Abstract Phonological Features: EEG Evidence from English Voicing

Philip J. Monahan, Alejandro Pérez, Jessamyn Schertz
University of Toronto

Introduction: Determining how the human brain encodes speech sound categories is integral for both models of our phonological system and its underlying neurophysiology[1]. While phonological theory posits distinctive features[2-4], evidence for such features in the brain has been equivocal[5-7]. Using electroencephalography (EEG), we report findings consistent with the brain supporting an abstract featural representation for English *voicing* that encompasses its phonetically distinct realizations: voice onset time (VOT) in stops[8] and laryngeal excitation in fricatives[9]. Our results suggest that the brain does code abstract featural representations.

Background: The mismatch negativity (MMN) is a powerful EEG paradigm for studying how the brain represents speech sounds[10-12]. In a typical MMN experiment, listeners hear a repeated standard stimulus occasionally interrupted by a deviant (ratio ~7:1), while the brain's electrical activity is measured. The MMN is the difference between the habituated standard and infrequent deviant in the event-related potential (ERP) EEG response (~150-200 ms after deviant onset). For an MMN to occur, the standards must be groupable to create this habituation and the deviants must be distinct. The standards need not be physically identical and can be grouped along representational dimensions[13]. Recent MMN findings appear to support monovalent phonetic features[14-19]. These tasks did not, however, require abstraction over phonetically distinct implementations of a single feature. As such, the observed responses may be driven by acoustic-phonetic and not abstract phonological featural representations.

Methods: Native Canadian English speakers (n = 30) heard two experimental blocks of naturally-produced syllables (voiced /ba, da, ga, va, za/, voiceless /pa, ta, ka, fa, sa/). One block had voiced standards and voiceless deviants (e.g., [… ba ga za da ga va **sa** da …]), and the other block had voiceless standards and voiced deviants (e.g., […fa ta sa ka fa sa ka **za** pa …]). We used a many-to-one oddball paradigm[20]. EEG recordings were acquired with a 32-channel system. Cluster-based permutation statistics[21] were computed over all electrode sites and time points, corrected for multiple comparisons.

Hypotheses: There are two hypotheses. First, the mere elicitation of an MMN to the deviants suggests that the brain grouped the standards by a shared phonological feature. Because both stops and fricatives were intermixed in the standards, grouping based on VOT or laryngeal state independently would eliminate the many-to-one relationship amongst standards, removing the necessary conditions to observe an MMN. Second, the directional amplitude of the MMN has been utilized to conclude about the precise nature of phonological features[22]: The standards in the block with the larger MMN have been taken to possess the monovalent feature responsible for the contrast[12,14-19]. Here, a larger MMN in the voiced standards block would suggest that [voice] is the underlying feature for English[23,24], while a larger MMN in the voiceless standards block would support [spread glottis][15,18,25].

Results: In the voiceless standards block, we observed a significant MMN between standards and deviants at approximately 125-200 ms post-deviant onset. This same difference was not observed in the voiced standards block. In addition to the ERP results, we also analyzed the time-frequency dimension of the EEG response to standards. These results revealed greater oscillatory power at 6-8 Hz from 50-200 ms for the voiced standards compared to the voiceless standards. While the ERP MMN differences were observed across most electrode sites, the differences in the time-frequency more centrally concentrated in frontal electrodes, where the MMN is typically observed[26].

Discussion: Given that the standards consisted of stimuli with distinct articulatory and phonetic implementations (i.e., stops and fricatives), unified only by their phonological category, the MMN response to deviants suggests that listeners construct an abstract phonological representation of the standards, including both stops and fricatives. Moreover, an MMN was observed only when the standard was voiceless, suggesting that only voiceless sounds have a stored feature for voicing[22], consistent with recent MMN findings[15,18] and primary linguistic research[25]. Finally, these differences were also reflected in the time-frequency analysis of the EEG response, potentially indexing a cost for integrating standards with underspecified representations in auditory memory[27].

References

1. Poeppel, D., Idsardi, W. J. & van Wassenhove, V. Speech perception at the interface of neurobiology and linguistics. *Phil Trans R Soc B* **363,** 1071–1086 (2008).
2. Jakobson, R., Fant, C. G. F. & Halle, M. *Preliminaries to Speech Analysis*. 1–44 (1961).
3. Chomsky, N. & Halle, M. *The Sound Pattern of English*. (MIT Press, 1968).
4. Prince, A. & Smolensky, P. *Optimality Theory: Constraint Interaction in Generative Grammar*. (Wiley-Blackwell, 2004).
5. Mesgarani, N., Cheung, C., Johnson, K. & Chang, E. F. Phonetic Feature Encoding in Human Superior Temporal Gyrus. *Science* **343,** 1006–1010 (2014).
6. Arsenault, J. S. & Buchsbaum, B. R. Distributed Neural Representations of Phonological Features during Speech Perception. *J Neurosci* **35,** 634–642 (2015).
7. Lawyer, L. & Corina, D. An investigation of place and voice features using fMRI-adaptation. *J Neuroling* **27,** 18–30 (2014).
8. Lisker, L. & Abramson, A. S. A cross-language study of voicing in initial stops: acoustical measurements. *Word* **20,** 384–422 (1964).
9. Smith, C. L. The devoicing of/z/in American English: effects of local and prosodic context. *J Phonetics* **25,** 471–500 (1997).
10. Näätänen, R. The perception of speech sounds by the human brain as reflected by the mismatch negativity (MMN) and its magnetic equivalent (MMNm). *Psychophysiology* **38,** 1–21 (2001).
11. Phillips, C. Levels of representation in the electrophysiology of speech perception. *Cognitive Science* **25,** 711–731 (2001).
12. Monahan, P. J. Phonological Knowledge and Speech Comprehension. *Annu. Rev. Linguist.* **4,** 21–47 (2018).
13. Gomes, H., Ritter, W. & Vaughan, H. G., Jr. The nature of preattentive storage in the auditory system. *J Cognitive Neurosci* **7,** 81–94 (1995).
14. Eulitz, C. & Lahiri, A. Neurobiological evidence for abstract phonological representations in the mental lexicon during speech recognition. *J Cognitive Neurosci* **16,** 577–583 (2004).
15. Hestvik, A. & Durvasula, K. Neurobiological evidence for voicing underspecification in English. *Brain Lang* **152,** 28–43 (2016).
16. Scharinger, M., Monahan, P. J. & Idsardi, W. J. Linguistic category structure influences early auditory processing: Converging evidence from mismatch responses and cortical oscillations. *NeuroImage* **128,** 293–301 (2016).
17. Schluter, K. T., Politzer-Ahles, S. & Almeida, D. No place for /h/: an ERP investigation of English fricative place features. *Language, Cognition and Neuroscience* **31,** 728–740 (2016).
18. Schluter, K. T., Politzer-Ahles, S., Kaabi, Al, M. & Almeida, D. Laryngeal Features Are Phonetically Abstract: Mismatch Negativity Evidence from Arabic, English, and Russian. *Frontiers in Psychology* **8,** 746 (2017).
19. Cornell, S. A., Lahiri, A. & Eulitz, C. Inequality across consonantal contrasts in speech perception: evidence from mismatch negativity. *J Exp Psychol Human Percept Perform* **39,** 757–772 (2013).
20. Phillips, C. *et al.* Auditory cortex accesses phonological categories: an MEG mismatch study. *J Cognitive Neurosci* **12,** 1038–1055 (2000).
21. Groppe, D. M., Urbach, T. P. & Kutas, M. Mass univariate analysis of event-related brain potentials/fields I: A critical tutorial review. *Psychophysiology* **48,** 1711–1725 (2011).
22. Lahiri, A. & Reetz, H. Distinctive features: Phonological underspecification in representation and processing. *J Phonetics* **38,** 44–59 (2010).
23. Hwang, S.-O. K., Monahan, P. J. & Idsardi, W. J. Underspecification and asymmetries in voicing perception. *Phonology* **27,** 205–224 (2010).
24. Kager, R. *et al.* in *Voicing in Dutch* (eds. van de Weijer, J. M. & van der Torre, E. J.) 1–40 (John Benjamins Publishing, 2007).
25. Avery, P. & Idsardi, W. J. in *Studies in Distinctive Feature Theory* (eds. Hall, T. A. & Kleinhanz, U.) 41–70 (Mouton de Gruyter, 2001).
26. Näätänen, R., Paavilainen, P., Rinne, T. & Alho, K. The mismatch negativity (MMN) in basic research of central auditory processing: A review. *Clinical Neurophysiology* **118,** 2544–2590 (2007).
27. Pérez, A., Molinaro, N., Mancini, S., Barraza, P. & Carreiras, M. Oscillatory dynamics related to the Unagreement pattern in Spanish. *Neuropsychologia* **50,** 2584–2597 (2012).