as in $A^1A^2B^1B^2$) as reflected in an increase in their Match proportions for the 1- and 2- embeddings during the first training stage. Receiving feedback on the completion responses in Experiment 2 facilitated learning the correct center-embedding structure. However, 25% of the participants in Experiment 3 managed to learn this structure without feedback.

Across the 3 experiments, the percentage of participants who showed evidence of learning the rule ranged from 25% to 38%, indicating individual differences in explicitly learning structural dependencies. The differences may be related to those observed in implicit statistical learning (e.g., Kaufman et al., 2010).

In conclusion the current study provides additional evidence for the conditions that support learning the abstract hierarchical structural relations generated by a center-embedding rule.

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