Neural Underpinnings of Phonotactic Rule Learning

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1 Introduction

Artificial grammar learning (AGL) studies have shown that learners can extract adjacent and non-adjacent phonotactic patterns with relatively short training in laboratory settings (see Moreton & Pater (2012a; 2012b) and Folia et al., (2010) for a review). This has been shown via behavioral measures such as reaction time, mean rating, accuracy, and d-prime: these behavioral measures show that learners can generalize from training stimuli. However, less is known about how the learned generalizations are encoded at the neurophysiological level.

Pattern extraction, whether in the laboratory or as part of human language acquisition, is essentially “implicit” learning, i.e. learning that does not come with conscious awareness of the rules. If a rule has been acquired, this means that the phonological parser has incorporated the rule into the mental grammar, which means that the rule should be observable as part of real-time parsing mechanisms. Specifically, we expect that laboratory-induced learning of phonotactic rules should be reflected in real-time predictions during incremental word parsing. In terms of neurophysiology, this means that an abstract rule should translate into neurally observable prediction mechanisms, as in Kuhl’s Native Language Neural Commitment (NLNC) Hypothesis (Kuhl et al. 2008). Kuhl argues for typical first language development that language exposure produces neural commitment that affects future learning. Initial exposure to a linguistic stimulus causes physical changes in neural tissue, which in turn reflect properties of the language input. This means that if a rule is learned after exposure to repeated stimuli, this learning should lead to an instant, measurable "tuning" of the perceptual system. Having learned the rule means that the brain comes to expect certain patterns in the input, and violations of the pattern should result in an expectation violation response. In other words, acquired rules should lead to neurophysiological reflexes in response to violations of those rules. What is less certain is whether such neurophysiological responses will only be detectable after years of “neural commitment” during natural language acquisition and development, or whether they also can be observed after very brief laboratory-based learning situations in adults.

We aimed to test this in the current study. Using Event-Related Potentials (ERPs), we looked for neurophysiological correlates of implicit learning of a phonotactic rule. ERPs are recorded using electroencephalography (EEG), a procedure that measures the electrical activity of the brain over time using electrodes placed on the scalp, which reflects underlying cognitive processes. We specifically measured how the brain responds to the violation of a non-adjacent phonotactic pattern. We constructed a controlled set of stimuli that follows a very simple grammar consisting of a sibilant harmony rule which prohibits words containing both [s] and [ʃ]. After a brief training session, participants were asked to categorize each stimulus according to the grammar they learned while their brain waves were being measured.

The results show that participants learned the simple rule at the behavioral level (as measured with d-prime, a sensitivity measure to rule violations). This rule learning is also reflected in the brain response to violations of the rule, which is indexed by the P3 rare-minus-frequent difference waveform. We discuss the implications of these results and conclude that brief sessions of laboratory learning of phonotactic rules result in a neural commitment which is reflected in the brain response.

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2 Background

Processing of phonological violations has been shown to elicit different kinds of electrophysiological responses including MMN, P3, and LPC. Aaltonen et al., (2008) reported mismatch negativity (MMN) in response to native language violations of non-adjacent phonological constraints. The study tested whether the linguistic difference between two languages (Finnish and Estonian) is reflected in the brain responses of native speakers of these languages. The results show that violations of a language-specific rule are automatically detected by the brain, indexed by the MMN response. The MMN is a negative-going potential peaking at fronto-central electrode sites at early latencies (usually at 150–250 ms from the onset of the sound). It is an ERP component which reflects an automatic auditory change-detection response originating in the auditory cortex (Alho 1995; Näätänen et al. 2007).

However, there is a rich literature demonstrating that the MMN is a limited perceptual response which uses the recent past to predict the present and is blind to higher order global rule violations (Bekinschtein et al. 2009; Wacongne et al. 2011; Chennu et al. 2013; Basirat, Dehaene, and Dehaene-Lambertz 2014; Tse et al. 2012). Using a hierarchical "local-global" paradigm, it has been shown that novelty detection in auditory stimulation includes two different neural components: (i) the MMN reflecting an unconscious pre-attentive response and (ii) the P3 indexing conscious access to working memory updates. Local violations of transition probabilities elicit an MMN while higher order regularities (global rules or non-local patterns) which solely reflect the deviance of the overall sequence rather than of its individual components are captured by the P3 (specifically P3b, which is a task-relevant potential elicited during target stimulus processing (Polich 2007)), a positive-going wave peaking at around 300 ms. P3 latency – the time from the onset of the stimulus to the point of maximum positive amplitude – reflects stimulus evaluation. The latency of the P3 encompasses the perception and categorization of the stimulus (for more information about P3-like responses, see Polich (2007)).

McLaughlin et al., (2010) tested L2 learners' processing of phonological violations (Finnish vowel harmony) and found a late positivity component (LPC), a positive-going potential beginning about 600 ms after the onset of the grammatical violation. According to Núñez-Peña & Honrubia-Serrano (2004), the LPC can be taken as "an index of detection for any anomaly in rule-governed sequences". The LPC can also be elicited in response to a range of syntactic violations (Gouvea et al. 2010). A similar late positivity has also been observed for phonological violations such as a long-distance restriction on the place of consonants in sCVC words in German by Domahs et al., (2009). Similarly, Moore-Cantwell et al., (forthcoming) also observed an LPC to violations of lab-learned phonotactic rules. Using an artificial grammar learning design, this study showed that novel words violating a phonotactic constraint elicited a larger LPC than novel words that satisfied it. It has been demonstrated that native English speakers who were trained in laboratory settings on a non-adjacent voicing agreement rule ([dugi] and [kuti]) showed an LPC in response to violations of this rule (*[todu] and [*kigo]).

The particular brain response elicited in an ERP study depends on several factors, such as the design features of the experiment (attentive or unattentive), the nature of the stimuli (linguistic or non-linguistic), and even the complexity of the pattern or rules (local or higher order). Our aim in this study is to correlate a phonotactic pattern violation with the P3 response. The current experiment was designed to use the P3 wave to determine whether the categorization of grammatical vs ungrammatical words (according to a lab-learned artificial grammar) is indexed by this ERP component within a specified time window. We used the oddball paradigm (presentation of consecutive standard stimulus before the occurrence of the deviant stimulus) and difference waves to isolate the cognitive processes related to deviance detection. Our participants were asked to categorize words following the pattern (frequent) and words violating it (rare). If the amplitude (µV) of the rare-minus-frequent difference wave is different from zero, it can be concluded that the process before and during the categorization is different for grammatical words compared to ungrammatical words.

3 Materials and methods

3.1 *Participants* A total of 28 University of Delaware students were recruited as participants and provided written consent for participation in the experiment. 4 participants were eliminated due to exceptionally noisy EEG data, yielding a final sample of 24 participants. Each subject received course credit for participation. 22 of the 24 participants were female (this imbalance arises from the fact that the population we sampled from was overrepresented with women). One participant was left-handed, but we did not exclude left-handers, as most left-handed people have left-lateralized language function (Szaflarski et al. 2011). The mean age was 19.87 (*SD = 1.68, range = 18 to 24*). None of the participants reported a history of hearing loss or speech/language impairments, and all reported speaking English as their first and only language.

3.2 *Stimuli* We chose a simple Sibilant Harmony rule as the phonotactic pattern to be learned by our participants. Sibilant Harmony requires sibilants in a well-formed word to agree in anteriority (/s/ or /ʃ/). This pattern is rare but is attested in Navajo (Sapir and Hoijer 1967). The stimuli used in this study were adapted from Lai (2015). All training and test stimuli consisted of two syllables of the form CV.CV, with sibilants ([s, ʃ]) as the first and second consonants. The vowels in the alphabet of the language were [a, ɛ, ɔ, i, u]. One hundred words were constructed with half agreeing in sibilant anteriority (e.g. [saso], [ʃeʃi]), and the other half disagreeing (e.g. [saʃi], [ʃeso]). Of the 50 words that had an agreement, 20 appeared only in the training session. The other 30 were used in the test phase as novel-fit items (together with 20 trained words). Table 1 below summarizes the types of training and test stimuli used.

Sibilant Tier	Grammatical	Ungrammatical
[s.s]	[sasi] or [suse]	None
[ʃ.ʃ]	[ʃeʃu] or [ʃoʃi]	None
[s.ʃ]	None	[saʃi] or [suʃe]
[ʃ.s]	None	[ʃesu] or [ʃosi]

Table 1. Sample grammatical and ungrammatical stimuli used in both training and test phases

The stimuli were originally recorded in CV.CV.CVC format from a native speaker of Mandarin Chinese with phonetic training. In order to exclude potential artifacts due to phonetic differences between stimuli, we modified the stimuli and constructed CV.CV words. The third syllable (minus the coda) was segmented from each word using the offset/onset of noise for the surrounding vowel and sibilant as a criterion. This left us with a set of CV syllables with a sibilant onset. We then applied a 10 ms sinusoidal fade-in and fade-out to the beginning and end of each recording to eliminate the effects of trimmed formants. Next, we recombined these CV syllables to form two-syllable CV.CV words As a final step, the peak amplitude of all items was normalized to their mean. As a result, the duration of each phoneme was strictly controlled at 100 ms, making each word 400 ms long, the second syllable beginning at 200 ms.

3.3 *Apparatus and procedure* The experiment was programmed with E-Prime Professional software v. 2.0.10.356, running on a Dell desktop PC. The experiment was conducted inside a single-walled electrically-shielded sound booth in the Experimental Psycholinguistics Lab at the University of Delaware. The presentation of sound stimuli was executed with two free field speakers placed in front of the participants at a comfortable listening volume, and visual input was delivered through an LCD display placed on a table in front of the participants. A PST Serial Response box was used for recording behavioral responses.

The procedure for the experiment consisted of two phases: a training phase and a testing phase. During the training phase, participants listened to 200 tokens (20 grammatical words repeated ten times) and were instructed to repeat each word orally after they heard it. The training lasted approximately 15 minutes. In the testing phase, the task for the participant was to press a button in response to each stimulus to categorize the stimulus as grammatical or ungrammatical, according to the rule they had learned in the training phase. Participants responded with the left hand for grammatical words and with the right hand for ungrammatical words. Participants were tested in an auditory oddball paradigm in which a deviant (ungrammatical) stimulus appeared infrequently among repeated occurrences of a standard (grammatical) stimulus. Participants discriminated between grammatical and ungrammatical words, with grammatical words appearing in 83% of trials (250 words) and ungrammatical words appearing in 17% of trials (50 words), with 300 total trials. The stimuli were delivered continuously, with a random number (between 3 and 7) of standards between each deviant. Each word was presented for 400 ms followed by a blank inter-trial interval of 1100 to 1500 ms. The duration of the test session was approximately 10 minutes. No explicit feedback was given to the participants during the test phase. All participants easily understood the instructions.

3.4 *Behavioral data recording and analysis* In the test phase, button presses made by participants in response to deviant stimuli (ungrammatical words) were recorded. Hits (when an ungrammatical word was present, and the participant detected it and reported hearing it) and false alarms (when a grammatical word was present, but the participant reported hearing an ungrammatical word) were counted. The sensitivity index *d'* was then derived from the hit and false alarm rates according to signal detection theory (Macmillan and Creelman 2004). The sensitivity index was calculated as $d'=Z(Phits)-Z(Pfalsealarms)$, where *P* hits is the hit rate, *P* false alarms is the false alarm rate and *Z* is the z-score for that particular probability. When participants cannot discriminate at all, hits would be equal to false alarms, which would give a $d' = 0$. Results higher than zero show that sensitivity is better than chance level. In the context of our study, positive *d'* means the rule was learned (in the sense that there is at least some sensitivity to ill-formed words). *d'* was compared to zero – which would indicate no learning – by using one sample t-test. Mean accuracy (ACC) and reaction times (RT) were also analyzed using paired samples t-tests comparing grammatical vs ungrammatical words.

3.5 *Electrophysiological data recording and analysis* Electrophysiological data was recorded continuously with 24-bit digitization at 250 Hz from 128 carbon fiber core/silver-coated electrodes in an elastic electrode net (Geodesic Hydrocel 128). The acquisition and digitization of the data were performed with EGI Net Station software v.4.5. Electrode impedances were lowered to below 50 kΩ before data collection. Each electrode was referenced to Cz. After recording, the continuous EEG was passed through a 0.1-40 Hz bandpass filter. The continuous EEG data was then segmented into epochs of 1200 ms for stimulus-locked averages and 1500 ms for response-locked averages. The baseline period was -200 to 0 ms for stimulus-locked and -1000 to -800 ms for response-locked averages. The next step was artifact detection in which bad channels, eye blinks, and eye movements were identified: if the difference between the maximum and minimum voltage exceeded 200 µV in a moving average of 80 ms, the channel was marked bad. If a channel was bad in over 20% of trials, it is considered bad in all trials; and trials containing more than 10 bad channels were marked as bad (Dien 2010). The spherical spline interpolation was used to replace bad channels. Each trial was then baseline corrected using the mean voltage of the 200 ms pre-stimulus period.

The signals were re-referenced offline to the average of the left and right mastoids. Trials with incorrect behavioral responses were excluded from the averages (Keil et al. 2014). The main P3 measurements were taken from rare-minus-frequent difference waves. The P3 was measured at frontal (F3, Fz, F4), central (C3, Cz, C4), and parietal (P3, Pz, P4) electrode sites. Amplitudes were measured as the mean voltage in a given measurement window: 400 to 700 ms for the stimulus-locked P3, and -200 to -100 ms for the response-locked P3, following Luck et al., (2009). Analysis of variance (ANOVA) was used for the P3 analyses that included factors of the region (frontal, central, parietal), and grammaticality (grammatical, ungrammatical words). All significant ANOVA effects are reported with the partial η^2 effect size measure and the t-tests with Cohen's *d*.

4 Results

4.1 *Behavioral* Ungrammatical words were detected with a mean sensitivity of 0.557 (*d'*) (*SD=.82*), a score significantly different from zero, t(23)=3.35, p=0.003, d=0.684, 1-β=0.894. This result indicates that all the deviants were detected with a mean sensitivity higher than zero. Sensitivity for ungrammatical words was higher than chance level, showing that participants learned the rule. Mean accuracy (percent correct) for grammatical words was .70 (*SD=.14*) and .48 (*SD=0.19*) for ungrammatical words. This difference was significant t(23)=4.78, p<0.01, d=.976, 1-β=.999. Mean reaction time was 545 ms (*SD=106*) for grammatical words and 564 ms (*SD=119*) for ungrammatical. This difference was also significant, t(23)=2.349, p=0.028, d=.479, 1-β=.736), see Figure 1 below.

4.2 *Absolute waveforms* Figure 2 shows stimulus-locked and response-locked ERP absolute waveforms. It can be seen that both frequent and rare stimuli revealed a typical auditory evoked potential (AEP) with an N1–P2 wave-form complex at fronto-central electrodes. It was important to get this AEP to the onset of the word whether it was grammatical or ungrammatical because it indicates that the auditory system has responded to the onset of the word. As for the response-locked absolute waveforms, specifically at the parietal region, a typical Bereitschafts potential (BP) was observed. The BP, which is also called a readiness potential, reflects the activity in the brain prior to the behavioral motor response (the button press) (Jahanshahi and Hallett 2004).

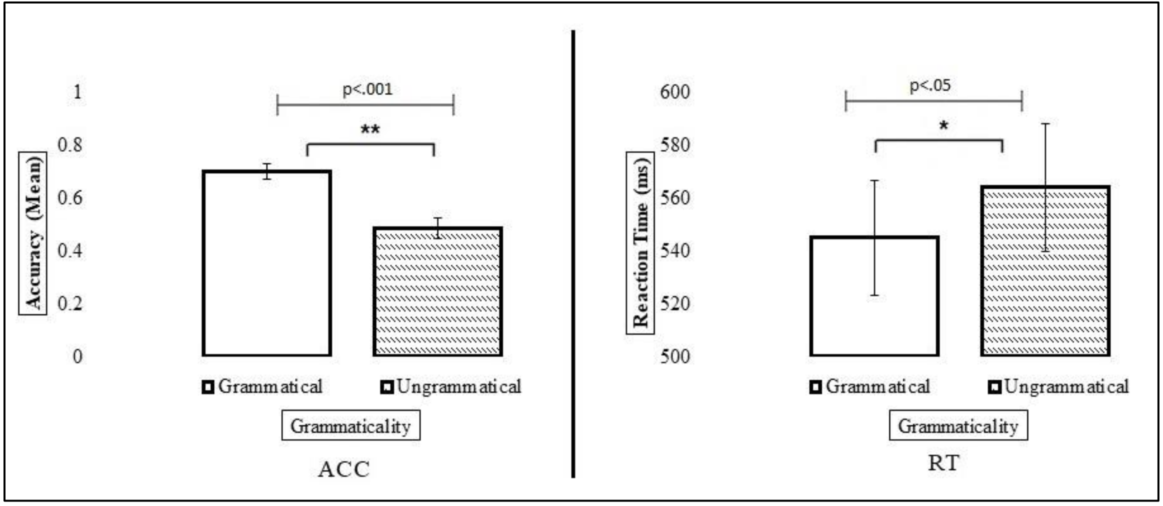

Figure 1. Mean accuracy rates (left panel) and mean reaction times (right panel). Error bars indicate standard error of the mean.

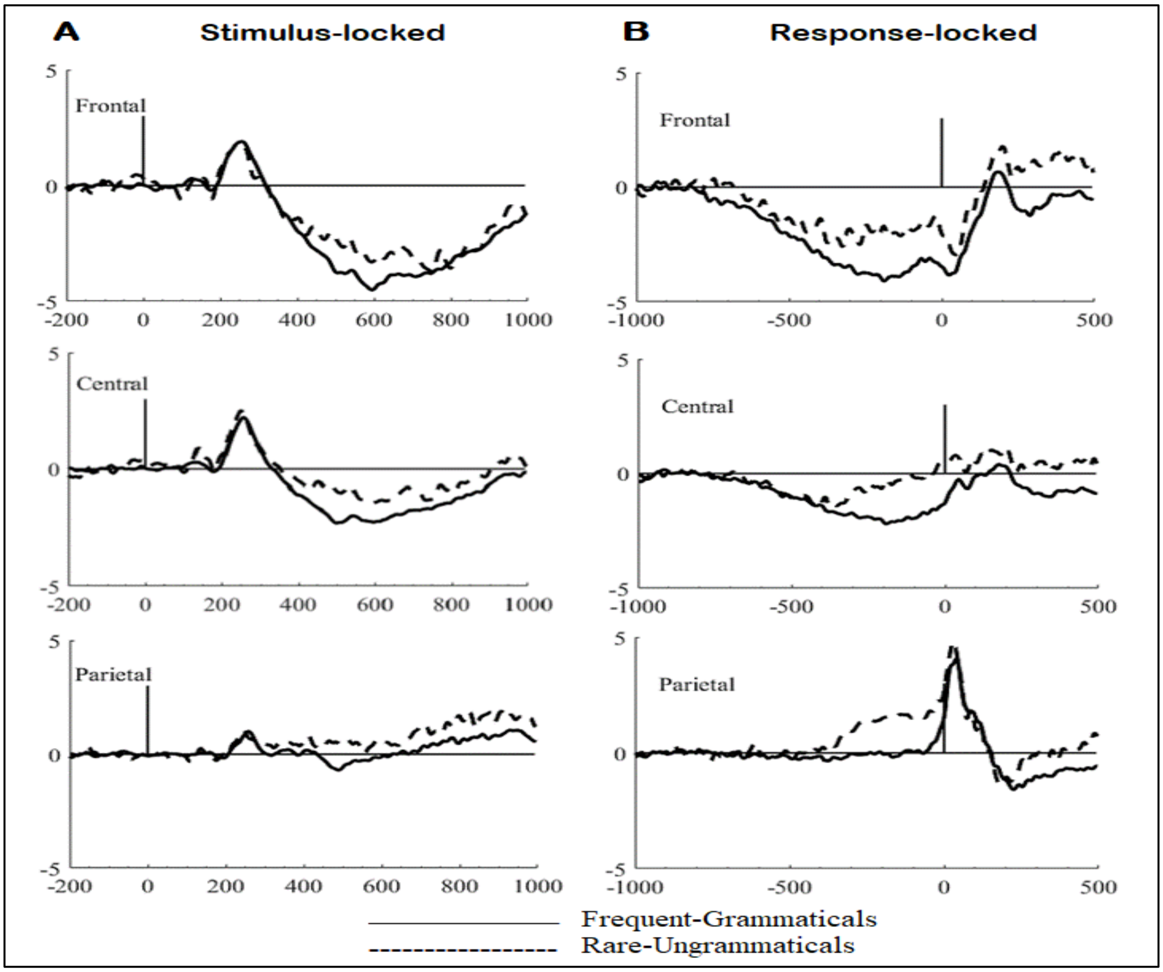

Figure 2. Stimulus-locked (A) and response-locked (B) grand average ERP absolute waveforms at the frontal, central, and parietal midline electrode sites.

4.3 *Stimulus-locked waveforms* Figure 3A shows the stimulus-locked ERP waveforms for the rare-minus-frequent difference waves. The amplitude (μV) of the difference wave was higher in the frontal region and lesser in the parietal region. The time course of the difference wave shows that the brain detected the violation at exactly 200 ms. This was marked by a P3 peak at 500 ms (~300 ms after the violation point). Figure 4A shows a whole scalp snapshot of the effect at this time point (500 ms). ANOVAs revealed a significant region effect and a grammaticality effect, but there was no interaction. These results are summarized in Table 2.

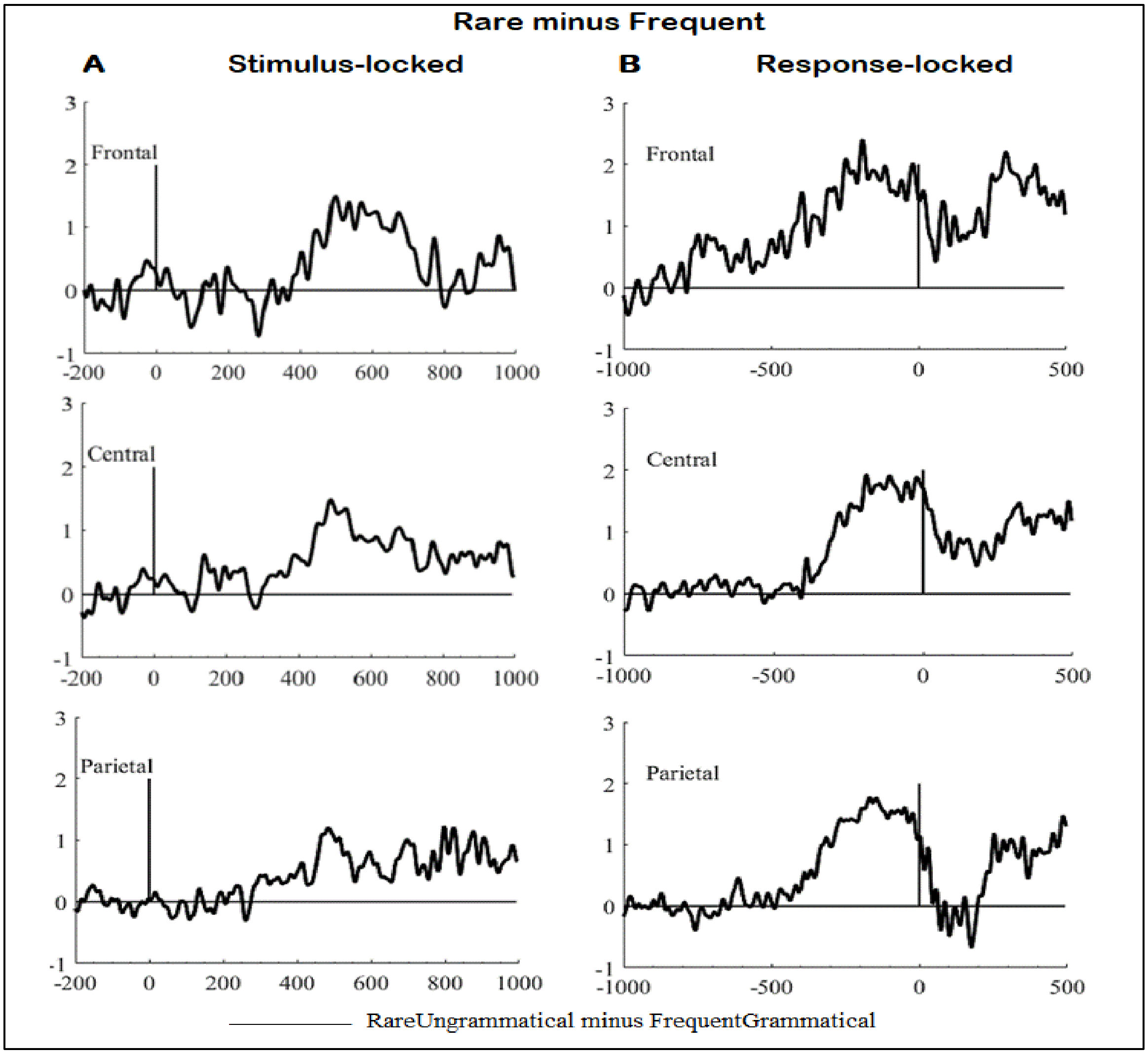

Figure 3. Stimulus-locked (A) and response-locked (B) grand average ERP difference waveforms (rare minus frequent) at the frontal, central, and parietal midline electrode sites. These waveforms isolate the brain's differential processing of grammatical and ungrammatical stimulus categories. Arrows indicate peak amplitude.

4.4 *Response-locked waveforms* Once participants had decided a stimulus was grammatical or ungrammatical, the next step was to press the button. When we time-lock to the response (the button press), the brain response should reflect whatever processing mechanism is active from the time between the decision and the response. This can be observed in the response-locked rare-minus-frequent difference waves (see Figure 3B, and Figure 4B for the spatial distribution at -200 ms). As expected, these results mirror the stimulus-locked results. Statistical analyses (Table 2) revealed a significant region effect and a grammaticality effect, but there was no interaction. As in the stimulus-locked averages, the amplitude of the difference wave was higher in the frontal region.

	Voltage (μV)			Statistics		
	Frontal	Central	Parietal	Grammaticality df= 1,23	Region df= 2,46	Region × Gramm. df= 2,46
Stim-locked	1.03 (.393)	0.95 (.294)	0.68 (.288)	F=11.436 p<.003 η^2=.332 $1-\beta$=0.875	F=31.415 p<.001 η^2=.577 $1-\beta$=0.999	F=0.573 P=.568 η^2=.024
Resp-locked	1.93 (.607)	1.76 (.467)	1.62 (.598)	F=12.499 p=.002 η^2=.352 $1-\beta$=0.910	F=44.650 p<.001 η^2=.660 $1-\beta$=0.999	F=0.240 P=.787 η^2=.010

Table 2. Rare-minus-frequent difference wave measures (within-subjects standard errors in parentheses), along with F, p, η^2, $1-\beta$ values for statistical analyses.

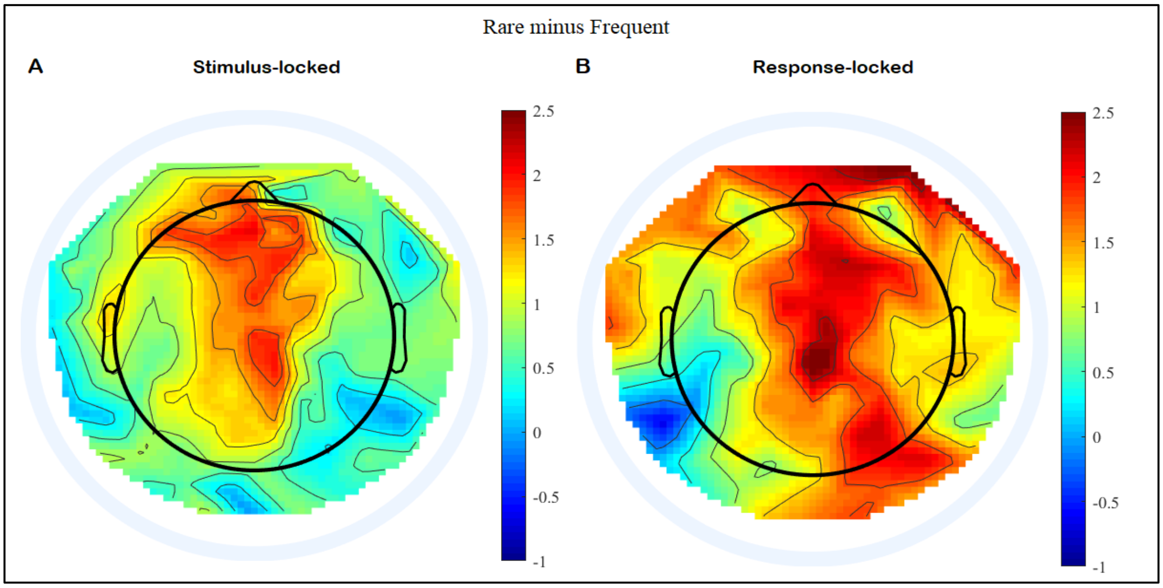

Figure 4. Spatial distribution of stimulus-locked (left panel) and response-locked (right panel) difference waveforms. Stimulus-locked topoplot shows the mean difference wave at 500 ms (Cz) and response-locked topoplot shows the mean difference wave at -200 ms (Cz).

5 Discussion

This study used behavioral measures and ERP difference waves to measure the underlying brain processes during the categorization of grammatical vs ungrammatical stimuli according to a learned phonotactic rule. Behavioral results showed that participants learned the non-adjacent phonotactic rule after a brief training session. The ungrammatical words were detected with a sensitivity higher than zero, and there was a significant grammaticality effect on accuracy and reaction time. The behavioral results demonstrate that participants were able to learn this simple artificial phonotactic rule in the laboratory and that the acquired knowledge was measurable in their behavior.

Measuring the neurophysiological correlates of this learning gives us insight into the brain processes that underlie phonotactic pattern learning. Behavioral data is end-point data that does not reveal what happens in the brain prior to the behavioral response. As explained by van Hell et al., (2018:p. 136) "… while behavioral measures necessarily reflect the cumulative sum of all of the processing in response to a stimulus, EEG dynamically measures the millisecond-by-millisecond neural response to the stimulus." What our ERP results show is that the newly acquired knowledge is directly "channeled" into incremental, real-time phonological predictive processing at the neural level, which can shed light on the time course of the process that leads to a behavioral response. For example, for ungrammatical stimuli, is a violation detected immediately at the parsing of a violating segment, or much later?

EEG results show a clear AEP and *Bereitschaft* potential prior to the onset of the button-press. The violating segment within the ungrammatical stimulus appeared at 200 ms. The peak of the difference waves appeared at 500 ms. This peak indicates the point in time when the subject has categorized the stimulus as grammatical or ungrammatical, prior to the behavioral response (one needs to determine grammaticality first to choose a response selection). This implies that the subject's brain understands that a particular stimulus is violating the pattern exactly at the violation point, not after the whole word has been processed. In other words, the phonological pattern detection mechanism does not wait until the end of the word to rule out an ungrammatical word. This time course information cannot be inferred from behavioral measures alone. Furthermore, when time-locked to the subject's response (the button press), a positive wave immediately preceded the response. This wave reflects the decision activity between the categorization and the button press response, which consists of selecting, preparing, and executing the appropriate response.

Eliciting a P3 requires an oddball (rare-vs-frequent) experimental design. The ungrammatical words appeared as infrequent 'deviants', so the grammatical-ungrammatical categorization coincides with a frequent-rare categorization. However, the difference wave obtained (grammatical vs ungrammatical) is not simply due to tracking the relative frequency of the stimuli. The difference reflects an underlying sensitivity to the phonotactic rule. Although the grammatical words were presented at a higher frequency than the ungrammatical, the relative frequencies cannot be informative to participants unless they understand the rule. Participants cannot track the relative frequencies without first recognizing the difference between grammatical and ungrammatical stimuli. Without having learned the rule, there is no phonetic or phonological feature that separates frequent grammatical tokens from the infrequent ungrammatical tokens.

The behavioral results indicate that the participants learned the rule. The neural results indicate that this learning took the form of a neural commitment. Participants learned the rule and used it to make active predictions, categorizing words as ungrammatical at the exact point of violation. This ability must be instantiated at the neural level, meaning rapid neural tuning has occurred in this lab setting. However, the question remains of where this neural commitment takes place. The fact that non-adjacent rules of this type have not been found to elicit MMN effects suggests that this neural commitment is not made at the perceptual level (in the auditory cortex). Instead, these more complex phonological patterns may be neurally encoded at a 'higher' level. Because the P3 is an attention-driven comparison process, the rule must be accessible to working memory, although it may not be accessible to the auditory sensory memory.

6 Conclusion

The aim of the current study was to correlate phonological rule-learning with a neurophysiological response. Previous research has found several types of evoked responses to violations of lab-learned phonological patterns, including the MMN, the LPC, and the P3. The particular response observed in each case is dependent on several factors, including study design, the mode of presentation, the type of stimulus, and the pattern or rule presented. We exposed participants to a non-adjacent phonotactic pattern (Sibilant Harmony) in an oddball paradigm and found evidence of learning in the participants' behavioral responses (categorization above chance level), as well as a robust brain response reflected in a P3 difference waveform.

This study establishes a reliable neurophysiological measure for further investigation of phonological rule-learning. As a planned follow-up, we intend to vary the length of the stimuli to observe a modulation in the latency of the P3 response. If the P3 response is a reflection of the categorization decision process, the peak of the wave should remain fixed relative to the position of the violating segment (the earliest point at which the phonological parser can determine that the rule has been violated). Future work will also be necessary to determine exactly what kinds of rules and rule-learning can be measured in this way.

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