Computational Complexity in Phonotactics Modulates Brain Response: Evidence from EEG

Summary. Exposure to novel linguistic patterns can result in the neural commitment that causes a physical change in neural tissue and affects future processing and learning (Kuhl et al., 2008). This study tests whether very brief exposure to computationally different (local vs nonlocal) phonotactic patterns results in different neural commitments. We examine the neurophysiological correlates of two computationally complex phonotactic patterns with EEG and sensitivity index measures. Participants were exposed to either a local or nonlocal phonotactic pattern and tested (while recording brain responses with EEG, participants categorized words as well-formed or ill-formed) in an artificial grammar learning paradigm. We found that only the group that was exposed to the local pattern displayed sensitivity indicating knowledge of the rule. Moreover, only the local pattern group exhibited an ERP response (P3 and Late Positive Component (LPC)) modulated by well-formedness, which we interpret as reflecting prediction error and anomaly detection. These results show that the degree of locality in the pattern modulates both learning and brain response. Brief exposure to the local pattern leads to a measurable change in the brain's predictive systems, while exposure to the nonlocal pattern has no effect. We conclude that exposure to computationally different patterns results in both different knowledge states and underlying neural commitments.

Methods. We ran an artificial grammar learning experiment testing the learnability of two patterns both of which are variants of the same phonotactic pattern – a sibilant harmony rule attested in Chumash language.

Stimuli. For the local pattern, all training and test stimuli consisted of two-syllable words of form CV.CV, with sibilants ([s, ʃ]) as the first and second consonants. This is a local dependency at the syllable level. All words were either "harmonic" (both sibilants identical, e.g., sasi or ʃeʃo) or "disharmonic" (mixed [s] and [ʃ], e.g., suʃa or ʃosi). The duration of each syllable was strictly controlled at 200ms, making each word 400ms long, and the violation at 200ms. For the nonlocal pattern, all training and test stimuli consisted of three-syllable words of the form CV.CV.CV, with sibilants ([s, ʃ]) as the first and third consonants, and a stop consonant ([k]) as the second. This is a nonlocal dependency at the syllable level. All words were either "harmonic" (both sibilants identical, e.g., sakose or ʃekuʃi) or "disharmonic" (mixed [s] and [ʃ], e.g., sokiʃa or ʃekuso). The duration of the first and third syllables was 200ms and the second was 250ms, making each word 650ms long, with the violation at 450ms.

Procedure. 44 monolingual American English speakers participated, divided into two groups (n=24 and 20). The procedure for both groups consisted of two phases: training and testing. In the training phase, participants listened only to harmonic words and were instructed to repeat each word orally. In the testing phase, participants were instructed to listen to a sequence of words and categorize each word as "part of the language" (i.e. novel harmonic words) or "not part of the language" (novel disharmonic words) that they had been exposed to during training. Participants were tested in an auditory oddball paradigm, with 80% harmonic words and 20% disharmonic words. The groups differed only in the pattern tested (local vs nonlocal).

Data Recording and Analysis. Participants' sensitivity to the rule was measured with *d'*, calculated from *hits* (when a disharmonic word was presented, and the participant reported it as disharmonic) and *false alarms* (when a harmonic word was presented, but the participant reported it as a disharmonic word). Learning was then modeled as a *d'* greater than 0. The main EEG P3 measurements were taken from rare-minus-frequent difference waves (Luck et al., 2009). The LPC was measured from absolute waveforms obtained for grammatical vs ungrammatical words. The P3 was measured at frontal (F3, Fz, F4), central (C3, Cz, C4), and parietal (P3, Pz, P4) electrode sites, and the LPC at a posterior region. Analysis of variance (ANOVA) was used for the P3 analyses that included factors of the region (frontal, central, parietal), and grammaticality (grammatical, ungrammatical words). LPC amplitudes were analyzed using paired samples t-tests comparing grammatical vs ungrammatical words.

Results. Behavioral results showed that the local group detected disharmonic words with a mean sensitivity (d') of 0.558, while the nonlocal group's sensitivity was -0.081. The difference between groups was significant: $t(42)=3.13$, $p=.003$, $1\text{-}\beta=.863$. Electrophysiological results for the P3 of the local group showed a significant region effect and harmony effect (all p values $<.005$). The P3 difference waveform peaked at 500ms (300ms after the violation), indicating that the brain detected the rule violation at exactly 200ms. Also, the waveforms show an enhanced posterior positivity (LPC) for ungrammatical words with a maximum around 800ms. For the nonlocal group, the P3 showed a significant region effect ($p<.001$), but NOT a harmony effect (p values $>.05$); also, neither the grammatical nor the ungrammatical waveforms were positive-going in the late time window. This means that the nonlocal group's absence of behavioral sensitivity of the rule violation was also not reflected in a P3 or LPC.

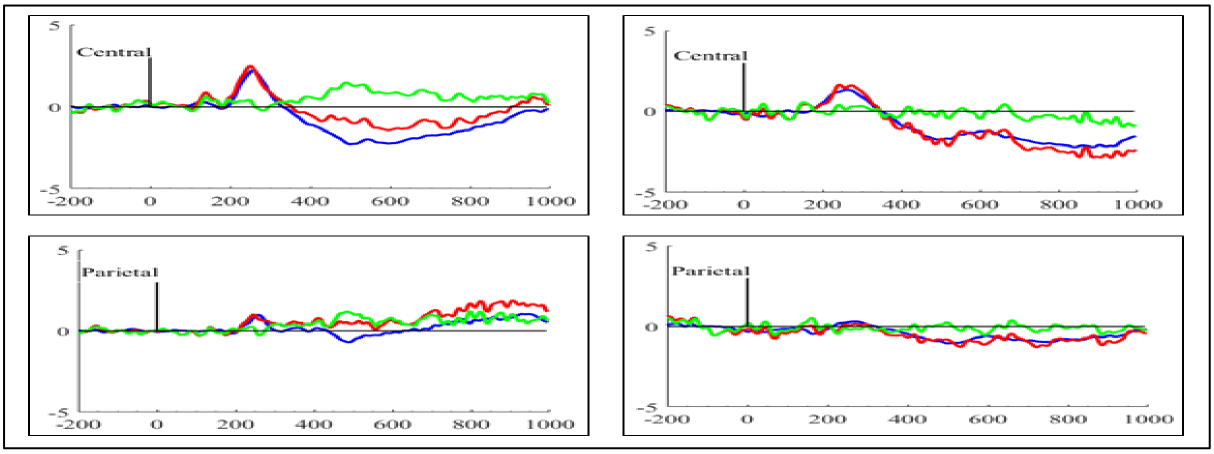

Figure. Grand average ERP waveforms: clear harmony effect reflected in P3 difference waveform and LPC in local (left panel) but not in the non-local group (right panel).

Discussion and Conclusion. Behaviorally, only the local group learned the phonotactic pattern, reflected in *d'*. The two groups also differed in their measured brain responses. The local group showed a predicted P3 and LPC modulation to rule violation, while the nonlocal group showed no modulation, despite the presence of a robust auditory evoked potential (AEP) and readiness potential (RP), which reflects the response selection process. We interpret these results to indicate that the degree of locality in the phonotactic pattern leads to different types of neural encoding of the acquired phonotactic rule. The computational complexity of the pattern plays a role in the pattern extraction process; participants easily extracted a local dependency rule at the syllable level. This interpretation is in line with Heinz (2010)'s Subregular Hypothesis in that local patterns are more easily learned than nonlocal patterns. Although the unlearnability of the nonlocal pattern poses a challenge for this hypothesis, the amount of training may have played a role in the rule extraction, specifically, the nonlocal group may have needed more training.

Selected References.

Heinz, J. (2010). Learning Long-Distance Phonotactics. Linguistic Inquiry, 41(4), 623–661.

Kuhl, P. K., Conboy, B. T., Coffey-Corina, S., Padden, D., Rivera-Gaxiola, M., & Nelson, T. (2008). Phonetic learning as a pathway to language: new data and native language magnet theory expanded (NLM-e). Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences, 363(1493), 979–1000.

Luck, S. J., Kappenman, E. S., Fuller, R. L., Robinson, B., Summerfelt, A., & Gold, J. M. (2009). Impaired response selection in schizophrenia: evidence from the P3 wave and the lateralized readiness potential. Psychophysiology, 46(4), 776-786.