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Explicit Learning of Phonotactic Patterns Disrupts Language Learning

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Explicit Learning of Phonotactic Patterns Disrupts Language Learning

A Thesis Presented

By

EVAN T. HARE

Submitted to the Graduate School of the
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of the requirements for the degree of

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Explicit Learning of Phonotactic Patterns Disrupts Language Learning

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ABSTRACT

EXPLICIT LEARNING OF PHONOTACTIC PATTERNS DISRUPTS LANGUAGE LEARNING

SEPTEMBER 2017

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Learning environment has been proposed to be a cause of age of acquisition effects in second language acquisition. Explicit learning in adults is linked to fast initial gains but poorer ultimate attainment whereas implicit learning in children requires more input but leads to greater proficiency in the long run. The current study used ERP measures to determine if explicit learning of a phonotactic pattern interferes with implicit learning of that same pattern in adults. Listeners were told to figure out the pattern of consonants that can go together in a word by listening to 16 CVCV nonsense words in which the two consonants all matched in voicing or never matched in voicing.

Listeners rated novel items that fit the pattern presented in training as far more likely to fit the rule than novel items that violated that pattern, indicating that they did indeed learn the pattern. For participants who heard the voicing-mismatch language, novel items that violated the pattern elicited a larger negativity 200-400 ms after onset compared to novel items that fit the pattern. This effect was entirely distinct from what was previously observed under implicit learning conditions. Further, three patterns of data suggest that difficult explicit learning of a phonotactic pattern decreased language learning. First, differences in N400 amplitude across training blocks were reduced compared to what was observed with implicit learning. Differences in N400 amplitude in response to trained and novel items were limited to the more easily learned matched-

voicing language. Second, the ERP index of implicit phonotactic learning, a larger Late Positive Component (LPC) in response to novel items that violate compared to fit the pattern, was absent under explicit learning conditions. Third, and supporting the idea that an absence of an LPC effect indicates an absence of implicit learning, the only hint of an LPC-like effect was evident for the more easily learned matched-voicing pattern.

These patterns of data suggest that, at least for patterns that native speakers have exclusively implicit knowledge of, challenging explicit learning can interfere with other aspects of language learning. Adults who approach second-language acquisition with class-room style explicit learning strategies may compromise implicit learning of complex patterns that are necessary for higher levels of ultimate proficiency.

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CHAPTER 1

INTRODUCTION

The best approaches for learning a second language are widely debated. At the heart of the debate is that all neurotypical children acquire a first language seemingly effortlessly and to a high level of proficiency. In contrast, most adults find learning a language to require extraordinary efforts and typically consider themselves to be proficient only in languages learned as a child. An appealing proposal is that adults placed in the learning environment of a typical child would learn in the same manner *and* to the same level as a child. Children are often described as learning language implicitly through immersion in contrast to classroom-style explicit learning that may be more typical of adults (Ifantidou & Matsui, 2013; Birdsong, 1992). However, others have argued that implicit and explicit learning systems are entirely independent, suggesting that explicit language learning in adults should in no way compromise concurrent implicit learning that could lead to native-like performance (Paradis, 1994). In studies that did report evidence of an interaction between implicit and explicit learning, explicit learning was reported to lead to more rather than less implicit learning (N. Ellis, 2008; R. Ellis, 2009). As such, it is not clear how the explicit language learning that adults engage in could be the cause of decreased implicit learning and lower ultimate proficiency. However, previous research on implicit and explicit learning have been limited to a language subsystems in which most native speakers have at least some implicit and explicit knowledge, namely syntax and morphosyntax. Perhaps some aspects of language can only be learned implicitly. If so, it is these subsystems where explicit learning might have a negative impact on implicit pattern learning. One such subsystem is phonotactics, the rules governing how sounds of a language can be put together into words. Further, with behavioral measures it is challenging to detect differences in the amount of implicit learning under conditions that support successful explicit learning of

the same pattern. The current study employed event-related potential (ERP) measures to determine if explicit learning interferes with implicit learning of novel phonotactic patterns in adults.

It is widely accepted that second language acquisition that begins earlier in life is more likely to result in higher proficiency in the long run (Asher & García, 1969; Collier, 1987; DeKeyser & Larson-Hall, 2005; Flege, Munroe, & MacKay, 1995; Oyama, 1975). However, the cause or causes of age of acquisition effects on ultimate language performance are not well understood. One prominent theory is that age of acquisition effects on language ability are driven by biology (Lenneberg, 1967). Animal models provide convincing evidence of critical periods for perceptual processing, times during development in which normal sensory experience is necessary for normal cortical organization (Harwerth, Smith, Duncan, Crawford, & von Noorden, 1986; Hubel & Wiesel, 1970; E. Knudsen & P. Knudsen, 1990). Similarly, it has been proposed that greater neural plasticity in human children compared to adults facilitates language acquisition, and is the primary reason why children typically reach higher levels of proficiency than adult learners (DeKeyser, 2000; Johnson & Newport, 1989; Oyama, 1975). However, other research raises doubts about the idea that fundamental differences in child and adult brains are responsible for age of acquisition effects in second language learning (Bialystok, 1997; Birdsong, 1992; McDonald, 2000; Nikolov 2000). Alternative explanations include interference from a first language on second language acquisition and differences in the learning environments of children and adults that result in differential reliance on implicit and explicit learning systems. The idea that interference from a first language results in age of acquisition effects is dependent on the assumptions that first languages become more instantiated with longer experience, and that more instantiation leads to greater interference (Kroll & Stewart, 1994; McDonald, 2000). This claim is supported by evidence that patterns of age of acquisition

effects are related to similarities and dissimilarities in first and second languages (Derahkshan & Karimi, 2015; Flege et al., 1995). The idea that learning environment results in age of acquisition effects is dependent on the assumptions that child and adult environments are systematically different, that different environments result in different use of distinct learning systems, and that those distinct learning systems support different patterns of second language acquisition. Part of the appeal of the learning environment hypothesis is that, although biology and first language instantiation are immutable, learning environment is flexible. If it is the case that learning environment is the cause of age of acquisition effects, then adults could achieve language proficiency equivalent to that of early second language learners simply by mimicking a child's learning environment.

It is clear that implicit and explicit learning support different patterns of second language acquisition. Explicit learners tend to rapidly acquire new patterns, but fail to reach the higher ultimate proficiency levels of implicit learners on the same task (Krashen, Long, & Scarcella, 1979; Miralpeix, 2006; Slavoff & Johnson, 1995). During the early stages of language acquisition, explicit learning is more effective. As a result, adults, who are better at explicit learning tasks than children, typically outperform children on tests given shortly after initial exposure to a language pattern (Ellis, 2009; Gass, Svetics, & Lemelin, 2003; Robinson, 1996). However, the large number of complex patterns in language, some of which are probabilistic rather than absolute, seems to benefit more from implicit learning (Moreton, Pater, & Pertsova, 2015). The reasoning behind the learning environment hypothesis is that children are more often put in language learning situations that favor implicit learning. Further, children are faster implicit learners than adults (DeKeyser, 2000; Smalle, Muylle, Szmalec, & Duyck, 2017). As such, the greater reliance on implicit learning in children is hypothesized to be responsible for higher ultimate proficiency in early second language learners. However,

the idea that implicit learning in children explains age of acquisition effects relies on the assumption that adults, who use their superior explicit learning abilities to show rapid increases in performance, are not engaging in implicit learning of the same material. If this were the case, language learning in adults would best be supported by conditions that both encourage implicit learning and specifically discourage explicit learning. We are not aware of evidence that explicit language learning in adults does preclude or interfere with implicit learning.

In fact, it has been suggested that implicit and explicit learning are entirely independent systems. Neuroanatomical data provide evidence that implicitly and explicitly learned second language knowledge is stored in different cortical areas (Paradis, 1994). Others have suggested that the systems are not independent, but that explicit knowledge can induce or even convert into implicit knowledge (N. Ellis, 2008; R. Ellis 2009; Pienemann, 1989). As such, there is no reason to believe that the explicit learning that adults engage in is problematic for implicit learning of the same material. If this were the case, language learning in adults would best be supported by conditions that encourage both explicit learning (for rapid improvements) *and* implicit learning for ultimate attainment.

Phonotactics provide a medium on which to observe any effects of explicit learning on implicit learning because native speakers typically have exclusively implicit knowledge of phonotactic patterns. Native speakers indicate that nonwords are “better” if they fit the phonotactic patterns of their language, despite no ability to describe what makes a nonword a better fit (Adler, 2006; Albright, 2009; Bailey & Hahn, 2001; Fais, Kajikawa, Werker, & Amano, 2005; Kager & Pater, 2012). Further, adults can quickly acquire new phonotactic patterns from artificial languages presented in the laboratory (Cristia & Seidl, 2008; Cristia, Mielke, Daland, & Peperkamp, 2013; Moreton & Pater, 2012a; 2012b; Moreton, 2008; Lai, 2012; Moore-Cantwell, Pater, Staubs, & Zobel,

submitted). Importantly, lab-learned phonotactics in artificial languages are also learned implicitly.

The behavioral measures used in the studies described above make it challenging to detect differences in the amount of implicit learning under conditions that support successful explicit learning of the same pattern. Therefore, it was necessary to use ERPs to index any implicit learning under conditions that encourage explicit learning. Other researchers have been successful at using this approach. For example, the effects of immersion language training were directly compared to those of more classroom-like training conditions (Morgan-Short, Steinhauer, Sanz, & Ullman, 2012; Morgan-Short, Finger, Grey, & Ullman, 2012). Even with similar performance on a grammaticality judgment task, there were differences in ERPs elicited by syntactic violations of the newly learned rules. Specifically, in higher proficiency participants, those who learned under implicit learning conditions showed more native-like responses. Nonwords that fit and violate native language phonotactics elicit distinct ERPs (Domahs, Kehrein, Kraus, Wiese, & Schlesewsky, 2009). Further, a previous study using artificial languages, showed that the differences in ERPs elicited by novel words that fit and violate a newly learned pattern are similar to those for native language phonotactics (Moore-Cantwell et al., submitted).

The current study was designed to measure the effects of explicit learning conditions on implicit learning using identical stimuli and testing conditions as the previous study that found exclusively implicit learning of phonotactic patterns (Moore-Cantwell et al., submitted). In that study, listeners were exposed to the novel phonotactic pattern through a word-picture matching task unrelated to the pattern to be learned. In other blocks, listeners were asked to rate the word-likeness of learned, novel words that fit the pattern, and novel words that violated the pattern. More specifically, 48 two-syllable CVCV English-like nonsense words were created from a set of vowels {/i/, /e/,

/a/, /u/} and consonants {/t/, /d/, /g/, /k/}. The phonotactic rule used to divide the words into categories was based on consonant voicing (/g/ and /d/ are voiced, /t/ and /k/ are voiceless). All words fell into one of two categories: the two consonants either matched in voicing or did not match in voicing. During training, participants heard 16 words from the same category (matched or mismatched voicing) and learned to associate each word with a specific picture. During testing, participants heard 8 words from training, 8 novel words that fit the same phonotactic rule as trained words, and 8 novel words that violated the phonotactic rule that governed trained words. Participants rated each word on a scale of 1-4 in response to the question “How likely is this a word in the language you’ve been learning?” Participants received no explicit information about the phonotactic patterns, and when prompted at the end of the experiment, were unable to describe any pattern related to speech sounds that described words that were in or out of their trained language. Thus, any learning of the phonotactic pattern that divided the words into groups was implicit.

As expected, participants got better at the word-picture matching task over time. Further, ERPs recorded during training showed a centro-parietal N400 230 - 500 ms after word onset that decreased in amplitude across blocks. Not only did participants learn the words, they also showed evidence of implicit learning of the phonotactic pattern. Novel words that fit the phonotactic pattern of trained words were rated as more likely to be in the language than novel words that violated that pattern. Further, novel words that violated the phonotactic pattern elicited a larger positivity over posterior regions 600-1000 ms after word onset (LPC) compared to novel words that fit the pattern. Participants implicitly learned the pattern established by the trained words, and that implicit learning affected processing of novel words.

The current study is based on the previous implicit learning study, with the exact same nonsense words, phonotactic patterns, and testing conditions. Further, in both

studies, training required explicit learning. However, in the previous study (Moore-Cantwell et al., submitted) participants explicitly learned the meanings of words and phonotactic learning was exclusively implicit. In the current study, explicit learning of the phonotactic patterns was encouraged by telling people to figure out the rule that governed which consonants could go together in words, and requiring that they identify the two consonants on every training trial. As such, there was equal exposure to the phonotactic pattern in the two studies. If explicit learning of phonotactic patterns can happen concurrently with implicit learning without interference, ERPs elicited by novel words that fit and violate the learned pattern should include the effects observed under implicit learning conditions (Moore-Cantwell et al., submitted) along with additional differences associated with explicit learning. If, however, explicit learning of the phonotactic pattern interferes with implicit learning of the same pattern, then the ERP effects observed under implicit learning conditions would be extremely diminished or absent.

Previous evidence showed that more complex patterns were harder to learn explicitly and easier to learn implicitly (Reber, 1976; Reber, 1993). In the previous implicit phonotactic learning study (Moore-Cantwell et al., submitted) there were no differences in performance or ERPs for participants who learned the voicing-match pattern compared to the voicing-mismatch pattern. However, the voicing-mismatch pattern can be considered to be more complex (/t/ can only co-occur with /d/ or /g/, /k/ can only co-occur with /d/ or /g/, /d/ can only co-occur with /t/ or /k/, and /g/ can only co-occur with /t/ or /k/) than the voicing-match pattern (/t/ and /k/ can co-occur with themselves, and /d/ and /g/ can co-occur with themselves). Therefore, under explicit learning conditions there may be differences in ability to learn the voicing-match and voicing-mismatch patterns. Further, any differences in difficulty explicitly learning the pattern might have consequences for implicit learning of the same pattern. Specifically,

more difficult explicit learning might show greater interference on implicit learning.

CHAPTER 2

METHODS

Participants

Data are from 27 monolingual English speakers (18-25 years of age; 15 females and 12 males). Of those 27, 14 were trained on the language in which consonants always matched on voicing and 13 on the language in which consonants always mismatched on voicing. Participants were right-handed, had normal hearing and normal or corrected-to-normal vision, and reported no neurological problems. An additional 24 adults participated in the experiment. Data from 9 were excluded because they failed to learn the pattern to a sufficient level (defined as an average rating of novel items that fit the phonotactic pattern that was at least 1 point higher than the rating of novel items that violated the pattern). Data from 15 were excluded because of frequent artifacts in EEG (2 for blinks or eye-movements, 7 for high-frequency noise caused by muscle tension, and 6 for low-frequency drift likely caused by skin potentials in a too-warm room). All participants were compensated for their time with either \$10/hour or research credit to be used towards extra points in undergraduate courses at the University of Massachusetts Amherst.

Stimuli

In order to make direct comparisons to implicit phonotactic learning, the auditory stimuli were identical to those employed in the previous study (Moore-Cantwell et al., submitted). For that study, two artificial languages were constructed to impart new phonotactic knowledge. Each language included 24 consonant-vowel-consonant-vowel (CVCV) nonsense words consistent with English phonotactics. The Match language contained words in which the consonants matched in voicing (i.e. are either from the set of {/d/, /g/} or {/t/, /k/}). In the Mismatch language, the two consonants never matched in voicing within a word (i.e. only one from the set of {/d/, /g/} and the other from the set of

{/t, /k/}). The two languages are shown in Table 1. All words were spoken by a male native-English speaker experienced in using the International Phonetic Alphabet for production. The words were spoken in a carrier phrase and with stress on the initial syllable. After recording, parts of the phrase surrounding each word were removed and peak amplitudes were normalized to their mean.

In the implicit learning study, images were used as part of a word-picture matching task. To encourage explicit learning of which consonants can co-occur in words, this experiment used images of consonants in a training task. The lowercase letters “k”, “t”, “d”, and “g” were shown in gray boxes sized 2.5 x 1.9”.

Match 1	Match 2	Match 3	Mismatch 1	Mismatch 2	Mismatch 3
TITEH	TAWTU	DADAW	TIDEH	TAWDU	DATAW
DIDU	DIDAW	TAWTI	DITU	DITAW	TAWDI
GAWGU	GIGEH	KUKI	GAWKU	GIKEH	KUGI
KAKAW	KIKAW	GAWGI	KAGAW	KIGAW	GAWKI
TIKEH	DAGAW	TAWKU	TIGEH	DAKAW	TAWGU
DIGU	TAWKI	DIGAW	DIKU	TAWGI	DIKAW
GAWDU	KUTI	GIDEH	GAWTU	KUDI	GITEH
KATAW	GIDAW	KAWTI	KADAW	GITAW	KAWDI

Table 1: Match and Mismatch languages. All words in the Match language have consonants that match in voicing. Consonants in the Mismatch language never matched in voicing. The 24 words in each language were divided into three sets for use in different conditions: training, novel words that fit the pattern, and for listeners learning the other language, novel words that violated the pattern.

Procedures

The previous implicit learning study (Moore-Cantwell et al., submitted) used a word-picture matching task during training. To encourage explicit learning of a phonotactic pattern, most of the items from one of the languages were presented with specific instructions to learn which consonants can go together within words. Further, on

each training trial participants were required to press buttons corresponding to the consonants they heard. The items and number of repetitions were identical to those in the implicit learning study. As such, implicit learning of the patterns should be identical unless the instruction to explicitly learn a rule that governs which consonants can go together interferes with implicit learning. Learning was assessed by asking participants to rate items presented during training (Trained), novel items that fit the rule (Novel-Fit), and novel items that violated the rule (Novel-Violate). Training and testing portions of the study were organized into 5 blocks such that sufficient ERP data could be collected during testing without presenting so many items that violated the phonotactic rule that participants would potentially unlearn the pattern.

During a training phase, participants heard 16 words from one of the languages five times each for a total of 80 trials. Training items were presented in a different random order in each block and for each participant. On each trial, participants were required to indicate which consonant or consonants occurred in the word. Further, they were specifically instructed to figure out which consonants can co-occur in words. Participants were told that all of the items presented during training fit the rule; if a training item violated a participant's hypothesized rule that rule needed to be revised. Two groups of participants were trained on each language; one group trained with lists 1 and 2 and the other with lists 1 and 3 (Table 1). The 16 words introduced in the first training block for a participant were presented in every block.

Each training trial began with a fixation cross shown on the computer monitor. After 700-1200 ms (randomly selected from a rectangular distribution) one of 16 words was presented at 65 dB SPL from a loudspeaker located 175 cm directly in front of the participant. 500ms after the offset of the word, the four images of consonants were shown in a row on the monitor. The targets and distractors were randomly assigned to the four positions. Following button presses to indicate which consonant or consonants

occurred in any order, images of the correct consonants were shown while the word was repeated. There were 80 training trials in each block for a total of 400 trials across all five blocks.

During a testing phase, participants performed a word-rating task identical to the one used in the implicit-learning study (Moore-Cantwell et al., submitted). They were instructed to rate how well each item fit the rule on a 4 points scale (1 = does not fit the rule, 2 = probably does not fit the rule, 3 = probably fits the rule, 4 = fits the rule well). Testing trials included three types of items: Trained, Novel-Fit, and Novel-Violate. Eight items (one list) from each of these categories were presented once in each block. Match list 2 (Table 1) served as Trained items for one group who learned the Match language, Novel-Fit items for the other group who learned the Match language, and Novel-Violate items for one group who learned the Mismatch language. The same balance was used for Match list 3, Mismatch list 2, and Mismatch list 3. As a result, Trained, Novel-Fit, and Novel-Violate conditions comprised identical items across groups and languages.

Each testing trial began with the word “Ready?” appearing on the computer monitor. When a button was pushed to start the trial, a fixation cross appeared on the screen. 700 - 1200 ms (randomly selected from a rectangular distribution) later, a word was played at 65dB SPL from the same central loudspeaker used in the training blocks. 500 ms after the offset of the word, the screen showed the text “Fit the rule?” Underneath the question the numbers 1-4 were shown from left to right, with 1 labeled “doesn’t fit” and 4 labeled “fits well”. The trial ended after a response was given. There were 24 testing trials in each of 5 blocks (total = 120), providing behavioral and ERP responses on up to 40 trials in each condition (Trained, Novel-Fit, and Novel-Violate).

All words were presented from an M-Audio StudioPro3 loudspeaker by means of a PC running EPrime software. The loudspeaker was located 25 cm above a CRT

computer monitor that displayed visual stimuli and instructions. The display was about 114 cm above the floor at eye-level with participants, who sat in a chair 178 cm away from the monitor (measured from head to screen). Before the start of each session, a participant was given a demonstration of blinking, eye movement, and muscle tension artifacts in EEG and was asked to avoid these artifacts when the fixation cross was shown on the computer monitor. Participants advanced from training to testing immediately within a block. After each block participants took a break and experimenters lowered all electrode impedances below 50 kOhms.

Analysis

Participants were asked to rate Trained, Novel-Fit, Novel-Violate words presented during testing using a 4-point scale (1 = “does not fit the rule” and 4 = “fits the rule well”). Ratings of Trained and Novel-Fit items were compared to index the effects of emphasizing rule-learning over word-learning. The ANOVA included the between-subjects factor Language (Match, Mismatch) as well as the within-subjects factors Word Type (Trained, Novel-Fit) and Block (1-5). Since the results of this analysis suggested there was at least some word-learning that resulted in higher ratings for Trained than Novel-Fit items, we also indexed the amount of word learning by directly comparing ratings of Trained items in the Match and Mismatch languages. As a more direct measure of rule learning, we compared ratings of Novel-Fit and Novel-Violate items. An initial ANOVA with the between-subjects factor Language (Match, Mismatch) and within-subjects factors Word Type (Novel-Fit, Novel-Violate) and Block (1-5) provided information about any differences in rule learning or rate of learning for the voicing-matched and voicing-mismatched languages. A subsequent ANOVA with the factors Language and Word Type was conducted on ratings provided in Block 1 alone to determine if there was sufficient learning in the first training block to include ERPs collected during the first testing block in analysis. The accuracy of the rules stated by

participants at the end of the experiment was also assessed.

During training, participants were asked to indicate the consonants in a word to facilitate learning of the allowable combinations of consonants. As a result, we did not expect participants to learn the trained words to the same extent that was observed when using a word-picture matching task in the implicit phonotactic learning design (Moore-Cantwell et al., submitted). However, to index any incidental word learning, we compared ERPs elicited by words presented during training across the five blocks. Mean amplitude measures were taken on auditory onset components (P1: 40–70 ms and N1: 90–130 ms) as well as in the N400 time window (250–500 ms) relative to word onsets. Mean amplitude measurements were taken in 25 regions of interest, each of which comprised 4 adjacent electrode sites (Figure 1). Data from each of the three measurement time-windows was subjected to an ANOVA with the between-subjects factor Language (Match, Mismatch), the within-subjects factor Block (1-5), and two electrode position factors: Anterior-Central-Posterior (ACP) with five levels (Anterior, Anterior-Central, Central, Posterior-Central, Posterior) and Left-Medial-Right (LMR) with five levels (Left, Left-Medial, Medial, Right-Medial, Right). Mauchly's corrected p-values (to account for violations of the sphericity assumption) and uncorrected degrees-of-freedom are reported. Interactions of Block and electrode-position factors were followed up by ANOVAs conducted on measurements taken at electrode groups where the numerical differences in mean amplitude for the five blocks were largest.

To further index incidental word learning, ERPs elicited by Trained and Novel-Fit items presented during testing were compared. There was not a sufficient number of trials of each word type presented during a single testing block to include Block as a factor in this analysis. Mean amplitude at the 25 regions of interest was measured for auditory onset components (P1: 40-70 ms and N1: 90-130 ms) as well as two N400 time windows (early: 200-400 ms and late: 400-600 ms) relative to word onsets. Data from

each of these four measurement windows was subjected to an ANOVA with the between-subjects factor Language (Match, Mismatch), the within-subjects factor Word Type (Trained, Novel-Fit), and the same electrode position factors: ACP (five levels) and LMR (five levels). Mauchly's correction was applied to p-values for all tests that included factors with more than two levels. Interactions that included Language and Word Type were followed up by separate within-subjects ANOVAs for the Match and Mismatch languages alone. Interactions of Word Type and electrode-position factors were followed up by ANOVAs at regions of interest where the differences in mean amplitude for Trained and Novel-Fit items were largest.

To index the effects of explicit learning and any implicit phonotactic learning, ERPs elicited by Novel-Fit and Novel-Violate items presented during testing were compared. Mean amplitude at the 25 regions of interest was measured for auditory onset components (P1: 40-70 ms and N1: 90-130 ms), two N400 time windows (early: 200-400 ms and late: 400-600 ms), and two overlapping Late Positive Component (LPC) windows (early: 600-1000 ms and late: 800-1200 ms) relative to word onsets. These time windows were selected both to best capture any differences in ERPs elicited by Novel-Fit and Novel-Violate items and to facilitate comparison with the previous implicit learning study (Moore-Cantwell et al., submitted). Data from each of these six measurements windows were subjected to an ANOVA with the between-subjects factor Language (Match, Mismatch), the within-subjects factor Word Type (Novel-Fit, Novel-Violate), and the same electrode position factors: ACP (five levels) and LMR (five levels). Mauchly's correction was applied to p-values for all tests that included factors with more than two levels. Interactions that included Language and Word Type were followed up by separate within-subjects ANOVAs for the Match and Mismatch languages alone. Interactions of Word Type and electrode-position factors were followed up by ANOVAs at regions of interest where the differences in mean amplitude for Novel-Fit

and Novel-Violate items were largest. To provide the strongest possible test of the LPC effects that were evident for Novel-Violate compared to Novel-Fit items following implicit phonotactic learning (Moore-Cantwell et al., submitted), ANOVAs were conducted on measurements taken in LPC windows over posterior regions for the Match and Mismatch languages alone, despite the lack of significant Language by Word Type by electrode position interactions.

The analyses of ERP data described above and to be included in results are on measurements made in time windows relative to the onsets of words. However, the information needed to determine if the consonants in a word match or mismatch in voicing is not available until the second consonant is presented. Therefore, we also selected time windows relative to the onset of second syllables that best captured differences between conditions. Further, we considered the possibilities that differences in ERPs elicited by Novel-Fit and Novel-Violate items might be evident only after explicit learning of the complete rule governing which consonants could co-occur, and that learning of this rule might occur at different rates for different participants. First, we defined having acquired the full rule as the first testing block on which a participant rated Novel-Fit items at least 2 points higher than Novel-Violate items (on the 4-point scale). Then, we excluded data measured in previous testing blocks (individuals differed in the number of excluded blocks) from ERP averages, and repeated the measurements and statistical analyses described above. Although there were significant differences between conditions for ERPs time locked to the onset of second syllables, and for ERPs that excluded trials in blocks before learning of the rule was demonstrated in ratings, those effects tended to be less consistent and smaller in magnitude. Therefore, the ERP results reported below are for data time locked to word onsets across all testing blocks.

CHAPTER 3

RESULTS

Behavioral responses

Across Language, participants rated Trained ($M = 3.87$, $SD = 0.24$) words as more likely to fit the rule than Novel-Fit words ($M = 3.60$, $SD = 0.50$) ($F(1,25) = 37.22$, $p < 0.0001$). Further, as shown in Figure 2, Trained items received higher ratings from those who heard the Match ($M = 3.92$, $SD = 0.18$) compared to Mismatch ($M = 3.81$, $SD = 0.276$) language ($F(1,25) = 4.74$, $p = 0.04$) suggesting more incidental word learning took place with the Match language. Although there were differences in ratings for Trained and Novel-Fit items in the current study, they were much smaller than those observed when word learning was emphasized (Trained: $M = 3.72$, $SD = 0.18$; Novel-Fit: $M = 2.71$, $SD = 0.29$) (Moore-Cantwell et al., submitted). The difference in ratings from Trained and Novel-Fit items got smaller across block ($F(1,25) = 15.80$, $p = 0.0005$), driven by larger increases for Novel-Fit compared to Trained items which were close to ceiling.

Novel-Fit items ($M = 3.60$, $SD = 0.50$) were rated far higher than Novel-Violate items ($M = 1.61$, $SD = 0.62$) ($F(1,25) = 466.73$, $p < 0.0001$) consistent with participants having learned the rule. This difference was much larger than the one observed under implicit learning conditions (Novel-Fit: $M = 2.71$, $SD = 0.29$; Novel-Violate: $M = 2.21$, $SD = 0.26$) (Moore-Cantwell et al., submitted). Further, as shown in Figure 3 and unlike what was observed with implicit learning, the difference in ratings of Novel-Fit and Novel-Violate items was larger for the Match than Mismatch language ($F(1,25) = 5.62$, $p = 0.026$). This pattern suggests that the voicing-match pattern was easier to learn than the voicing-mismatch pattern under explicit learning conditions. Across languages, the difference in ratings for Novel-Fit and Novel-Violate items grew across blocks ($F(1,25) = 37.86$, $p < 0.0001$), both because ratings for Novel-Fit got higher and because ratings for

Novel-Violate got lower. Importantly, even in the first testing block ratings of Novel-Fit and Novel-Violate items differed ($F(1,25) = 39.73, p < 0.0001$), indicating that sufficient learning had taken place in the first training block to include ERPs from this block in analysis.

Experimenters also recorded participants' verbalization of the rule they learned. Among the participants who reached the rating criteria, all 14 who heard the Match language and 9 who heard the Mismatch language reported all of the allowable consonant pairs by the end of the experiment. For example, one participant trained on the Mismatch language described the rule as "T & D, K & G, D & K, and T & G can go together in each word while T & K, D & G, and double consonants cannot go together." Three of the participants trained on the Mismatch language accurately described part of the rule but left out one or more allowable or disallowed combination. For example, one participant stated "K & D and G & T go together, but never T & K." One participant trained on the Mismatch language who rated Novel-Fit items a full point higher than Novel-Violate items nonetheless added, after reporting some accurate combinations, that "both T & K go with everything." More accurate reporting of allowable and disallowed consonant pairs among those who heard the Match language provides additional evidence that explicit learning favored this pattern over the more difficult one in the Mismatch language.

Event-related potentials

There were not differences in auditory evoked potentials (P1 and N1) elicited by words presented during training. Block by electrode position interactions suggested that words presented during training elicited an N400 (250-500 ms) that decreased in amplitude across blocks at some locations (Block x ACP: $F(16,400) = 1.80, p = 0.03$; Block x LMR: $F(64,1600) = 1.48, p = 0.008$). However, even over Anterior and Anterior-Central regions where the differences were largest, the main effect of Block ($p = 0.06$)

did not reach significance. Even though ratings provided during testing suggested more word learning occurred for the Match compared to Mismatch language, no Language effects on ERPs were evident during training.

To index word learning, ERPs elicited by Trained and Novel-Fit items presented during testing were compared. These Word Types showed no effect on mean amplitude during the auditory onset components (P1 and N1). In the early N400 time window (200-400 ms) there was some indication of a difference in mean amplitude for Trained and Novel-Fit items (Word Type x LMR: $F(4,100) = 3.30, p = 0.01$; Word Type x ACP x LMR: $F(16,100) = 3.62, p < 0.0001$). However, the main effect of Word Type failed to reach significance even at the locations where the mean amplitude differences were largest ($p = 0.06$). The difference in response to Trained and Novel-Fit items was better captured in the late N400 time window (400-600 ms) (Word Type x ACP: $F(4,100) = 4.12, p = 0.004$; Word Type x LMR: ($F(4,100) = 3.82, p = 0.006$; Word Type x ACP x LMR: $F(16,400) = 5.48, p < 0.0001$). Over anterior and medial regions (Anterior/Anterior-Central and Left-Medial/Medial/ Right-Medial) the Word Type effect differed by Language ($F(1,25) = 4.30, p = 0.048$). Specifically, as shown in Figure 4, for the Match language Trained items elicited a smaller negativity than Novel-Fit items over these regions ($F(1,13) = 8.10, p = 0.014$). In contrast, no differences in response to Trained and Novel-Fit items were evidence for the Mismatch language ($p = 0.35$). The reduced N400 in response to trained words for the Match language only is consistent with greater incidental word learning.

To index rule learning, ERPs elicited by Novel-Fit and Novel-Violate items presented during testing were compared. There were no differences in P1 or N1 amplitude for these Word Types. However, in the early N400 time window (200-400 ms), there was evidence that the Word Type effect differed for the two languages (Language x Word Type x ACP: $F(4,100) = 5.04, p = 0.001$). For the Mismatch language alone

(Figure 5), Novel-Violate items elicited a larger negativity than Novel-Fit items across Anterior and Anterior-Central regions ($F(1,12) = 8.01, p = 0.02$). There was no such Word Type effect for the Match language ($p = 0.32$). Similarly, in the later N400 time window (400-600 ms), there were interactions of Language and Word Type with electrode position factors (Language x Word Type x ACP: $F(4,100) = 2.89, p = 0.03$; Language x Word Type x LMR: $F(4,100) = 2.47, p = 0.049$). However, even for the Mismatch language at the locations where the effect was largest (Anterior/Anterior-Central and Left-Medial/Medial/Right-Medial) the difference for Novel-Fit and Novel-Violate did not quite reach significance ($p = 0.06$) indicating the effect was better captured in the previous time window. The larger negativity 200-400 ms after onset in response to novel words that violated the voicing-mismatch rule is an effect of explicit learning that is entirely distinct from the ERP effects of implicit learning.

In the implicit learning study (Moore-Cantwell et al., submitted) Novel-Violate items elicited a larger Late Positive Component (LPC) compared to Novel-Fit items. To determine if a similar index of implicit learning was evident under explicit learning conditions, we compared responses to these item types (Figure 6) in two late time windows (600-1000 and 800-1200 ms). There was no evidence of a Word Type effect 600-1000 ms after word onset. However, in the later LPC time window (800-1200 ms) there was a marginal Word Type interaction with electrode position (Word Type x ACP: $F(4,100) = 2.04, p = 0.095$). To avoid dismissing potential differences between conditions that did not reach statistical significance, we measured the effects of rule learning where the differences in mean amplitude were largest. For the Match language alone at Central-Posterior and Medial sites, Novel-Violate items elicited a numerically larger positivity than Novel-Fit items ($F(1,13) = 3.41, p = 0.088$). There was no evidence of a similar effect for the Mismatch language.

CHAPTER 4

DISCUSSION

In this study, participants successfully engaged in explicit learning of a novel phonotactic pattern. When asked to rate how much testing items fit with the learned rule, participants rated trained items slightly higher than novel items that fit the pattern. There was a large difference in ratings for novel items that fit and violated the pattern, with the difference in ratings larger for participants who heard the language in which voicing of the consonants always matched. This pattern of results indicates that participants learned the rule to a greater extent than was observed under implicit learning conditions. Further, the data show that explicit learning of the voicing-match pattern was more successful than learning of the voicing-mismatch pattern. These differences in performance are interpreted as reflecting greater difficulty in learning the voicing-mismatch pattern. Further, ERP results indicated that less word learning occurred when participants were trying to explicitly learn the phonotactic pattern. The differences in N400 amplitude across blocks were smaller than those observed under implicit learning conditions. Further, differences in N400 amplitude for trained and novel items that fit the pattern were limited to the more easily learned match-voicing pattern. Finally, across languages there was no evidence of the LPC that was observed under implicit learning conditions. The only indication of an LPC-like effect was marginal and observed only for the more easily learned matched-voicing language. A lack of LPC is suggestive of a lack of implicit learning, but could be interpreted as a failure to use implicitly gained knowledge when explicit knowledge is available. The indication of an LPC-like effect for the more easily learned language indicates it is possible to observe effects of implicit learning with the current paradigm. That pattern lends to a stronger interpretation of the complete lack of an LPC for the explicitly learned voicing-mismatch language. As a whole, this pattern of results supports the hypothesis that difficult explicit learning of

patterns that are typically learned implicitly can interfere with that implicit learning. As such, the explicit second-language learning that adults engage in could, in some cases, be responsible for lower ultimate proficiency.

The larger differences in ratings for items that do and do not fit the pattern under explicit learning conditions compared to the previously reported implicit learning conditions (Moore-Cantwell et al., submitted) is consistent with the finding that initial acquisition proceeds more quickly with explicit learning (Krashen et al., 1979; Miralpeix, 2006; Slavoff & Johnson, 1995). Further, there were differences in learning for the two patterns that were not observed with implicit learning. The differences in language effects under implicit and explicit learning conditions are likely driven by different things being learned. Typical listeners lack explicit knowledge of phonological features. However, listeners do have implicit knowledge of phonological features in their native language (Saffran & Thiessen, 2003). As such, implicit learning of a rule based on phonological features is possible, with no differences in difficulty for learning “voicing must match” and “voicing cannot match.” Even though participants were successful at learning patterns of sounds that can go together in words through explicit learning, they did not report using phonological features to do so. To the extent that the voicing-match and voicing-mismatch patterns were learned without reference to phonological features and instead as arbitrary patterns of which consonants could go together, the mismatch pattern is more complex. In the voicing-mismatch language, people had to learn that /t/ can only co-occur with /d/ or /g/, /k/ can only co-occur with /d/ or /g/, /d/ can only co-occur with /t/ or /k/, and /g/ can only co-occur with /t/ or /k/. The result of this difficulty was a higher rate of incomplete rule verbalizations in this condition such as “T & D, K & G, D & K, and T & G can go together in each word while T & K, D & G, and double consonants cannot go together” as well as incorrect verbalizations such as “K & D and G & T go together, but never T & K.” In contrast, for the voicing-match pattern, people only

had to learn that /d/ could go with /d/ or /g/, etc. This resulted in no incomplete or incorrect verbalizations. The pattern of behavioral results strongly indicates that the ratings given in the current study were based on explicit learning, with the mismatch pattern being more difficult.

Explicit learning of the phonotactic pattern along with differences in the training task resulted in less word learning. Specifically, the differences in ratings of trained and novel items that fit the pattern were far smaller in the current experiment compared to the previous implicit learning study (Moore-Cantwell et al., submitted). The finding that trained words were rated slightly higher for the voicing-match language further suggests this pattern was easier to explicitly learn, leaving additional resources for word learning during training. However, even for the voicing-match language, the large word-learning effects observed under implicit learning conditions were absent. Further evidence of different amounts of word learning for the two languages, an effect that was absent with implicit learning, is found in there only be differences in ERPs elicited by trained and novel-items that fit the pattern for the voicing-match language. It is not clear from the current study whether the lack of the word-picture matching task employed to encourage implicit learning or the explicit learning itself limited word learning. However, the fact that more word learning was evident for the matched-voicing compared to mismatched-voicing language suggests difficulty of explicit pattern learning impedes word learning.

As described in the introduction, under implicit learning conditions of natural or artificial languages, sound sequences that violate an implicitly learned phonotactic pattern elicit an LPC (Moore- Cantwell et al., submitted; Domahs et al., 2009). In the current study, the LPC in response to phonotactic violations was completely absent (for mismatch-voicing) or greatly reduced (matched-voicing). Further, an ERP effect that was not observed under implicit learning conditions was evident, a larger negativity 200-400 ms after onset for items that violated the pattern. In and of itself, this pattern is indicative

of participants drawing on different sources of information during the rating task. However, it is possible that implicit learning of the pattern happened under explicit learning conditions. In that case, the lack of LPC would be interpreted as listeners not accessing implicit knowledge when, perhaps more readily available, explicit knowledge was available. The comparison of ERP effects for the voicing-match and voicing-mismatch language suggest this is not the case. That is, there is ample evidence that explicitly learning the voicing-mismatch pattern was more difficult. As such, if listeners had implicit knowledge they could rely on, they would be expected to do so more when explicit knowledge was harder to come by. The opposite was true. The pattern of ERP data suggests listeners engaged in more implicit learning for the easier voicing-match language. This pattern of results indicates that the current paradigm can index use of implicit knowledge during the rating task. Further it suggests that listeners had more implicit knowledge that they could draw on when presented with the easier task of explicitly learning the voicing-match pattern.

The finding that learning conditions affect not only performance, but how information is represented in the brain is consistent with previous research on syntactic language learning. Participants learned an artificial language including new words and the order they needed to go in for correct sentence structure (Morgan-Short et al., 2012a). Some participants were exposed to correct sentence structure through immersion with the language. Others were put in a more classroom-like situation to learn the language. Immersion was designed to promote implicit learning through many examples of correct structure. Classroom-like teaching was designed to promote explicit learning of word-order rules. In a testing phase, participants listened to sentences with the same words that either fit or violated the language's sentence structure. For participants who achieved high proficiency, those who learned under implicit learning conditions evidenced ERPs in response to word order violations that were more similar

to those of native speakers listening to real language syntactic violations. This same pattern of results was found after 3-6 months of delay and retraining that was greatly decreased from the initial training (Morgan-Short et al., 2012b). In fact, those who initially learned the language under implicit conditions showed ERP effects that looked even more native-like after the delay. The authors concluded that, even in adults, immersion in a language environment results in implicit learning and native-like representations of language patterns. The current results compared to previous ones under implicit learning conditions (Moore-Cantwell et al., submitted) support a similar conclusion for phonotactic patterns; implicit learning results in representations that are more similar to those in native speakers (Domahs et al., 2009).

This study serves to add to the existing literature discussing the nature of implicit and explicit learning in language and how these systems interact. Our results are in contrast to those suggesting implicit and explicit learning systems are entirely independent (Paradis, 1994). The finding that explicit learning affected implicit learning is consistent with previous studies that showed at least some interaction between implicit and explicit learning of second language syntax (N. Ellis, 2008; Pienemann, 1989; Suzuki & DeKeyser, 2017; R. Ellis, 2009 for review). However, in those previous studies explicit learning was shown to facilitate rather than impede implicit learning. We propose two possible explanations for the different directions of interactions between explicit and implicit learning. First, syntax may be different from phonotactics. For example, native speakers of a language typically have at least some explicit knowledge of syntax, but not of phonotactics. Second, explicit learning may support implicit learning when the explicit and implicit rules are identical, as they would be for syntax. However, the phonotactic patterns that were learned in the current study and under implicit learning conditions (Moore-Cantwell et al., submitted) were not identical. Specifically, the lack of language effects for implicit learning suggests listeners learned rules based on phonological

features. Those rules were equal in complexity for the voicing-match and voicing-mismatch patterns. In contrast, the differences in performance and ERPs for the two languages under explicit learning conditions suggest listeners learned combinations of letters that could co-occur in words instead of anything about voicing. Potentially, when the rule that is learned explicitly is non-identical to what listeners would learn implicitly, the antagonistic relationship between the two learning systems is revealed.

Our results might be interpreted as supporting making second language learning environments more like first language learning environments even for adults. That is, by avoiding explicit learning that might get in the way of implicit learning from immersion environments, adult second-language learners might reach more native-like proficiency. However, recent data shows that immersion-only second language acquisition in adults has disappointing outcomes. A review of implicit and explicit language learning generally suggests that a mix of implicit and explicit learning produces better results in adults (N. Ellis, 2008). The results from this study serve as a reminder that some aspects of language, specifically phonotactics, are best learned solely under implicit conditions. Unlike second language acquisition studies focusing on morpho-syntax, increasing the amount of explicit learning reduced the use of implicit learning. Further research is needed to determine the full range of language patterns that are best acquired with an exclusively implicit learning approach. Additionally, longitudinal studies are required to observe the longer-term results of interactions between implicit and explicit learning of phonotactics.

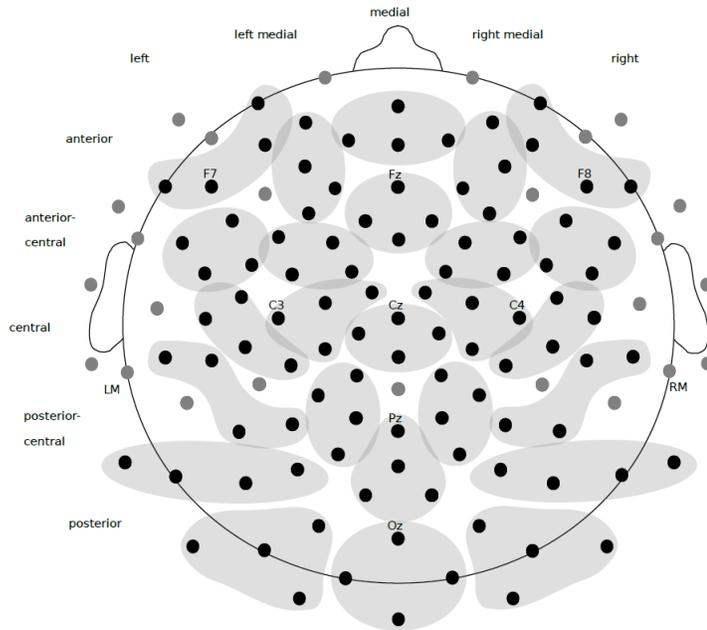


Figure 1: Electrode Array. The approximate location of 100 electrodes that contributed data included in analysis. Data were averaged across 4 adjacent electrodes. Electrode position was included as two five-level factors in ANOVAs. Data from the additional 28 electrodes (gray dots) were used in artifact rejection, but not in analysis.

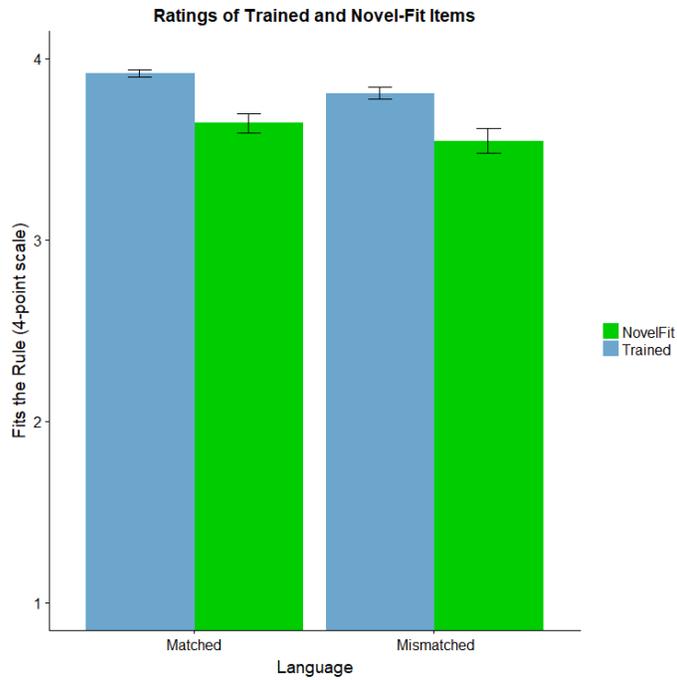


Figure 2: Ratings of Trained and Novel-Fit items. Participants were asked to rate each item based on how well it fit the rule (1 = does not fit, 4 = fits the rule well). Average ratings with standard error bars are shown.

Ratings of Novel-Fit and Novel-Violate Items Over Blocks

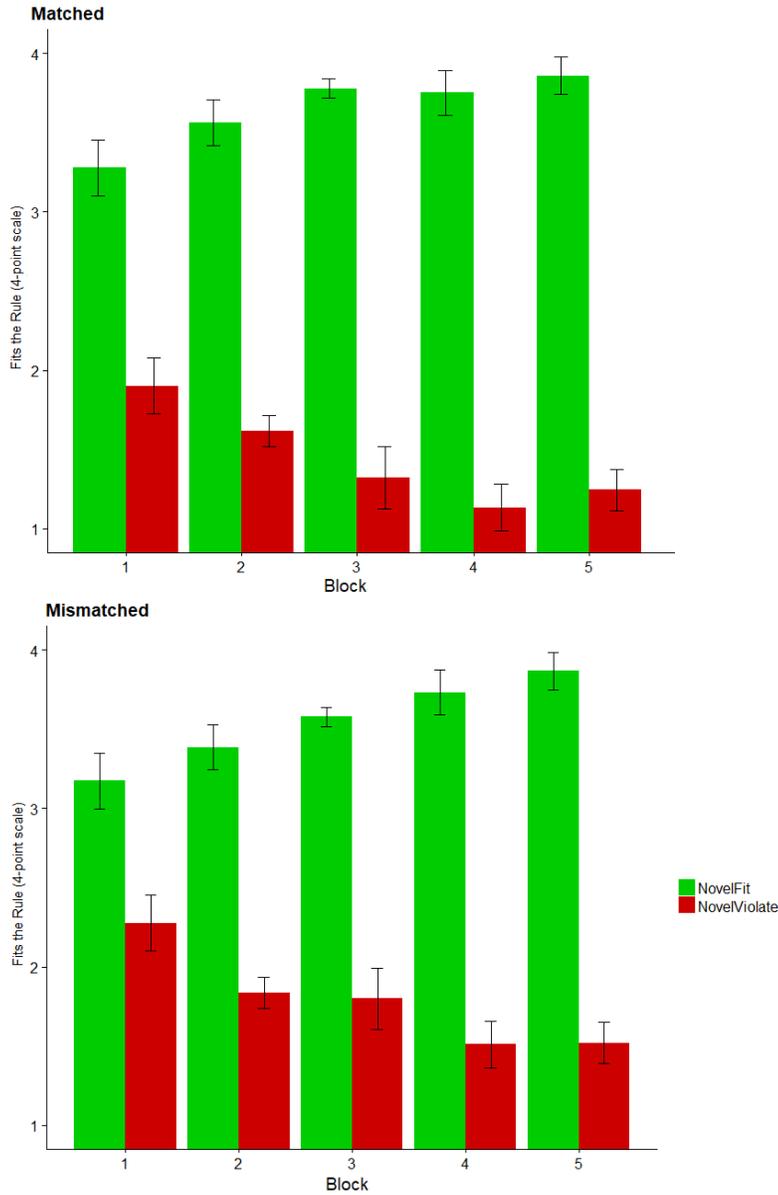


Figure 3: Ratings of Novel-Fit and Novel-Violate items by block. Performance on the Match language is shown on top and Mismatch language on bottom. Participants were asked to rate each item based on how well it fit the rule (1 = does not fit, 4 = fits the rule well). Average ratings with standard error bars are shown.

Training Effects - Matched Language

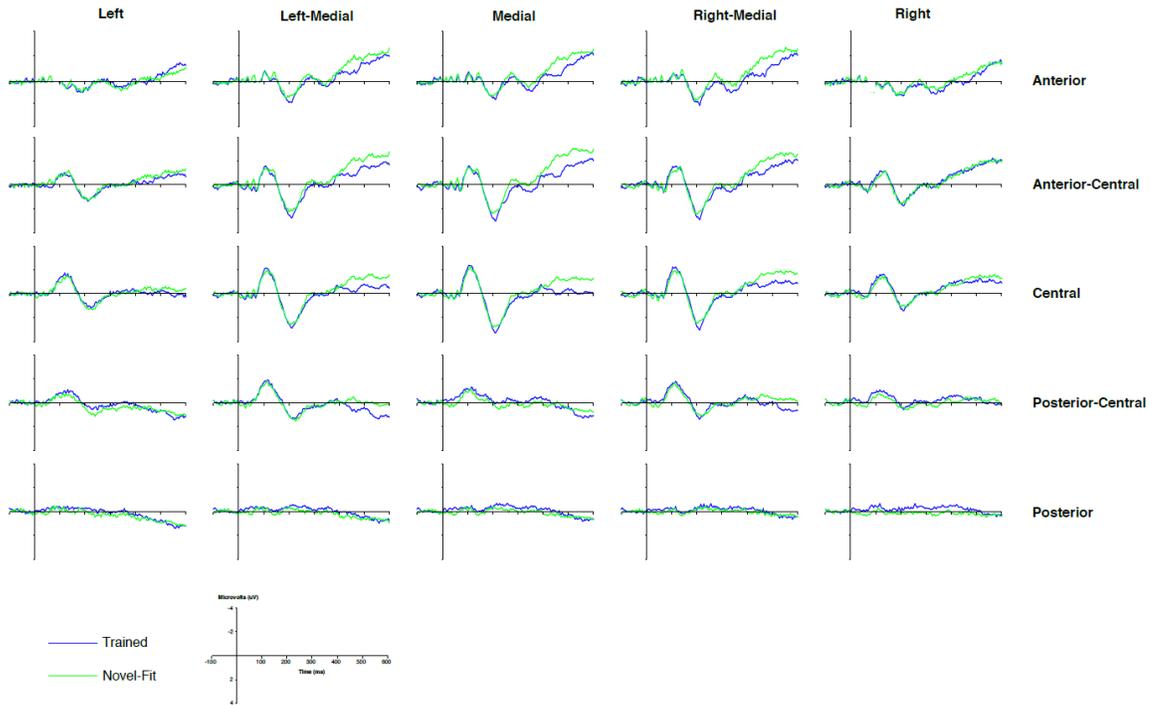


Figure 4: ERPs elicited by Trained and Novel-Fit items in Matched language. Each axis shows data averaged across four electrodes and corresponding to the scalp positions shown in Figure 1. Trained items showed a reduced negativity 200-400 ms after onset in comparison to novel items that fit the rule.

Phonotactic Violation Effects - Mismatched Language

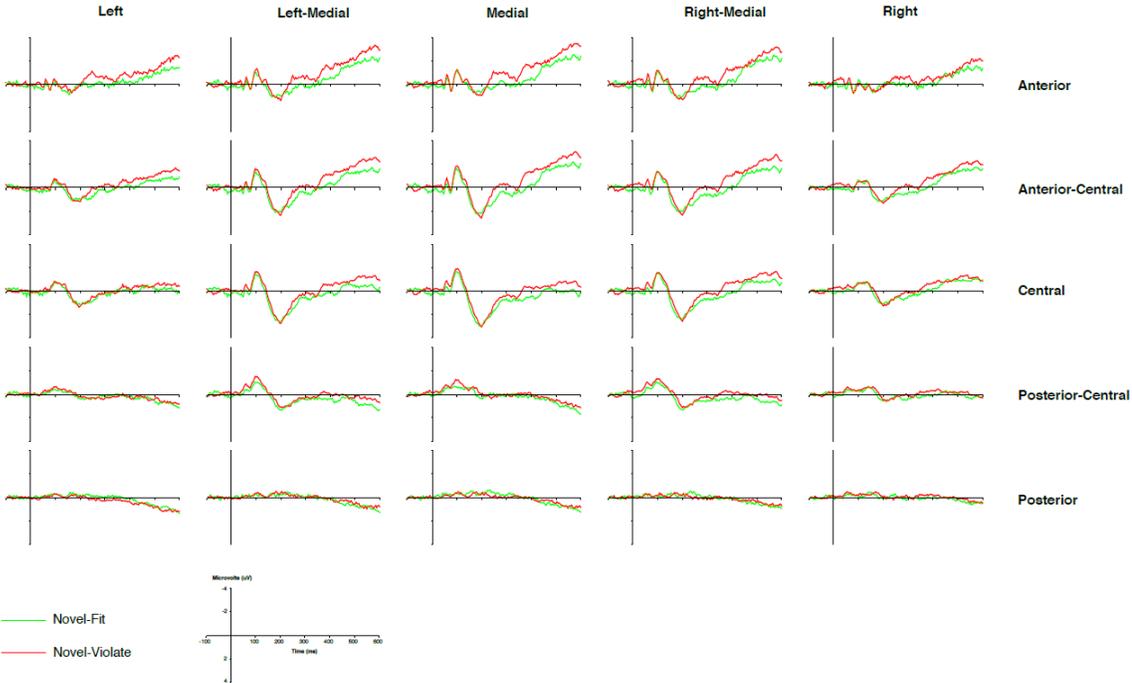
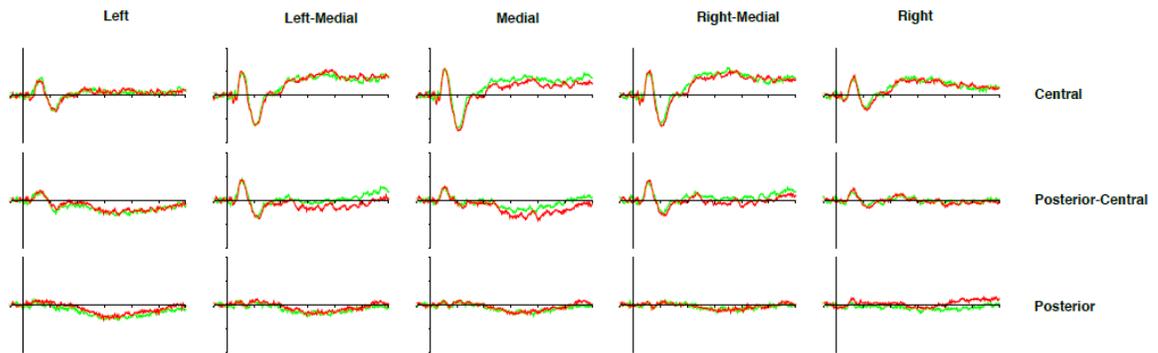


Figure 5: ERPs elicited by Novel items in Mismatched language. Each axis shows data averaged across four electrodes and corresponding to the scalp positions shown in Figure 1. Novel items that violated the pattern elicited a larger negativity 200-400 ms after onset in comparison to novel items that fit the rule.

Late Phonotactic Violation Effects - Matched Language



Late Phonotactic Violation Effects - Mismatched Language

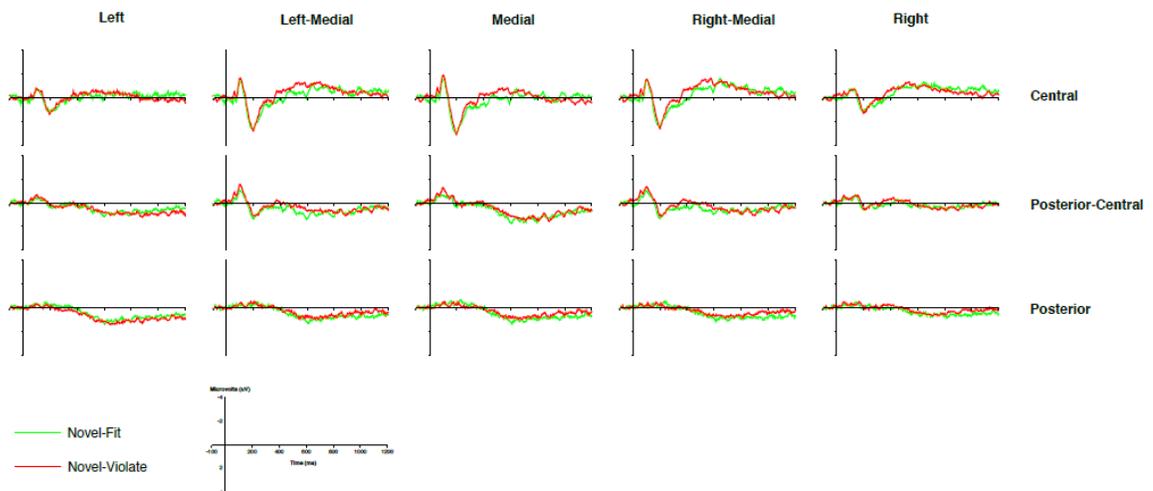


Figure 6: ERPs elicited by Novel items by language in LPC time window. ERPs are measured through the full 1200 ms post-stimulus onset over central and posterior regions. Under implicit learning conditions, novel items that violated the pattern elicited a larger LPC at these locations. The only hint of an LPC under explicit learning conditions was seen for the Match language at a single electrode group (Posterior-Central and Medial).

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