From Sound to Meaning: Changes in EEG Source-Localized Brain Activity with Foreign-Language Training

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Abstract. Learning a foreign language is a complex human task, involving multiple processes and a dynamic network of brain activity. The present study used 256-channel dense-array electroencephalography (dEEG) and linear-inverse source analysis (sLORETA) to identify changes in brain activity during the early stages of language training. Twenty native English speakers attended two 50-minute sessions of computer-assisted, virtual-reality Dari language instruction. Training-specific changes in neural activity were observed in both articulatory-motor and semantic processing regions, including increases in left posterior inferior temporal gyrus and left lateral inferior frontal regions. Also observed was increasing left lateralization, and an increase in mediotemporal regions suggestive of memory reconsolidation. These findings illustrate the ability to track changes with training in recognized language-processing brain regions using source-localized EEG recorded while listening to continuous, naturalistic speech. Subsequent research will explore individual differences and the development of adaptive training based on neural indices.

Keywords: language learning, training, dense-array EEG, linear-inverse source analysis, electroencephalography, event-related potentials.

1 Introduction

When acquiring a foreign language, a stream of initially unintelligible sounds slowly emerges into distinct words and meaningful phrases. This transition includes the ability to perceive speech sounds (phoneme perception), parse the phonetic stream into words (speech segmentation), encode and retrieve word meanings (lexical and semantic access), and combine individual words into comprehensible sequences (syntactic processing and sentence integration). Underlying this acquisition, which is typically experienced in behavior or self-observation of learning, are changes in the learner's brain responses during exposure to the new language. Tracking these brain responses during the learning process may guide the development of more efficient and effective training, and the formation of real-time, customized, adaptive training regimes.

Event-related potential (ERP) studies of bilingualism and foreign language learning have revealed interesting differences in brain responses to language acquired

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as a native versus non-native speaker. For example, Sanders and Neville [1] showed that when native English speakers listened to continuous speech, they evidenced large, auditory N1 and N200-300 responses to the onset of each content word, accompanied by a distinct absence of such responses to the onset of syllables internal to a word, indicative of their ability to parse a continuous stream of speech into individual words. In contrast, the brain responses of relatively proficient Japanese non-native English speakers did not differentiate between word-initial and word-medial syllables, presumably due to less efficient speech segmentation processes [2]. These findings by Sanders and Neville revealed that differences in the brain responses of native versus non-native speakers can persist even after several years of exposure to the foreign language. Within-subject longitudinal studies of foreign language learning by Osterhout and colleagues, however, have also revealed striking changes in brain responses to a foreign language as a function of learning, even very early in acquisition. For example, Osterhout et al. [3] examined changes in the N400, an ERP index of lexico-semantic access that is typically larger for words whose meanings are more difficult to retrieve (e.g., words that are low-frequency, less predictable, or semantically anomalous). After only 14 hours of instruction, learners evidenced a significantly larger N400 to pseudowords than words, even though they performed at chance when distinguishing real words from pseudowords. Importantly, this study shows that brain responses can reveal a learner's acquired knowledge, here about the lexical status of these words, even before the learners are aware or able to demonstrate this learning behaviorally. Thus, ERP studies have been shown to be sensitive to both native versus non-native contrasts in brain activity, as well as longitudinal changes within non-native brain responses as a function of language training.

The majority of ERP studies of language processing to date, however, have relied on mapping the brain's detection of, or differential response to, linguistic anomalies, such as pseudowords, semantically incongruous words, or syntactic violations, as compared to well-formed linguistic input. Furthermore, these studies typically describe ERP responses on the scalp surface, measured by relatively sparse electrode arrays (e.g., 16, 32, or 64 sensor locations), and rely on a limited number of well-established scalp ERP components, such as the N1, N400, and P600. Ideally, one would like to track changes in brain responses while the learner is actively engaged in training, and listening and responding to natural language for comprehension and communication. Not only would this better characterize the brain's processing of authentic language processing, it would also provide the neural signatures that would be required for aligning language training with the brain's current learning state. In addition, electrical source analysis of dense-array (i.e., 128 or 256-channel sensor arrays) EEG (dEEG) recordings would allow the ERP researcher to relate the scalp data to brain regions and networks previously revealed by fMRI and lesion research on language.

Prior research on the functional neuroanatomy of speech [e.g., 4, 5] has identified a widely distributed network of regions engaged during speech comprehension. These include the classic Broca (inferior frontal gyrus) and Wernicke (posterior superior temporal gyrus) areas, as well as extensive processing along the superior temporal gyrus, lexical and semantic processing along middle and inferior temporal gyri and temporal pole, and sensorimotor processing in frontal premotor and parietal regions.

Hickok and Poeppel [4] proposed these regions can be divided into two processing networks, a dorsal network processing the articulatory sounds of speech perception, and a ventral stream focusing on meaning.

The present study aimed to track processing associated with early language acquisition by measuring changes in brain activity across language training sessions using dense-array electroencephalography (dEEG) and linear-inverse electrical brain source analysis. This study is distinguished from traditional event-related potential (ERP) language research by the incorporation of several features. First, brain activity was recorded as subjects listened to naturalistic samples of continuous speech for comprehension. Thus, it measured the brain's natural response to auditory language as communication, a more ecologically valid task than typical ERP studies that rely on the brain response to linguistic violations as a measure of language processing. Second, source analysis was conducted to identify the underlying brain regions engaged during speech comprehension. This made it possible to draw upon fMRI and lesion literature and relate observed regional changes to specific aspects of language processing. Third, repeated measurements at multiple time points across early stages of language acquisition was better suited to documenting the actual learning process than cross-sectional contrasts and will permit more effective exploration of individual differences.

2 Method

2.1 Participants

Twenty right-handed, native English speakers (12 male, mean age = 25 years) were recruited from the University of Oregon. All participants gave informed consent prior to participation and received $60 in remuneration. The study was approved by the institutional review boards at Electrical Geodesics and the University of Oregon.

2.2 Materials

Language Training. Training consisted of two identical 50-minute sessions of Tactical Dari (Alelo, TLT, Los Angeles, CA), a computer-assisted, foreign-language training software for Dari, an Afghani language similar to Persian. These training sessions covered greetings and introductions through interactive dialogues and exercises controlled by the learner with a mouse. Integrated voice recognition software was used to enable the computer characters to interact with the learner utterances and to provide automated feedback to the learner.

Pretest-Posttest. The 30-minute pretest and posttest were identical and consisted of 76 mini-dialogues in Dari read aloud by a single native-speaker of Dari. Half the dialogues were composed of phrases from the lesson in which they then received training (Trained), and half were composed of Dari phrases from a lesson in which they received no training (Untrained). The Trained and Untrained dialogues were intermixed across the length of the test. Participants actively listened to each dialogue and rated after each one, on a scale from 1 to 4, both how well they recognized the words in the dialogue and how well they understood the dialogue.

2.3 Procedure

Participants attended two training sessions, separated by a day with no instruction. At the start of each day, participants were fitted with a 256-channel HydroCel Geodesic Sensor Net for recording of EEG data during the Dari pretest, training, and posttest. Participants were seated in front of a computer monitor and listened to all dialogues and the Tactical Dari lesson via air canal insert earphones (Etymotic Research, Elk Grove Village, IL). During the pretest and posttest, stimulus presentation was controlled by E-Prime Software, Version 1.2.1.795 (Psychology Software Tools, Pittsburgh, PA), and synchronized with EEG acquisition via the E-Prime Extension for Net Station. During the pretest and posttest dialogues, participants maintained fixation on a cross (+) presented in the center of the computer monitor in order to reduce eye movement artifact during EEG recording. Following the 30-minute pretest on Day 1, participants completed a module on how to use the Tactical Language Training software in which French was substituted as the foreign language so as not to confound exposure to Dari. They then completed a 40-minute Lesson 1 in Tactical Dari, Greetings and Introductions, followed by a 10-minute quiz. The session concluded with the 30-minute posttest. Day 2 was identical to Day 1, except that participants did not complete the module on how to use the software on Day 2. Each session, including net application, pretest, language training, and posttest, lasted approximately three hours.

2.4 EEG Recording, Preprocessing, and Source Analysis

The EEG was recorded during the pretest and posttest using the 256-channel HydroCel Geodesic Sensor Net, Net Amps 300 amplifier, and Net Station, Version 4.4.1, software (Electrical Geodesics, Eugene, OR). Electrode impedances were maintained below 100 kΩ [6]. The EEG was recorded with a 100 Hz low-pass filter, amplified at a gain of 1,000, with a 250 Hz sampling rate, and digitized with a 24-bit A/D converter. All channels were referenced to Cz during data acquisition.

After acquisition, the continuous EEG was filtered with a 0.1-Hz to 30-Hz bandpass filter, and segmented by word onset into 1,000-ms epochs with a 100-ms baseline period. Epochs contaminated by eye or movement artifact were identified by computer algorithm and eliminated. Individual bad channels were identified and interpolated on a segment-by-segment basis using spherical spline interpolation. For each subject file, the EEG was averaged into event-related potentials (ERPs), time-locked to the onset of each word, for each of eight categories: Test (Pre, Post) x Day (1, 2) x Lesson (Trained, Untrained). Following visual inspection, the data from one participant was eliminated due to a bad reference electrode. A grand average file was computed from the remaining 19 participant ERP averages.

Linear-inverse source analysis was performed on the grand-averaged scalp ERPs using GeoSource, Version 2.0, software (Electrical Geodesics, Eugene, OR). A finite difference model (FDM) of a typical human head was computed using a segmented, high-resolution T1-weighted MRI scan of the brain and CT of the skull in order to model realistic head tissue geometry and conductivity. Conductivity values used in the FDM model were 0.25 S/m (Siemens/ meter) for the brain, 1.8 S/m for the cerebral spinal fluid, 0.018 S/m for the skull, and 0.44 S/m for the scalp. These conductivity values reflect the more accurate 14:1 ratio between brain and skull conductivity rather than the traditional 80:1 estimate [7, 8]. Dipole triples (x, y, z orthogonal orientations) were placed in 2447 7-mm voxels distributed throughout cortical gray matter based on the MNI305 probabilistic map. This FDM lead field matrix was inverted using the standardized low-resolution electromagnetic tomography analysis (sLORETA) method [9]. The resulting voxel intensities at each time point for each condition were displayed on MRI slice views of a typical Talairach-transformed brain.

3 Results

Rated comprehension increased significantly from pretest to posttest on each day of training for dialogues composed of trained, but not untrained, words (see Figure 1), $p < 0.0001$. For the trained-word dialogues, rated comprehension also decreased a small, but significant, amount from the posttest immediately following training on Day 1 to the time of the pretest on Day 2, $p < 0.0002$.

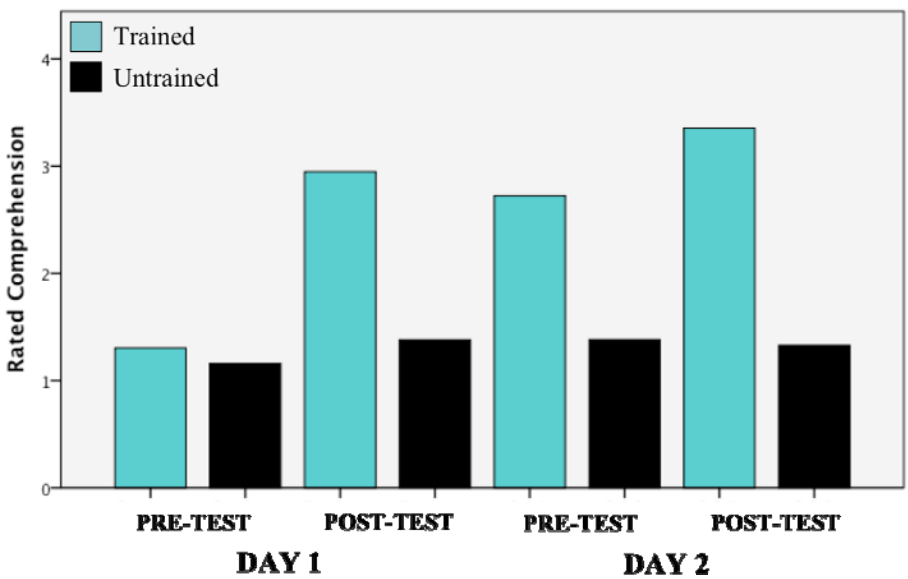

Fig. 1. Rated comprehension of pretest and posttest dialogues composed of trained or untrained words

Figure 2 illustrates training-specific changes in brain activity, changes that were observed in both articulatory-motor and semantic processing networks. Premotor activity was larger on Day 1, both before and after training, than on Day 2. Activity in Broca’s area, however, was observed only after training on Day 1, and persisted through Day 2. Activity in semantic processing regions, including the left posterior inferior temporal lobe (anterior fusiform gyrus) and left temporal pole increased with training, especially on Day 2.

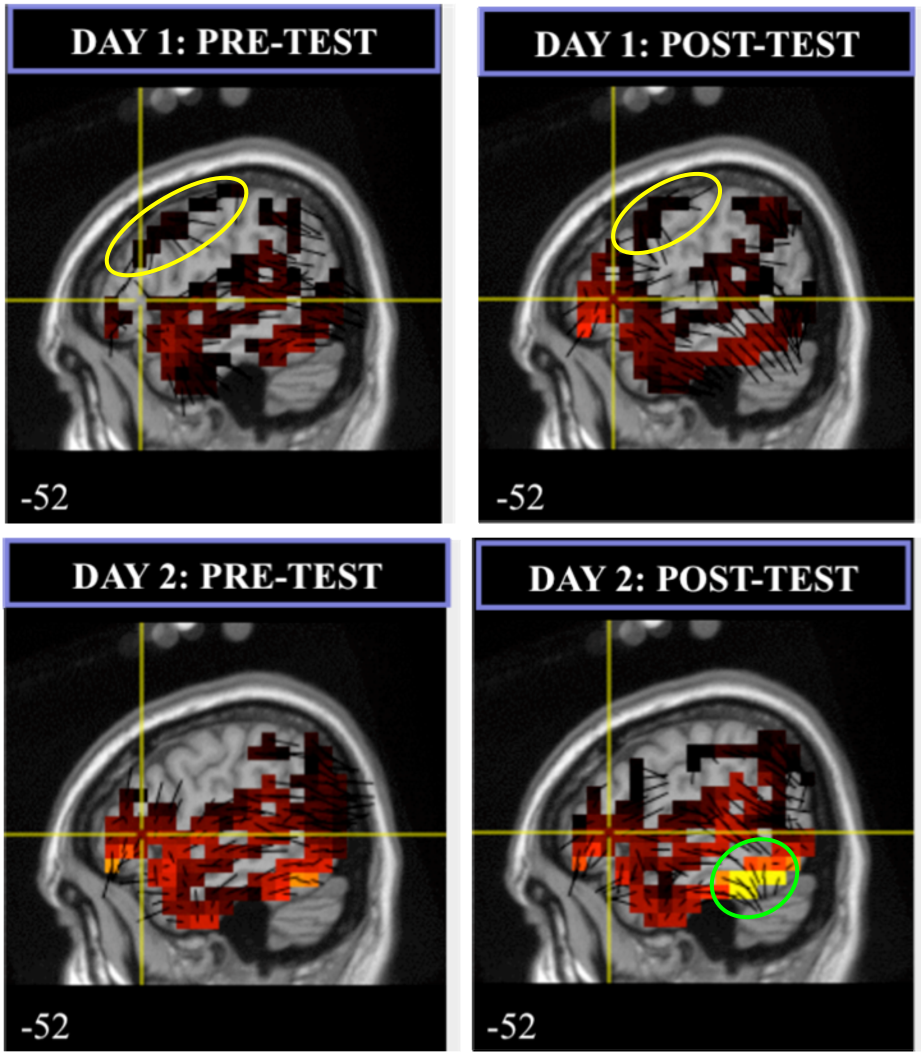

Fig. 2. Grand-average source solution for the left hemisphere for trained words at pretest and posttest on Days 1 and 2. Yellow circles highlight articulatory-motor activation present on Day 1. Crosshair indicates Broca's Area, which is engaged only after training on Day 1 and continues through Day 2. The green circle marks the fusiform gyrus of the semantic network, which increases in activity with training.

Figure 3 shows the source localized brain activity for both trained and untrained words superposed on sagittal (x = -45) and axial MRI views. As can be observed in the axial slice view, there is increasing left lateralized activity on Day 2, particularly for the trained words. Finally, a large increase in medial temporal regions of the left hemisphere also obtains on Day 2 in both the pre- and posttest for trained, but not untrained, words.

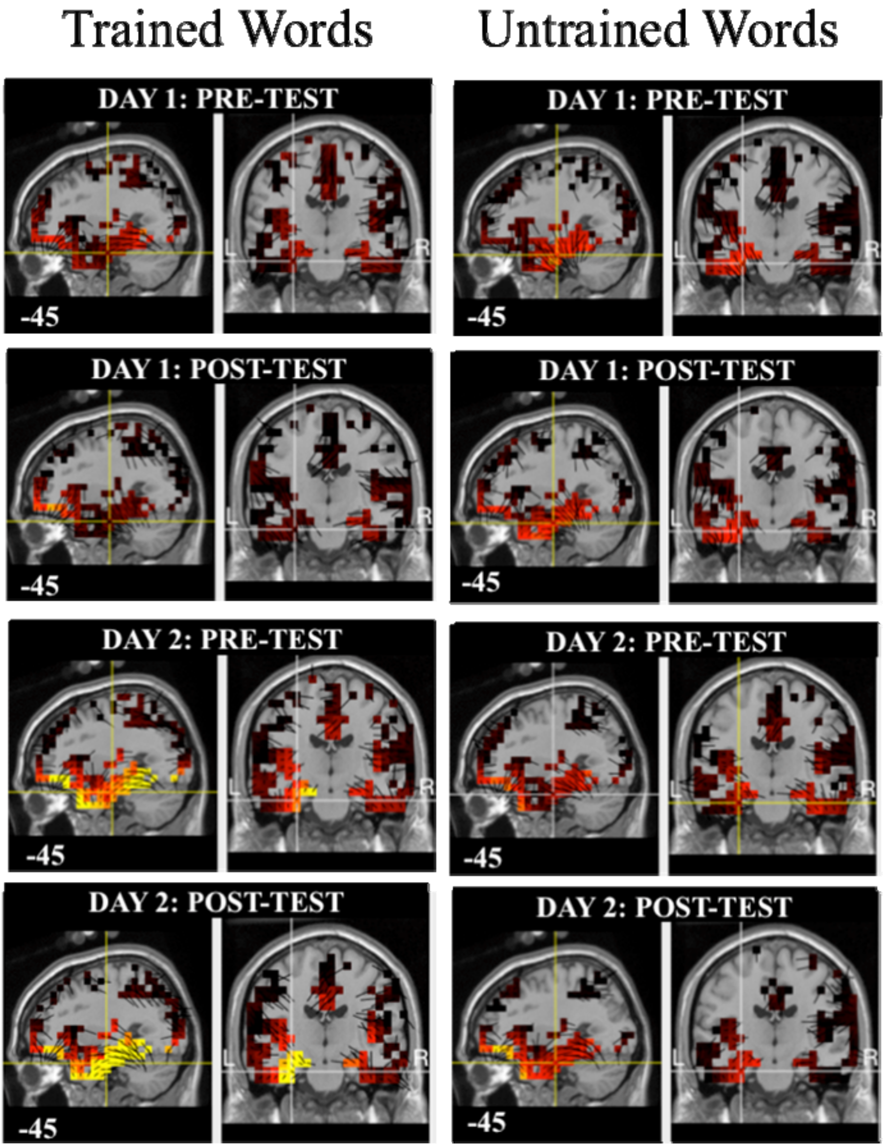

Fig. 3. Sagittal and axial views of source-localized grand-averaged electrical activity for trained and untrained words showing increased left-lateralized activity with training, and a large increase in medial temporal activity on Day 2 pretest and posttest for trained words only

4 Discussion

As expected, behavioral results for self-ratings of comprehension on the pretests and posttests indicated a strong effect of learning from language training on each day.

Furthermore, the small decrease in perceived comprehension from the Day 1 posttest to Day 2 pretest suggests that learners may have experienced some forgetting over the one-day break between sessions, but largely retained their learning from the first day of training.

The pattern of changes in source-localized brain activity also indicated striking training-specific changes that are highly consistent with fMRI-based models of language processing [e.g., 4, 5]. The decrease, from the first to the second day of training, in articulatory-motor regions accompanied by an increase in ventral semantic processing regions for trained words suggests a shift away from focusing on the sound and articulation of Dari to focusing on the meanings of the Dari words. This is reinforced by the observed increase in left lateralized activity, stronger for trained words, but also present to a lesser degree for the untrained words by the Day 2 posttest. Such a pattern suggests that the learners' brains are increasingly processing the Dari input within a left-lateralized language-specific network. Finally, the large increase in activity in medial temporal regions following the one-day break between training sessions suggests that important memory reconsolidation processes may have occurred such that on Day 2, even at the time of the pretest before any additional training had been given, the learners' medial temporal memory regions were actively engaged, retrieving the word meanings from consolidated semantic memories. This effect is clearly absent during the processing of dialogues composed of untrained words for which no consolidated memory traces can exist.

In summary, these findings illustrate the ability to measure changes associated with language learning in recognized language-processing brain regions using source-localized EEG recorded while listening to continuous, naturalistic speech. Future analyses will explore statistical analysis of these source activations and individual differences in performance and brain indices of learning. Subsequent studies will attempt to identify and track these same changes during engagement in Tactical Dari training itself, rather than examining changes from pre- to posttest. This should, ultimately, permit the development of adaptive language training based on real-time monitoring of neural indices of language acquisition.

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