# Decoding Metaphors and Brain Signals in Naturalistic Contexts: An Empirical Study based on EEG and MetaPro

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**Abstract**

Metaphors are seen as psycholinguistic phenomena that reveal human cognition. However, their neural basis in naturalistic contexts remains underexplored, although it offers insights into how metaphors shape everyday cognition at the neural level. In this study, we examine how metaphors are reflected in brain activity using electroencephalography (EEG). We analyze EEG data collected during naturalistic reading conditions, where participants read texts without explicit cues indicating the presence of metaphors. Using MetaPro, an advanced metaphor processing tool, we aim to identify the neural signatures of metaphor perception in real-world contexts. Our results reveal significant differences in EEG patterns between metaphorical and literal language. Metaphorical cognition is associated with increased high-frequency EEG variability and enhanced functional connectivity in the left hemisphere. Case studies suggest that different metaphorical concept mappings correspond to distinct neurocognitive patterns. These findings provide important neural evidence for the use of metaphorical concept mappings to analyze and differentiate cognitive processes.

**Keywords:** Metaphor; EEG; Cognition; Brain; MetaPro

## Introduction

Conceptual Metaphor Theory (CMT) (Lakoff & Johnson, 2008) has had great impact in cognitive science. The main argument is that metaphors are not just linguistic phenomena, but fundamental to human cognition. Metaphors frame the conceptualization of abstract ideas into concrete concepts in the way of concept mappings. For example, LOVE IS JOURNEY emphasizes the evolving characteristics of LOVE (a target concept, the central idea being conveyed) in the form of JOURNEY (a source concept, which provides a metaphorical framework for understanding the target concept). Personal experiences often shape the metaphors people use, leading to variations such as LOVE IS MAGIC or LOVE IS UNION. The differences in concept mapping highlight the individualized cognitive frameworks in metaphors, paralleling the approaches of cognitive assessments, for example, the word association test, Rorschach test, and thematic apperception test (Rapaport, Gill, & Schafer, 1946). While these assessments aim to uncover individual cognitive processes by eliciting the projection from textual or visual concept stimuli to associative responses, metaphorical cognition achieves a similar effect by projecting target concepts onto source concepts, thereby revealing distinctive patterns of cognition (Rajagopal, Cambria, Olsher, & Kwok, 2013).

Empirical research has further illuminated the influence of metaphors on human behavior. For example, using different metaphors to describe crime, such as portraying it as a "beast" versus a "virus", has been shown to lead participants to propose different solutions to address crime (Thibodeau & Boroditsky, 2011). More recently, researchers have identified a moderate correlation between concept mappings and voting behaviors at the United Nations (Mao, Zhang, Liu, Hussain, & Cambria, 2024), suggesting that metaphorical cognition may extend to significant decision-making contexts.

Despite these insights, the relationship between metaphors and brain activity remains largely unexplored, particularly in task-independent and naturalistic settings. Previous studies examined neural responses to metaphors by using controlled stimuli, such as isolated phrases contrasting metaphorical and literal expressions (Arzouan, Goldstein, & Faust, 2007; Sun et al., 2022). Some electroencephalography (EEG) studies analyzed metaphor processing in short sentences where metaphors only appeared at the final word (Lachaud, 2013; Bambini, Bertini, Schaeken, Stella, & Di Russo, 2016). Other experiments required participants to explicitly evaluate the comprehensibility and metaphoricity of short texts using binary response systems (Adamczyk et al., 2021). While these studies provide valuable insights, they involve highly structured tasks that prompt participants to consciously focus on metaphor identification. Such approaches do not reflect how metaphors are encountered in naturalistic contexts. The artificial emphasis on metaphoricity in controlled experiments limits their ecological validity, making it difficult to generalize findings to real-world cognitive processing.

To address the gap, we study EEG signals recorded in naturalistic reading contexts from a public dataset (Hollenstein, Troendle, Zhang, & Langer, 2020). Participants engaged with descriptive texts commonly found in everyday reading materials, either reading the material without specific purposes or actively searching for specific relational information within the text. Unlike previous studies, these materials were not artificially designed to emphasize the contrast between metaphorical and literal expressions. Instead, they reflected the types of texts encountered in daily life. The reading tasks also reflected daily reading behavior. Then, we use MetaPro (Mao, Li, He, Ge, & Cambria, 2023), an advanced metaphor processing tool to identify metaphors to obtain EEG signals associated with metaphorical words.

Table 1: The statistics of reading materials of ZuCo 2.0 dataset. NR is natural reading; TSR is task-specific reading.

| | NR | TSR | All |
|---|---|---|---|
| No. of reading scripts | 349 | 390 | 739 |
| Avg. no. of words per script | 19.6 | 21.3 | 20.5 |
| No. of metaphors in total | 139 | 95 | 234 |
| Percentage of metaphorical scripts | 26.9 | 19.5 | 23.0 |
| Avg. no. of metaphors per script | 1.5 | 1.2 | 1.4 |
| No. of uniq. concept mappings | 121 | 76 | 179 |

By maintaining naturalistic reading conditions, this approach ensures that our investigation of metaphorical cognition and neural activity is closely aligned with real-world language comprehension. Since participants were not instructed to explicitly interpret metaphors and reading materials were derived from everyday texts, the neural response to metaphorical expressions likely reflects implicit cognitive mechanisms. The naturalistic approach enables the investigation of the subconscious effects of metaphors on neural processing. We investigate the following Research Questions (RQs):

1) Can metaphorical and literal language perceptions be differentiated based on neural responses in naturalistic contexts?
2) Which brain regions and neural signatures are specifically influenced by the processing of metaphorical language?

Through the analysis of EEG signals between metaphorical and literal words in both natural and task-oriented reading conditions (the task is irrelevant to explicit metaphor identification or interpretation), we observe statistically significant differences in neural responses. Metaphorical words increase high-frequency EEG variability and brain connectivity in the left hemisphere while suppressing neural oscillations in the right, creating clear hemispheric asymmetry. In the task-oriented reading condition, e.g., searching for specific information from sentences, the differences between metaphorical and literal expressions become more pronounced. Case studies further confirm that there are distinct neurocognitive patterns across different metaphorical concept mappings.

This study contributes to the understanding of how metaphorical expressions influence brain activity, particularly in naturalistic contexts. Our findings offer empirical support for the distinct neural processing of metaphorical versus literal language, reinforcing the neuroscientific basis for investigating cognitive patterns and differences through metaphors.

# Material

ZuCo 2.0 dataset (Hollenstein et al., 2020) is used for our EEG and metaphor analysis. The original dataset was developed for capturing simultaneous eye-tracking and EEG data during reading tasks from 18 participants (demographic information of the participants is available in the original paper). It comprises 739 textual scripts, sourced from a Wikipedia corpus, split into two conditions: 349 scripts were read in a normal reading (NR) condition; 390 scripts were read in a task-specific (TSR) condition where participants had to search and identify relation types within the scripts.

Our analysis examines the differences in EEG signals between metaphorical and literal words across both NR and TSR conditions. Sentences sourced from Wikipedia can help reduce the influence of participants' emotional responses in EEG recordings, as their language style is typically objective and descriptive. The recordings were organized into 14 blocks of approximately 50 sentences each, alternating between normal reading and task-specific reading. EEG signals and reading words are aligned by eye movements. Among all reading scripts, the average length is 20.5 words per script (see Table 1). MetaPro detects 234 metaphors and 179 unique concept mappings in total.

# Methodology

## Brain Signal Processing

The EEG of ZuCo 2.0 was recorded with a 128-channel EEG Geodesic Hydrocel system at a sampling rate of 500 Hz. Our preprocessing method follows the original paper. ZuCo 2.0 excluded the peripheral and EOG electrodes, retaining a total of 105 EEG electrodes. For the extraction of EEG data related to metaphorical expressions, we only considered the EEG signals recorded during the participants' first fixation upon encountering a metaphor. As a result, we obtained a total of 2,482 EEG segments associated with metaphorical expressions, including 1,574 segments from the NR condition and 908 segments from the TSR condition. We extracted EEG signals associated with literal expressions from sentences containing metaphorical words. These selected literal words have the same parts of speech as the metaphors, ensuring both contextual consistency and a balanced number of EEG data samples for metaphorical and literal analysis.

To enhance the comprehensiveness and depth of understanding of the cognitive neural mechanisms involved in metaphor processing, this study extracted three types of EEG features, namely time-domain, frequency-domain, and brain network features. In the time domain, we calculated the mean difference (MD) and variance difference (VD) (Ma et al., 2020; T. Wang, Liu, et al., 2025). The MD reflects the overall trend of neural activity in different cognitive states, while the VD quantifies the fluctuations in EEG signals. These time-domain features are vital for understanding the dynamic characteristics of brain activity. In the frequency domain, we analyzed the power spectral density (PSD) to assess the energy distribution of EEG signals across different frequency bands (X. Wang et al., 2024; Natnithikarat, Wilaiprasitporn, & Kongwudhikunakorn, 2023). PSD can reveal brain activation properties during metaphor processing. We constructed brain networks based on functional connectivity (FC) to explore the synchronization and information interaction between different brain regions during metaphor processing. FC is given by a variety of metrics, including Pearson correlation coefficient (COR), coherence (COH), and phase locking value (PLV) (T. Wang, Mao, Liu, Cambria, & Ming, 2025). The above features were analyzed across five frequency bands and eight key brain regions.

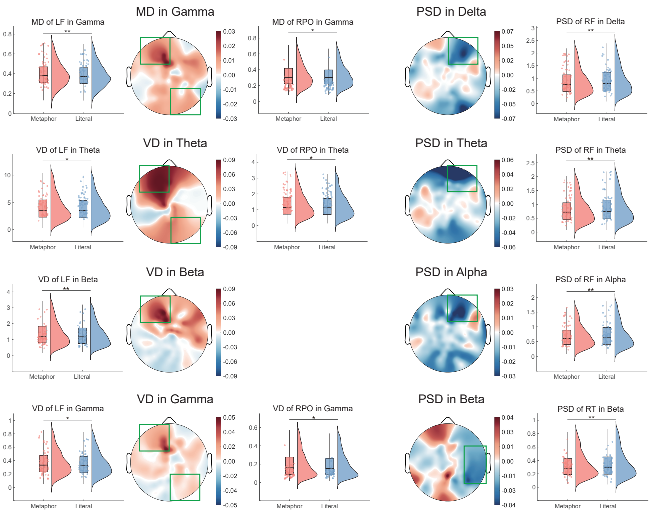


Figure 1: Time- and frequency-domain analysis of metaphorical and literal expressions. Brain maps show the feature difference for each EEG channel after subtracting literal from metaphorical expressions. Green boxes show brain regions with significant differences. Violin graphs are the value distributions of the significant regions. $*$: $p < 0.05$; $**$: $p < 0.01$.

The frequency bands cover delta (1–3 Hz), theta (4–7 Hz), alpha (8–13 Hz), beta (14–30 Hz), and gamma (31–50 Hz). The eight brain regions are the left/right frontal lobes (LF/RF), left/right central regions (LC/RC), left/right parietal-occipital lobes (LPO/RPO), and left/right temporal lobes (LT/RT) (Bian et al., 2014).

## Metaphorical Language Processing

MetaPro was used to detect metaphors and derive concept mappings in this work. It was trained on VU Amsterdam Metaphor Corpus (Steen et al., 2010), the largest available metaphor detection dataset, as well as its extended version, VU Amsterdam Metaphor Corpus with Paraphrases (Mao, He, Ong, Liu, & Cambria, 2024), for metaphor interpretation. Concept mappings are constructed by abstracting the target concept from the paraphrased interpretation of an identified metaphor and the source concept from the original metaphorical expression. These mappings follow the structure of "a target concept is a source concept", e.g., generating PLEASURE IS BODILY_PROCESS from "She devoured his novel.", aligning with CMT. The performance of MetaPro in metaphor identification (Mao & Li, 2021), interpretation (Mao, He, et al., 2024), and concept mapping generation (Ge, Mao, & Cambria, 2022) is documented in the respective research publications. To ensure the reliability of our analysis, the final set of identified metaphors and concept mappings were independently validated and manually corrected by three linguistic experts. They are native English speakers with master's degrees in linguistics, trained with CMT and Metaphor Identification Procedure (Steen et al., 2010) before the validation.

# Results and Discussion

## Cognitive differences of metaphorical and literal expressions in general

**Time- and frequency-domain feature analysis.** We first analyzed the differences in neural mechanisms between the processing of metaphorical and literal words. To achieve this, we conducted a comparative analysis based on time-domain features, e.g., MD and VD, and frequency-domain features, e.g., PSD. The significant differences between the two groups across frequency bands and brain regions are illustrated in Figure 1. An independent-sample t-test was conducted to compare the two groups. The results were further corrected using the false discovery rate (FDR) correction (Genovese, Lazar, & Nichols, 2002).

As shown in Figure 1, for the time-domain features MD and VD on the left column, all significant differences are observed in the higher frequency bands. Moreover, the time-domain features in metaphorical expressions are significantly greater than those in literal expressions. In terms of brain regions, these significant increases are primarily located in the left frontal lobe and the right parietal-occipital lobe. These findings indicate that metaphorical expression processing elicits more active high-frequency neural oscillations, particularly in brain regions associated with contextual integration and deep semantic analysis, such as the left frontal lobe. This result is consistent with previous results from the left prefrontal lobe in semantic cognition studies (L. Wang, Hagoort, & Jensen, 2018; Bastiaansen & Hagoort, 2015). Furthermore, we observe significant differences in the PSD features in the frequency domain across four frequency bands, excluding the gamma band (see the right column in Figure 1). Notably, the PSD features of metaphorical expressions are significantly lower than those of literal expressions. Regarding brain regions, the significant reduction in PSD for metaphorical expressions is primarily observed in the right frontal lobe and the right temporal lobe.

The observations suggest that when processing metaphors, the left hemisphere may play a more dominant role in information processing, while the right hemisphere might contribute through inhibitory mechanisms to optimize global resource allocation and information processing across the brain (Proverbio, Crotti, Zani, & Adorni, 2009).

**Brain network feature analysis.** In the previous section, we examined the time- and frequency-domain features of individual EEG channels, focusing on signal variations within single channels. However, these analyses do not address the interactions between different brain regions during metaphorical cognition. Here, we explore the differences in brain region interactions between metaphorical and literal cognition, using various FC features. The interaction is visualized in brain networks with BrainNet Viewer (Xia, Wang, & He, 2013). An independent-sample t-test is performed to compare FC between the two groups. The t-values of significantly different connections ($p < 0.05$) are visualized in Figure 2.

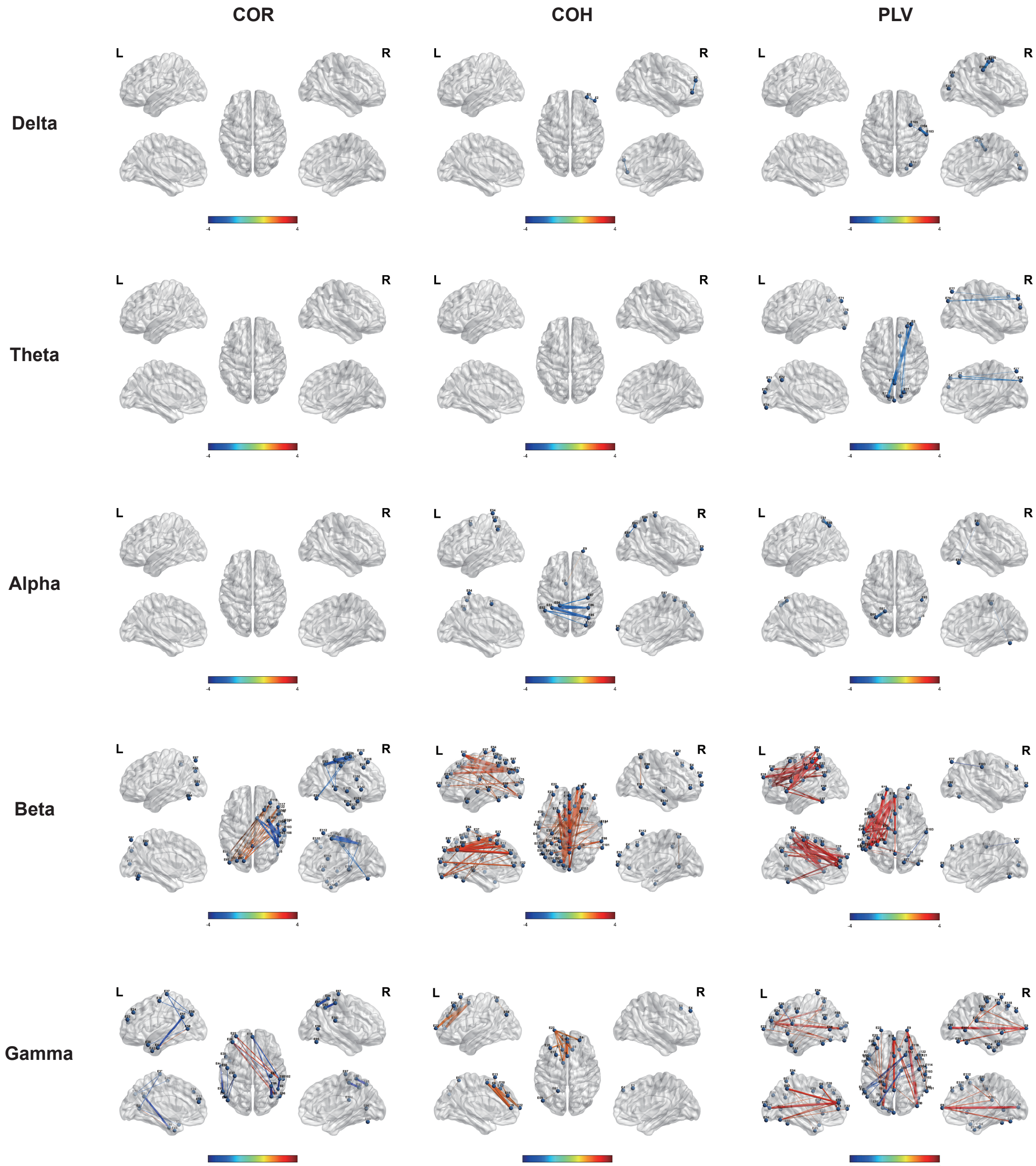


Figure 2: Brain network analysis of metaphorical and literal expressions. The lines indicate significant connectivity differences between metaphors and literals. The line colors indicate t-values. For better visualization, the sparsity threshold was set to 0.05.

As shown in Figure 2, cognitive differences between metaphorical and literal expressions are observed mainly in the beta and gamma bands. Compared to literal expressions, metaphorical expressions exhibit stronger brain connectivity in the frontal, central and temporal lobes (indicated by denser red connection lines). These differences are observed primarily in the left hemisphere, demonstrating a significant hemispheric asymmetry. These findings reflect an increased demand for semantic comprehension during metaphor processing, involving cross-regional functional coupling and high-frequency information exchange in the left hemisphere.

This may reflect the left frontotemporal network's key role in semantic integration and reasoning (Barbey & Barsalou, 2009). Similar phenomena have also been observed in other complex semantic analysis tasks (Bizas et al., 1999; Adamczyk et al., 2021). Besides, the most significant intergroup differences in metaphorical expressions are observed in the left frontal lobe, involving long-range connections between the left frontal lobe and other regions. This inter-regional synchrony highlights the role of the left frontal lobe in processing metaphorical expressions, aligning with previous semantic cognition studies (Kacinik & Chiarello, 2007).

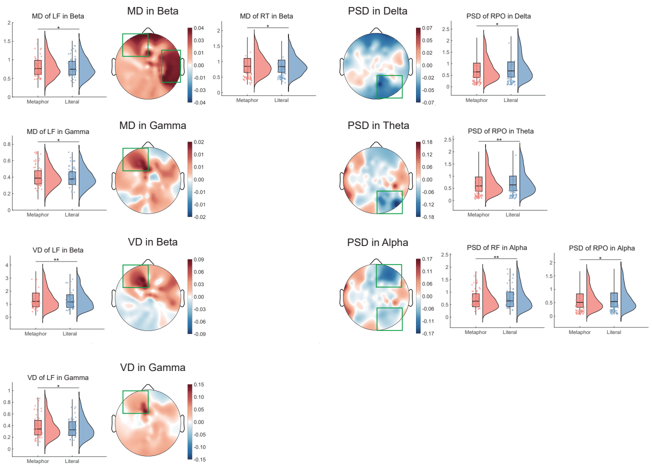


Figure 3: Time- and frequency-domain analysis of metaphorical and literal expressions in an NR condition.

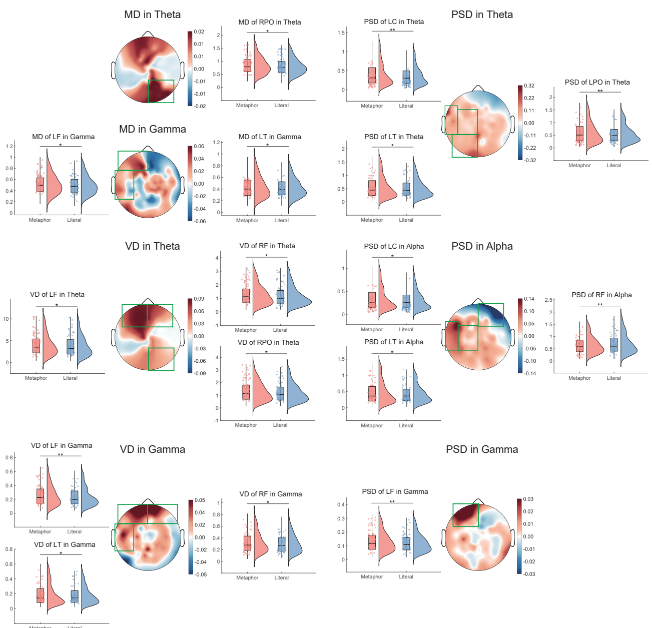


Figure 4: Time- and frequency-domain analysis of metaphorical and literal expressions in a TSR condition.

**Summary.** The statistical results of the three types of features, e.g., time- and frequency-domain features, and brain network features, indicate that metaphorical expressions are associated with increased EEG signal fluctuations in the high-frequency bands of the left hemisphere, significantly enhanced brain connectivity of the left hemisphere, and suppressed neural oscillations in the right hemisphere. This asymmetric activity between the brain hemispheres is closely related to metaphorical cognition. The left frontal lobe plays a crucial hub-like role in the processing of metaphorical expressions. These findings suggest that metaphor processing involves not only the engagement of higher-order cognitive functions such as conceptual mapping but also the coordi-

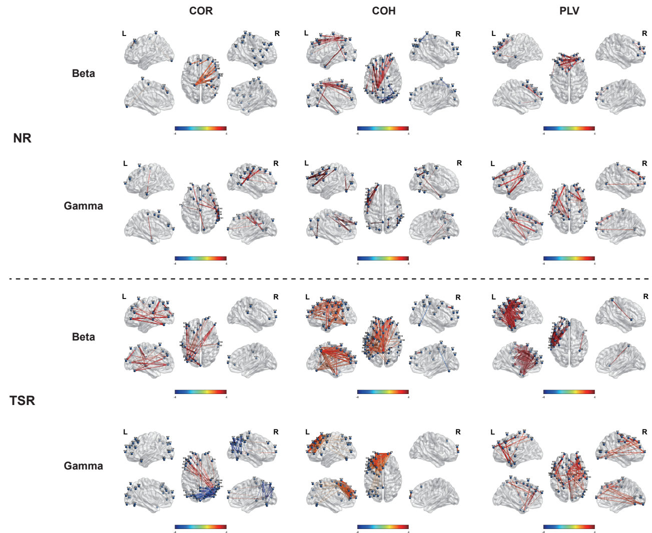


Figure 5: Brain network analysis of metaphorical and literal expressions in NR and TSR conditions.

nation between specialized brain regions in the left hemisphere (Rapp, Leube, Erb, Grodd, & Kircher, 2004). The hemispheric asymmetry suggests the left hemisphere dominates metaphor integration, while reduced right-hemisphere activity points to lesser involvement in literal processing. These findings highlight the brain's dynamic, lateralized, and networked mechanisms for handling linguistic abstraction (Bohrn, Altmann, & Jacobs, 2012).

## Cognitive differences of metaphorical and literal expressions in NR and TSR conditions

**Time- and frequency-domain feature analysis.** This section examines the impact of different reading conditions (NR and TSR) on metaphorical cognition. We first analyze cognitive differences in time- and frequency-domain. As shown in Figure 3 with the NR condition, during the processing of metaphorical expressions, the left frontal lobe exhibits significantly enhanced high-frequency neural oscillations, while the right frontal lobe and right parietal-occipital lobe show inhibited neural activity (as observed in Figure 1). However, in Figure 4 with the TSR condition, the differences between metaphors and literals are more pronounced. The frequency-domain features indicate stronger neural oscillations in the left hemisphere for metaphors at high-frequency bands, while activity in the right hemisphere is relatively reduced.

**Brain network feature analysis.** Brain network differences between metaphorical and literal expressions under NR and TSR conditions are shown in Figure 5. The results show that metaphorical expressions lead to enhanced brain connectivity in the left frontal lobe, central region, and temporal lobe in the TSR condition, in contrast to patterns in the NR condition. Moreover, metaphor processing exhibits more pronounced hemispheric asymmetry in brain connectivity.

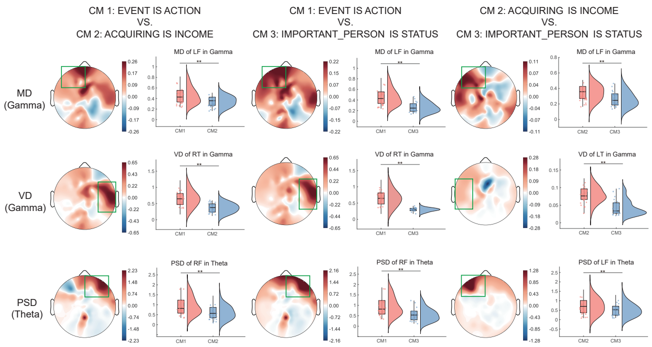


Figure 6: Time- and frequency-domain analysis of different concept mapping. CM denotes concept mapping.

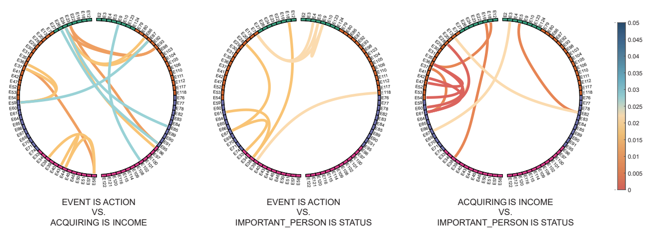


Figure 7: Brain network analysis of different concept mappings. The circular plots show FC patterns, with nodes representing EEG channels and lines indicating significant connectivity differences. The line colors indicate p-values.

**Summary.** The analyses of the time-domain, frequency-domain, and brain networks suggest that cognitive differences between metaphorical and literal words become more significant in the TSR condition. This heightened distinction may be attributed to the increased cognitive demands of task-oriented reading, which necessitates greater attention for content comprehension. Metaphorical processing was particularly salient in this context. Unlike literal expressions, which can often be processed through direct semantic retrieval, metaphorical expressions engage higher-order neural mechanisms to map abstract concepts onto familiar frameworks to fully understand the required information for specific reading purposes.

This increased processing demand is reflected in the enhanced neural oscillations in the left hemisphere, accompanied by a significant increase in left-hemisphere brain connectivity. The enhanced neural oscillations indicate that in task-oriented reading scenarios, the brain allocates additional cognitive resources for integrating and synthesizing abstract metaphorical content, facilitating deeper semantic processing. The increased left-hemisphere brain connectivity shows that the TSR condition promotes more coordinated and efficient communication between regions responsible for language processing, and conceptual thinking, supporting the construction of meaningful interpretation of metaphorical expressions.

## Cognitive differences between different concept mappings in metaphorical expressions

We randomly sample three different concept mappings, e.g., EVENT IS ACTION ($N = 46$), ACQUIRING IS INCOME ($N = 34$), and IMPORTANT_PERSON IS STATUS ($N = 28$), and use their EEG signals. We analyze the cognitive differences of these concept mappings in the time- and frequency-domain in Figure 6. Based on previous analyses, we focus on time-domain features in the gamma band and frequency-domain features in the theta band. Only the brain regions with the most significant differences are reported. We also examine the brain network differences among these concept mappings with a focus on COH in the beta band in Figure 7.

In Figures 6 and 7, distinct concept mappings exhibit significant differences across time- and frequency-domain, and brain network features, indicating that distinct concept mappings engage specific cognitive mechanisms. For example, in the comparison between EVENT IS ACTION and ACQUIRING IS INCOME and the comparison between EVENT IS ACTION and IMPORTANT_PERSON IS STATUS, the most significant differences manifest in left frontal lobe in MD, right temporal lobe in VD and right frontal lobe in PSD in Figure 6. However, in the comparison between ACQUIRING IS INCOME and IMPORTANT_PERSON IS STATUS, the VD variations change from the right temporal lobe to the left temporal lobe, and the PSD variations change from the right frontal lobe to the left frontal lobe. This dynamic change suggests that different concept mappings rely on specific brain regions for processing, involving distinct cortical resources and information integration mechanisms. Furthermore, in Figure 7, different concept mappings exhibit significant differences in connectivity patterns. For instance, in the comparison between EVENT IS ACTION and ACQUIRING IS INCOME, the inter-group differences are mainly reflected in inter-hemispheric information exchange, indicating significant differences in the transfer and integration of information between the hemispheres for these two concept mappings. In contrast, in the comparison between EVENT IS ACTION and IMPORTANT_PERSON IS STATUS and the comparison between ACQUIRING IS INCOME and IMPORTANT_PERSON IS STATUS, the significant differences are reflected in intra-hemispheric interactions within the left hemisphere.

These findings indicate that different metaphorical concept mappings are processed through distinct neural mechanisms, rather than a uniform cognitive pathway. Each concept mapping recruits specialized neural circuits that align with its unique conceptual demands, suggesting the multifaceted nature of metaphorical cognition across both localized brain regions and large-scale neural networks. This biological differentiation implies that metaphorical cognition is not merely a linguistic phenomenon but also reflects concept-specific neural dynamics. Thus, metaphors can be used as a medium for cognitive analysis, characterized by measurable variations in brain activity associated with their concept mappings.

## References


Adamczyk, P., Jáni, M., Ligeza, T. S., Płonka, O., Błądziński, P., & Wyczesany, M. (2021). On the role of bilateral brain hypofunction and abnormal lateralization of cortical information flow as neural underpinnings of conventional metaphor processing impairment in schizophrenia: an fMRI and EEG study. *Brain Topography*, *34*(4), 537–554.

Arzouan, Y., Goldstein, A., & Faust, M. (2007). Dynamics of hemispheric activity during metaphor comprehension: Electrophysiological measures. *Neuroimage*, *36*(1), 222–231.

Bambini, V., Bertini, C., Schaeken, W., Stella, A., & Di Russo, F. (2016). Disentangling metaphor from context: an ERP study. *Frontiers in Psychology*, *7*, 559.

Barbey, A., & Barsalou, L. (2009). Reasoning and problem solving: Models. *Encyclopedia of Neuroscience*, *8*(2), 35–43.

Bastiaansen, M., & Hagoort, P. (2015). Frequency-based segregation of syntactic and semantic unification during online sentence level language comprehension. *Journal of Cognitive Neuroscience*, *27*(11), 2095–2107.

Bian, Z., Li, Q., Wang, L., Lu, C., Yin, S., & Li, X. (2014). Relative power and coherence of EEG series are related to amnestic mild cognitive impairment in diabetes. *Frontiers in Aging Neuroscience*, *6*, 11.

Bizas, E., Simos, P., Stam, C., Arvanitis, S., Terzakis, D., & Micheloyannis, S. (1999). EEG correlates of cerebral engagement in reading tasks. *Brain Topography*, *12*, 99–105.

Bohrn, I. C., Altmann, U., & Jacobs, A. M. (2012). Looking at the brains behind figurative language—a quantitative meta-analysis of neuroimaging studies on metaphor, idiom, and irony processing. *Neuropsychologia*, *50*(11), 2669–2683.

Ge, M., Mao, R., & Cambria, E. (2022). Explainable metaphor identification inspired by conceptual metaphor theory. *Proceedings of the AAAI Conference on Artificial Intelligence*, *36*(10), 10681-10689.

Genovese, C. R., Lazar, N. A., & Nichols, T. (2002). Thresholding of statistical maps in functional neuroimaging using the false discovery rate. *Neuroimage*, *15*(4), 870–878.

Hollenstein, N., Troendle, M., Zhang, C., & Langer, N. (2020). ZuCo 2.0: A dataset of physiological recordings during natural reading and annotation. In *Proceedings of the 12th Conference on Language Resources and Evaluation* (pp. 138–146).

Kacinik, N. A., & Chiarello, C. (2007). Understanding metaphors: Is the right hemisphere uniquely involved? *Brain and Language*, *100*(2), 188–207.

Lachaud, C. M. (2013). Conceptual metaphors and embodied cognition: EEG coherence reveals brain activity differences between primary and complex conceptual metaphors during comprehension. *Cognitive Systems Research*, *22*, 12–26.

Lakoff, G., & Johnson, M. (2008). *Metaphors we live by*. University of Chicago Press.

Ma, C., Li, W., Cao, J., Du, J., Li, Q., & Gravina, R. (2020). Adaptive sliding window based activity recognition for assisted livings. *Information Fusion*, *53*, 55–65.

Mao, R., He, K., Ong, C. B., Liu, Q., & Cambria, E. (2024). MetaPro 2.0: Computational metaphor processing on the effectiveness of anomalous language modeling. In *Findings of the Association for Computational Linguistics: ACL* (p. 9891-9908).

Mao, R., & Li, X. (2021). Bridging towers of multi-task learning with a gating mechanism for aspect-based sentiment analysis and sequential metaphor identification. In *Proceedings of the AAAI Conference on Artificial Intelligence* (Vol. 35, p. 13534-13542).

Mao, R., Li, X., He, K., Ge, M., & Cambria, E. (2023). MetaPro Online: A computational metaphor processing online system. In *Proceedings of the 61st Annual Meeting of the Association for Computational Linguistics (Volume 3: System Demonstrations)* (Vol. 3, pp. 127–135).

Mao, R., Zhang, T., Liu, Q., Hussain, A., & Cambria, E. (2024). Unveiling diplomatic narratives: Analyzing United Nations Security Council debates through metaphorical cognition. In *Proceedings of the Annual Meeting of the Cognitive Science Society* (Vol. 46, p. 1709-1716).

Natnithikarat, P., Wilaiprasitporn, T., & Kongwudhikunakorn, S. (2023). Combining EEG and NLP features for predicting students' lecture comprehension using ensemble classification. In *2023 RIVF International Conference on Computing and Communication Technologies* (pp. 218–223).

Proverbio, A. M., Crotti, N., Zani, A., & Adorni, R. (2009). The role of left and right hemispheres in the comprehension of idiomatic language: An electrical neuroimaging study. *BMC Neuroscience*, *10*, 1–16.

Rajagopal, D., Cambria, E., Olsher, D., & Kwok, K. (2013). A graph-based approach to commonsense concept extraction and semantic similarity detection. In *WWW* (p. 565-570).

Rapaport, D., Gill, M., & Schafer, R. (1946). *Diagnostic psychological testing: The theory, statistical evaluation, and diagnostic application of a battery of tests*. The Year Book Publishers.

Rapp, A. M., Leube, D. T., Erb, M., Grodd, W., & Kircher, T. T. (2004). Neural correlates of metaphor processing. *Cognitive Brain Research*, *20*(3), 395–402.

Steen, G. J., Dorst, A. G., Herrmann, J. B., Kaal, A., Krennmayr, T., & Pasma, T. (2010). *A method for linguistic metaphor identification: From MIP to MIPVU* (Vol. 14). John Benjamins Publishing.

Sun, L., Chen, H., Zhang, C., Cong, F., Li, X., & Hämäläinen, T. (2022). Decoding brain activities of literary metaphor comprehension: An event-related potential and EEG spectral analysis. *Frontiers in Psychology*, *13*, 913521.

Thibodeau, P. H., & Boroditsky, L. (2011). Metaphors we think with: The role of metaphor in reasoning. *PLOS One*, *6*(2), e16782.

Wang, L., Hagoort, P., & Jensen, O. (2018). Language prediction is reflected by coupling between frontal gamma and posterior alpha oscillations. *Journal of Cognitive Neuroscience*, *30*(3), 432–447.

Wang, T., Liu, S., He, F., Du, M., Dai, W., Ke, Y., & Ming, D. (2025). Affective body expression recognition framework based on temporal and spatial fusion features. *Knowledge-Based Systems*, *308*, 112744.

Wang, T., Mao, R., Liu, S., Cambria, E., & Ming, D. (2025). Explainable multi-frequency and multi-region fusion model for affective brain-computer interfaces. *Information Fusion*, *118*, 102971.

Wang, X., Hu, R., Wang, T., Chang, Y., Liu, X., Li, M., … Ming, D. (2024). Resting-state electroencephalographic signatures predict treatment efficacy of tACS for refractory auditory hallucinations in schizophrenic patients. *IEEE Journal of Biomedical and Health Informatics*.

Xia, M., Wang, J., & He, Y. (2013). BrainNet Viewer: A network visualization tool for human brain connectomics. *PloS One*, *8*(7), e68910.