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Brain Activity Composing Word Structure
An MEG Study

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Abstract: By using MEG, we found neural activity reflecting the construction of a hierarchical structure in *yojikango* with binary-branching structures. These findings support prior findings regarding the neural basis of hierarchical morphological processing and indicate that the common neural mechanisms generate hierarchical structures of sentences, phrases, and complex words.

Keywords: Magnetoencephalography (MEG), Steady-state Evoked Fields (SSEFs), Complex Words

Introduction

Recent studies have revealed brain activity involved in the construction of hierarchical structures in language. By using magnetoencephalography (MEG) and electrocorticography, Ding et al. (2016) reported that steady-state evoked fields/potentials (SSEFs/SSEPs) reflect the hierarchical structure of language — comprising syllables (words), phrases, and sentences [1]. Sheng et al. (2018) further identified the critical loci corresponding to different linguistic units [2]. For instance, the processing of phrasal structures engaged the left anterior temporal lobe (LATL), left middle temporal gyrus, and bilateral superior temporal gyrus (STG). In contrast, sentence processing recruited the left inferior frontal gyrus, left posterior STG, and LATL. Since the LATL was involved in both phrase and sentence processing, they suggested that the LATL supports conceptual integration across linguistic levels. However, since previous studies using steady-state visual evoked fields (SSVEFs) did not investigate morphologically complex words, which also have hierarchical structures, it remained unclear whether SSVEFs reflect the hierarchical structures of complex words. Therefore, we examined whether the SSVEFs reflected the hierarchical structures of complex words in this MEG study.

Methods

We recruited 26 native Japanese speakers (13 males, 21.8 ± 1.6 years). All participants were confirmed to be right-handed based on the handedness questionnaire [3]. Written informed consent was obtained from each participant before the experiment. One participant was excluded from the analysis due to the unavailability of individual MRI data.

For the visual stimuli, we targeted Japanese *yojikango*, i.e., words composed of four Chinese characters, such as 男子学生 (male student), 未回答者 (a person who has not responded), and 大学院生 (graduate student). We used three types of *yojikango* with different internal structures—binary branching (e.g., [[男子][学生]]), embedding (e.g., [未[[回答]者]]), and left branching (e.g., [[[大学]院]生])—along with four-character non-words created by reordering the characters of real *yojikango* (114 words per condition). Each character was presented to participants every 250 ms (4 Hz) in a continuous stream lasting 12,000 ms, resulting in a word (*yojikango*) presentation rate of 1 Hz (i.e., 12 words per trial). We asked the participants to detect outliers using hiragana (e.g., るいべつ).

MEG data were recorded at Kyushu University Hospital using an Elekta Neuromag system (1000 Hz, 0.3–330 Hz band-pass). Structural MRIs were acquired with a 3.0-T scanner (Achieve; Philips) for source localization. MEG data were first processed with an oversampled temporal projection and band-pass filtered between 0.1 and 80 Hz. Independent component analysis (ICA) was then applied to remove artifacts such as eye blinks, cardiac signals, and external noise. Source estimation was performed using a linearly constrained minimum variance (LCMV) beamformer based on each participant's MRI. For each condition, the mean time series at each cortical vertex was extracted from 2 to 12 seconds after stimulus onset. Fast Fourier Transform (FFT) was applied to these time series to obtain amplitude spectra at 0.1 Hz resolution. Statistical analysis was performed in two steps. First, we tested whether amplitudes at the target frequencies corresponding to the construction of *yojikango* (i.e., 1 Hz, 2 Hz, and 4 Hz) were significantly higher than those at surrounding frequencies. Cluster-based permutation tests (one-sided t-tests) were conducted, focusing on the temporal and temporoparietal regions as a region of interest (ROI), comparing the amplitude at each frequency of interest to the average amplitude of the two adjacent frequency bins on either side. Second, for frequencies showing significant peaks in the first analysis, we examined whether these responses differed across conditions. Again, focusing on the same ROI, we compared the amplitudes across the four conditions using a cluster-based permutation test based on one-way ANOVA. Data preprocessing, source estimation, and statistical analysis were performed using MNE-Python software [4].

Results

Accuracy exceeded 95% in all conditions, and reaction times were approximately 1300 ms, suggesting that the participants paid attention to the stimuli. Statistical analysis of the source-estimated data revealed neural activity at 4 Hz—corresponding to the presentation rate of individual kanji characters—in all conditions. This activity did not differ between conditions, indicating that the processing of individual characters was unaffected by whether they appeared in real words or not. Activity reflecting the hierarchical structure of *yojikango* was observed specifically in the binary-branching condition. Significant clusters appeared at 1 Hz in the anterior temporal lobe and at 2 Hz in the temporoparietal region. However, neural activity reflecting the hierarchical structure was not observed in the embedding or left-branching conditions.

Discussion

Previous studies have proposed that the anterior temporal lobe is involved in conceptual combination, while the temporoparietal region is associated with semantic information [5], [6], [7]. In the binary-branching compounds, the 2 Hz activity is thought to correspond to the construction of two-character words with semantic content, and the 1 Hz activity reflects the combination of these into the full *yojikango*. Thus, our results support prior findings regarding the neural basis of hierarchical morphological processing.

Regarding the non-significant results in the embedding or left-branching conditions, we propose two possible explanations. First, the difference in morphological formation: binary-branching compounds are formed by combining two two-character compounds (compounding), whereas embedding and left-branching are formed through two successive derivations. This difference between compounding and derivation may be reflected in the neural responses. Second, frequency effects may play a role. Nomura (1975) reported that the binary-branching structure accounts for over 90% of *yojikango*, making embedding and left-branching structures minority types [8]. The relative rarity of these structures may have made it difficult for participants to process them as coherent compounds. Frequency effects have been highlighted as important factors in morphological complexity studies, using mismatch negativity and priming effects. Future research should manipulate factors such as word frequency and transparency to further elucidate brain activity underlying the processing of complex words.

Conclusions

In this study, we conducted an experiment using SSVEFs to explore brain activity involved in constructing hierarchical structures in morphologically complex words. We observed neural activity reflecting the construction of a hierarchical structure in *yojikango* with binary-branching structures. These findings indicate that the common neural mechanisms generate hierarchical structures of sentences, phrases, and complex words.

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