Neural Signatures of Argument Structure Constructions

PEGAH RAMEZANI[1,2], ACHIM SCHILLING [1,2,*], PATRICK KRAUSS[1,2,*]
[1]Neuroscience Lab, University Hospital Erlangen, Germany
[2]CCN Group, Pattern Recognition Lab, FAU Erlangen-Nürnberg, Germany

Abstract

Understanding how the brain processes language, particularly abstract grammatical structures like Argument Structure Constructions (ASCs), is a key goal in cognitive neuroscience. Exploring how the brain differentiates these constructions helps uncover the neural basis of language comprehension.

To investigate this, EEG data was recorded from 12 native English speakers as they listened to sentences representing each ASC type. Analysis of neural signals revealed distinct patterns linked to specific constructions. Significant differences emerged in comparisons between several pairs, especially between transitive and resultative and caused-motion and ditransitive. Other comparisons showed weaker or no differentiation. Machine learning classification supported these findings, identifying construction-specific neural signatures.

Although individual variation existed, the Alpha frequency band consistently played the most prominent role in distinguishing constructions, followed by Beta and Delta bands, with Gamma showing minimal impact.

These results demonstrate that the brain processes grammatical constructions in distinct ways, challenging the notion of uniform syntactic processing. The findings highlight how neural oscillations, particularly in the Alpha band, are sensitive to grammatical patterns, deepening our understanding of the neural and cognitive architecture underlying language comprehension.

Keywords: EEG; Neurolinguistics; Construction Grammar; Argument Structure Constructions

Introduction

Understanding how the brain processes and represents language is a fundamental challenge in cognitive neuroscience (Pulvermüller, 2002). This paper adopts a usage-based constructionist approach, which views language as a system of form-meaning pairs (constructions) that link patterns to specific communicative functions (Goldberg, 2009, 2003). Argument Structure Constructions (ASCs), such as transitive, ditransitive, caused-motion, and resultative constructions, are particularly important for language comprehension and production (Goldberg, 1995, 2006, 2019). These constructions are key to syntactic theory and essential for constructing meaning in sentences. Exploring the neural and computational mechanisms underlying the processing of these constructions can yield significant insights into language and cognition (Pulvermüller, 2012, 2021; Henningsen & Pulvermüller, 2022; Pulvermüller, 2023).

Materials

The EEG signal was recorded from 12 native English speaker participants with 64 active electrodes. The participants listened to the audio format of the sentences created using GPT-4. This data set was designed to include sentences that exemplify four distinct ASCs: transitive, ditransitive, caused-motion, and resultative constructions (see Table 1). Each ASC category consisted of 50 sentences, resulting in a total of 200 sentences. After preprocessing, signal quality and trigger placement accuracy are assessed by visualizing event-related potentials (ERPs). An averaged ERP waveform across all participants and sentence types reveals a clear P200 component in response to the auditory onset of sentences.

Table 1: Name, structure, and example of each construction

Constructions	Structure	Example
Transitive	Subject + Verb + Object	The baker baked a cake.
Ditransitive	Subject + Verb + Object1 + Object2	The teacher gave students homework.
Caused-Motion	Subject + Verb + Object + Path	The cat chased the mouse into the garden.
Resultative	Subject + Verb + Object + State	The chef cut the cake into slices.

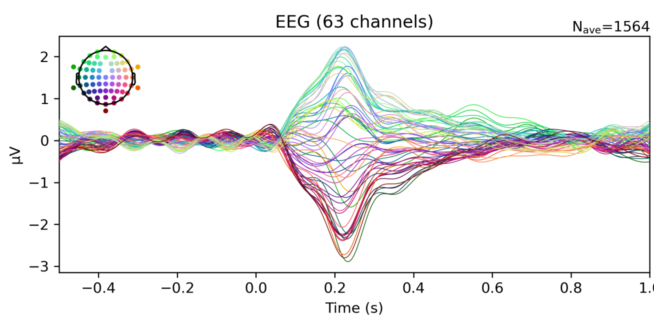

Figure 1: ERP waveform time-locked to the onset of sentences.

Methods

A statistical analysis was conducted to identify EEG-based patterns associated with different syntactic constructions by extracting features from EEG signals corresponding to the subject, verb, and object roles. Since the samples varied in length, direct signal comparisons were not possible, so statistical features were calculated from both the full frequency range signal and individual frequency bands, including delta, theta, alpha, beta, and gamma. Pairwise t-tests were applied to compare each construction class, with p-values adjusted using the Benjamini-Hochberg method to control for false positives. Features with p-values below 0.05 were considered significant, and the results were examined per subject.

For the classification task, a simple Support Vector Machine (SVM) with an RBF kernel was chosen to explore whether brain activity patterns could distinguish between different sentence constructions. A pairwise classification approach was used, evaluated through Leave-One-Out cross-validation. Performance metrics such as accuracy, F1-score, and recall were calculated for each class pair to assess how well the model could separate constructions based on EEG data.

Results

The analysis revealed(Fig.2) no significant differences for the subject role, likely because participants had not yet encountered enough sentence context to distinguish constructions. A small number of significant differences were found in the verb role, which was expected since verbs are not uniquely tied to any specific construction. The object role, appearing later in the sentence when the context is clearer, showed the highest number of significant differences across constructions.

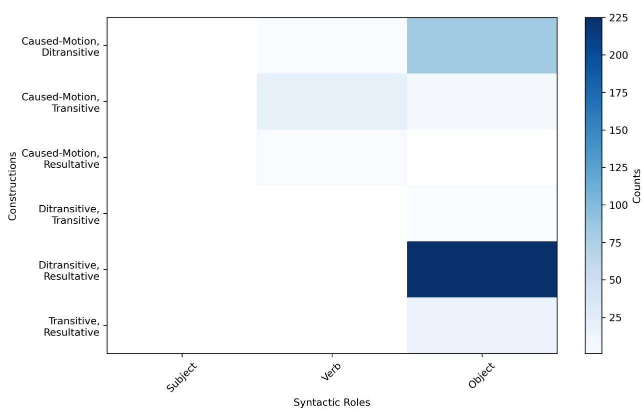

Figure 2: The number of features with p-values less than 0.05 across each pair of constructions.

When comparing construction pairs, the greatest differences were found between ditransitive and resultative constructions, followed by caused-motion and ditransitive constructions. Other pairs showed smaller differences, and there was no significant difference between caused-motion and resultative constructions. While variability in frequency band responses was high among participants, alpha band features generally played a more prominent role in differentiating constructions, followed by beta and delta, with gamma contributing the least. This does not imply that brain activity related to processing constructions is confined to these bands, but rather that they were more responsive to constructional differences.

In the final stage, a token-level classification was conducted using two extracted features—signal kurtosis and peak amplitude—which had previously shown promise in capturing construction-related patterns. These features were computed for subject, verb, and object epochs. When attempting to classify all four constructions simultaneously, the model reached an average accuracy of 30 percent, only slightly above the 25 percent chance level, indicating limited success. As statistical analysis had already suggested that not all constructions were easily distinguishable, the focus shifted to pairwise classification for a more nuanced understanding.

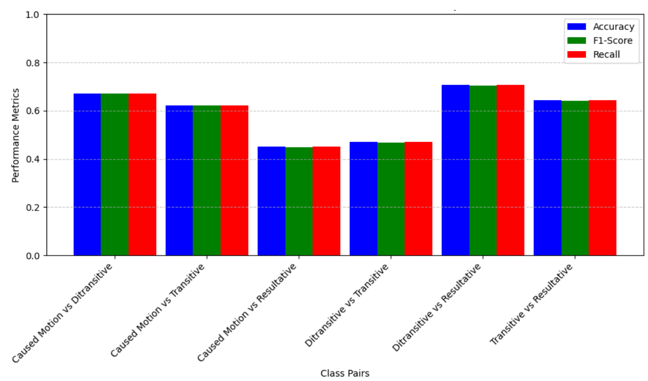

Figure 3: accuracy, recall, f1 score for every pair of constructions classification.

The results(Fig.3) showed that cause-motion vs. resultative and ditransitive vs. transitive pairs had low classification accuracy(the chance level accuracy is 0.5), reflecting the minimal differences observed in the statistical tests. In contrast, the ditransitive vs. resultative pair showed the highest accuracy, reinforcing the earlier finding that these constructions are more distinct in terms of neural responses.

Conclusion

This study demonstrates that the brain distinguishes between abstract grammatical constructions, particularly in the object role and the alpha frequency band, during auditory sentence comprehension. These neural differences were most pronounced between transitive and resultative constructions. The observed object-based effects mirror findings in large language models, such as BERT, where object token embeddings exhibited the most discriminative power for differentiating ASCs (Ramezani, Schilling, & Krauss, 2025). These converging results from brain and model data strengthen the view that both biological and artificial systems encode constructional structure in a graded and feature-sensitive manner, offering promising avenues for bridging neurolinguistics and computational modeling.

Acknowledgments

This work was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation): grants KR 5148/2-1 (project number 436456810), KR 5148/3-1 (project number 510395418), KR 5148/5-1 (project number 542747151), and GRK 2839 (project number 468527017) to PK, and grant SCHI 1482/3-1 (project number 451810794) to AS. Furthermore, the research leading to these results has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (ERC Grant No. 810316 to AM).

References

Goldberg, A. E. (1995). *Constructions: A construction grammar approach to argument structure*. University of Chicago Press.

Goldberg, A. E. (2003). Constructions: A new theoretical approach to language. *Trends in Cognitive Sciences*, *7*(5), 219–224.

Goldberg, A. E. (2006). *Constructions at work: The nature of generalization in language*. Oxford University Press.

Goldberg, A. E. (2009). The nature of generalization in language. *Cognitive Linguistics*, *20*(1), 93–127.

Goldberg, A. E. (2019). *Explain me this: Creativity, competition, and the partial productivity of constructions*. Princeton University Press.

Henningsen, K., & Pulvermüller, F. (2022). Modelling the processing of argument structure constructions in the brain. *Neurobiology of Language*, *3*(1), 1–23.

Pulvermüller, F. (2002). *The neuroscience of language: On brain circuits of words and serial order*. Cambridge University Press.

Pulvermüller, F. (2012). *Meaning in the brain*. MIT Press.

Pulvermüller, F. (2021). Neural reuse of action perception circuits for language, concepts and communication. *Progress in Neurobiology*, *205*, 102127.

Pulvermüller, F. (2023). Neurobiological mechanisms for generalization and specialization in language. *Philosophical Transactions of the Royal Society B*, *378*(1875), 20210358.

Ramezani, P., Schilling, A., & Krauss, P. (2025). Analysis of argument structure constructions in the large language model bert. *Frontiers in Artificial Intelligence*, *8*, 1477246.