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Visual Analysis of Research on N400 in the Past Decade Based on CiteSpace

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Abstract

As a classic event-related potential (ERP) component closely associated with semantic processing, the N400 has long been a core research topic in cognitive neuroscience. To clarify the research status, evolutionary trends and hotspots of N400 studies over the past decade, this study conducted a bibliometric and visual analysis based on 2166 articles retrieved from the Web of Science Core Collection (2016-May 2026) using CiteSpace. We systematically analyzed annual publication trends, keyword co-occurrence, clustering, keyword bursts and thematic evolution. The results revealed that the number of publications on N400 presented a fluctuating upward trend, and the research field maintained high academic vitality. The overall research system formed a three-tier structure consisting of basic neural mechanisms, core linguistic application and frontier exploratory research. Research hotspots gradually shifted from classic semantic violation and semantic integration paradigms to cross-language processing (especially Chinese), word frequency effects, brain network dynamics and cognitive aging in older adults. Thematic evolution showed an obvious tendency of multi-dimensional and interdisciplinary integration. This study objectively maps the overall landscape of contemporary N400 research. Limitations and future research directions are also discussed, providing references for subsequent exploration on the neural mechanisms of human semantic construction.

Subject Areas

Linguistics

Keywords

N400, Event-Related Potentials (ERP), Semantic Processing, Bibliometric Analysis, CiteSpace, Research Trend, Cross-Language Research

1. Introduction

Semantic processing is a defining characteristic of human behavior. It constitutes the core of language comprehension and supports the retrieval of existing knowledge during human reasoning, planning and problem-solving [1]. Semantic processing involves extensive functional brain networks. In recent years, the rapid development of neuroscientific techniques such as event-related potentials (ERPs) has enabled the visualization of real-time dynamic brain potentials during semantic cognition, providing new perspectives and methodological foundations for relevant research.

Event-Related Potentials (ERPs) refer to neuroelectrophysiological responses closely linked to specific cognitive events. These responses are extracted from spontaneous electroencephalography (EEG) by time-locking and averaging brain activities elicited by repeatedly presented stimuli. A major strength of EEG is its millisecond-level temporal resolution for tracking real-time brain activity, which allows researchers to clearly observe dynamic changes in cognitive processes [2]. This advantage makes EEG a vital tool for exploring the dynamic neural mechanisms underlying higher-order cognitive functions including language, attention and memory. With advances in signal processing technology and electrode arrays, ERP research has expanded from early investigations of primary responses to sensory stimuli (e.g., P100, N100) to explorations of higher-order cognitive components related to complex semantic and syntactic processing. Among these components, the N400 has become one of the most classic ERP components in language processing research [3] and is most closely associated with semantic processing.

In 1980, Kutas and Hillyard first identified a negative potential highly sensitive to semantic congruity in language comprehension research [4]. This component typically peaks 300 to 600 milliseconds after stimulus onset and presents prominent negative deflections over the central-parietal scalp region, thus it is named the N400. The N400 effect describes the phenomenon that semantically incongruent or hard-to-integrate stimuli elicit larger negative amplitudes than semantically congruent stimuli [4]. Widely observed across experimental paradigms such as semantic priming [5] [6] and sentence contextual violation [7] [8], this effect reflects differences in semantic integration and lexical access in the brain. The discovery of the N400 not only establishes its status as a key neural marker for semantic integration, but also initiates decades of systematic research on its functional implications, cross-modal features and clinical applications.

The N400 is not exclusive to the language processing system and can realize cross-modal representation of semantic processing. Studies have shown that the N400 can be elicited by various meaningful stimuli, including sign language [9], pictures [10]-[12], and human faces [13] [14]. It indexes a domain-general process of meaning construction [2] [15].

Currently, the N400 has been widely adopted in experimental research. Existing reviews mainly focus on its functional implications and experimental paradigms, while systematic bibliometric analyses concerning the overall intellectual structure,

developmental context and research hotspots in the N400 field remain scarce. Nevertheless, N400 research has maintained steady popularity across multiple disciplines in recent years. As an essential tool for scientific knowledge mapping, CiteSpace can effectively identify core publications, key authors, dominant topics and evolutionary trends within a research field. Accordingly, this study conducts a visual analysis of N400-related literature using CiteSpace. It aims to systematically summarize research progress and intellectual structure in the N400 field, and identify core research themes and evolutionary trends. Based on the bibliometric results, this study provides empirical evidence for theoretical integration in neurolinguistics, offers references for paradigm optimization in ERP research, and delivers literature support for exploring semantic processing mechanisms across languages (especially Chinese) and developing assessment tools for clinical cognition.

2. Data Source

To ensure the completeness and accuracy of data, this study adopted the Web of Science (WOS) Core Collection developed by the Institute for Scientific Information as the data source. The WOS Core Collection includes tens of thousands of high-impact academic journals worldwide, covering natural sciences, life sciences, social sciences and other disciplines. It boasts high academic authority and comprehensive literature coverage particularly in cognitive neuroscience and psychology [16]. Compared with Scopus and Dimensions, WOS data structures are highly compatible with CiteSpace, which enables stable bibliometric analyses of institutions, countries, citations and keywords.

In formulating the data retrieval strategy, we conducted multiple rounds of testing and adjustments to ensure that the search results comprehensively and objectively reflect the current research landscape of the "N400" field. Specifically, the search was performed using the Topic (TS) field, which covers titles, abstracts, and keywords, with the search query set as TS = ("N400"). Regarding document types, to maximize data completeness and coverage, we did not impose strict restrictions; instead, we included articles, reviews, proceedings papers, and other document types. The retrieval time span was set from January 1, 2016, to May 1, 2026, aiming to systematically capture research outputs and developmental trends in this field over the past decade.

Because the search term contains the letter combination "N," which commonly serves as the abbreviation for nitrogen in disciplines such as chemistry, agriculture, and materials science, the search results could easily include a large number of irrelevant documents. To ensure data accuracy, after retrieval we manually combined subject category information to exclude non-relevant disciplines, including chemistry, agriculture, and ecology, thereby eliminating interference from nitrogen-related research and obtaining a clean sample of domain-relevant literature.

Following the above retrieval strategy, a total of 2166 relevant papers were obtained. All retrieved records were then exported in the "full records and cited references" format and saved as plain text files, which served as the foundational data for subsequent knowledge map visualization and bibliometric analysis using

CiteSpace software.

Because CiteSpace filters out low-relevance data during the generation of knowledge maps, we did not perform manual screening of the records to preserve data integrity.

2.1. Publication Trends

Annual publication volume reflects the research output and developmental trajectory of a research field. Based on 2166 eligible articles published between January 2016 and May 2026, a publication trend graph was generated (see **Figure 1**).

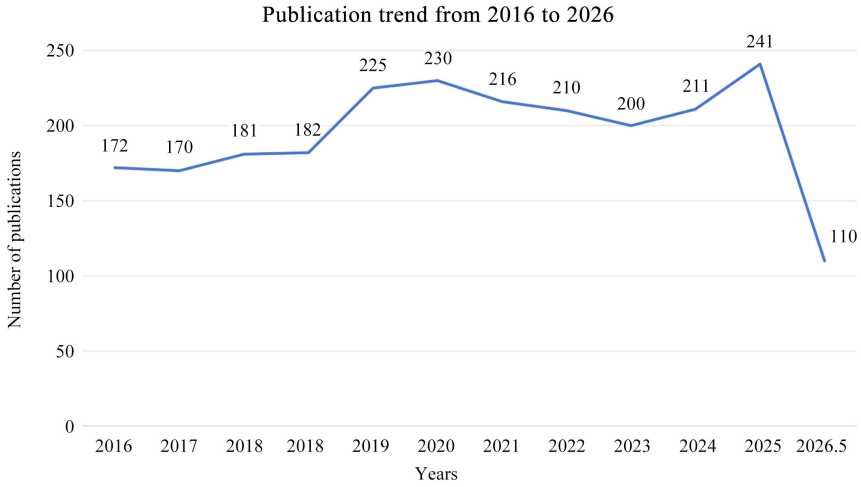

Figure 1. Publications on N400 (2016-May 2026).

As illustrated in the figure, publications on N400 research showed an overall fluctuating upward trend from 2016 to 2025, with output remaining at a high level. This period can be divided into three distinct stages. First, the phase of steady development spanned 2016 to 2018. Annual publications ranged from 170 to 182 with moderate growth, indicating stable research interest and continuous refinement of fundamental theories in this field. Second, the period from 2019 to 2020 witnessed rapid growth. The number of publications rose sharply from 182 in 2018 to 225 in 2019 and 230 in 2020, forming the first minor peak within the research timeframe. The average annual publication count exceeded 220 during this stage, accounting for 22.36% of the total publications. These figures reveal a research boom in N400 studies and a marked acceleration in research output. Third, the years 2021 to 2025 represented a period of high-level fluctuation and renewed growth. Although publication numbers declined slightly, they stayed above 200 per year and reached the highest point of 241 in 2025. It demonstrates that research enthusiasm did not wane; after a brief adjustment, the field entered another phase of rapid expansion with an enlarging research scale.

It should be noted that the publication data for 2026 only covered records up to May, with 110 publications in total, which cannot reflect the full-year output. Overall, the fluctuating increase in annual publications from 2016 to 2025 suggests

growing global academic attention to N400 research. This field maintains strong academic vitality and sustained research interest, with promising prospects for future development.

2.2. Keyword Co-Occurrence

Keywords are concise representations of research themes. Keyword co-occurrence analysis can intuitively reveal research hotspots, core topics, and thematic correlations within a field. In this study, standardized sample data were imported into CiteSpace, with the time span set from January 2016 to May 2026. Keywords were selected as the analysis item to generate the keyword co-occurrence map of N400 research.

To capture the micro-dynamic evolution of annual research hotspots in the N400 field, we set the CiteSpace time-slicing parameter to 1 year. For node threshold selection, we tested three schemes with Top N values of 50, 60, and 80, respectively. Comparative analysis revealed that the core cluster compositions and the distributions of the top 15 burst terms did not change substantially across the three schemes, indicating that the analytical results are not sensitive to the threshold choice. Further examination showed that at N = 50, high-centrality nodes were over-pruned, whereas at N = 80, increased noise nodes led to a looser modular structure. Based on a comprehensive balance between cluster silhouette clarity and network coherence, we ultimately adopted Top N = 60 as the threshold.

Using the optimized parameters, the resulting keyword co-occurrence network consists of 158 nodes and 180 links, with a network density of 0.0145. Node size is positively correlated with keyword frequency, and link thickness is positively correlated with keyword co-occurrence frequency. The overall network presents a clear structure with prominent core topics and a complete hierarchical layout (See Figure 2).

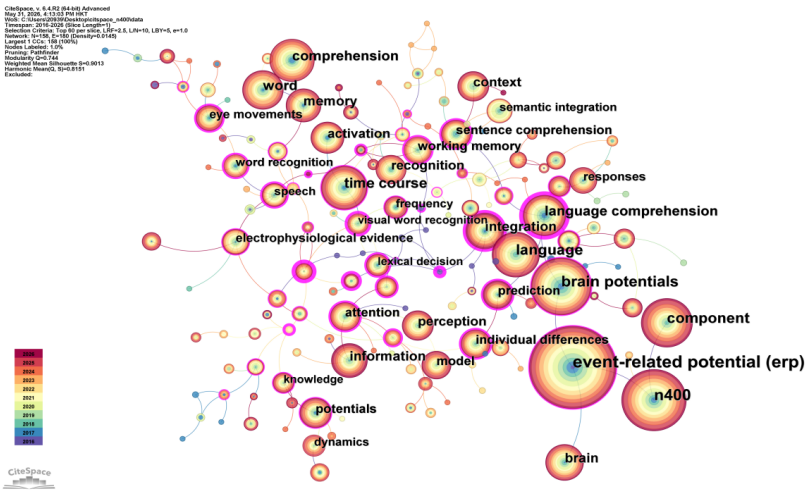

Figure 2. Keyword co-occurrence knowledge map.

A total of 158 keywords were extracted in this study, with a cumulative total

frequency of 10,141. Based on the literature from the Web of Science (WOS) Core Collection, the top 30 keywords are summarized in Table 1. Centrality indicates the importance of each keyword within the keyword co-occurrence network and reflects the prevailing research hotspots and themes in this field during the study period.

Table 1. Keyword frequency table.

Number	Count	Centrality	Year	Keywords
1	984	0.1	2016	Event-relatedpotential (erp)
2	587	0.05	2016	N400
3	538	0.12	2016	Brainpotentials
4	395	0	2016	Component
5	369	0.08	2016	Language
6	325	0.16	2016	Timecourse
7	287	0.64	2016	Language comprehension
8	281	0	2016	Comprehension
9	267	0.05	2016	Word
10	238	0	2016	Brain
11	224	0.5	2016	Integration
12	210	0.05	2016	Information
13	202	0.08	2016	Memory
14	177	0	2016	Activation
15	173	0.03	2016	Perception
16	171	0.03	2016	Context
17	167	0.06	2016	Recognition
18	156	0.1	2016	Potentials
19	151	0.32	2016	Attention
20	149	0	2016	Model
21	145	0.37	2016	Working memory
22	143	0.25	2017	Individual differences
23	141	0.23	2016	Prediction
24	138	0.28	2016	Sentence comprehension
25	126	0.1	2016	Responses
26	124	0.15	2016	Electrophysiological evidence
27	114	0.22	2016	Eyemovements
28	111	0.35	2016	Speech
29	104	0.26	2016	Word recognition
30	99	0	2016	Semantic integration

The keyword co-occurrence network visually reveals a tiered distribution pattern of research themes within the collected literature, which can be summarized as core, intermediate and peripheral thematic clusters based on keyword frequency and centrality metrics. The core cluster gathers foundational technical keywords such as N400, ERP and brain potentials, reflecting the fundamental methodolog-

ical framework adopted across most N400 publications. The intermediate cluster centers on terms related to linguistic cognition (language comprehension, semantics, sentence processing etc.), corresponding to the mainstream research directions that dominate existing empirical studies. The peripheral cluster covers keywords about individual variation and cross-language paradigms (age, older adults, Chinese etc.), which capture emerging expanding research themes in recent years. This hierarchical grouping merely describes the distribution of published research topics visualized via bibliometric mapping, rather than reflecting inherent hierarchical neural mechanisms of N400 semantic processing.

2.3. Keyword Clustering Analysis

Keyword clustering classifies and summarizes research themes based on keyword co-occurrence maps. It can directly display core thematic clusters and the distribution of research hotspots, and serves as a core method to sort out the research system of a field.

Using the clustering function of CiteSpace, this study conducted a keyword clustering analysis on N400-related research from 2016 to May 2026 and generated a keyword clustering map. The modularity Q of the map is 0.8135, which is much higher than the critical value of 0.3, indicating a statistically significant cluster structure. The weighted mean silhouette S is 0.9419, exceeding the critical value of 0.7. This result demonstrates that the clustering outcomes are highly reliable and can fully and clearly reflect the distribution of research topics in this field (See Figure 3).

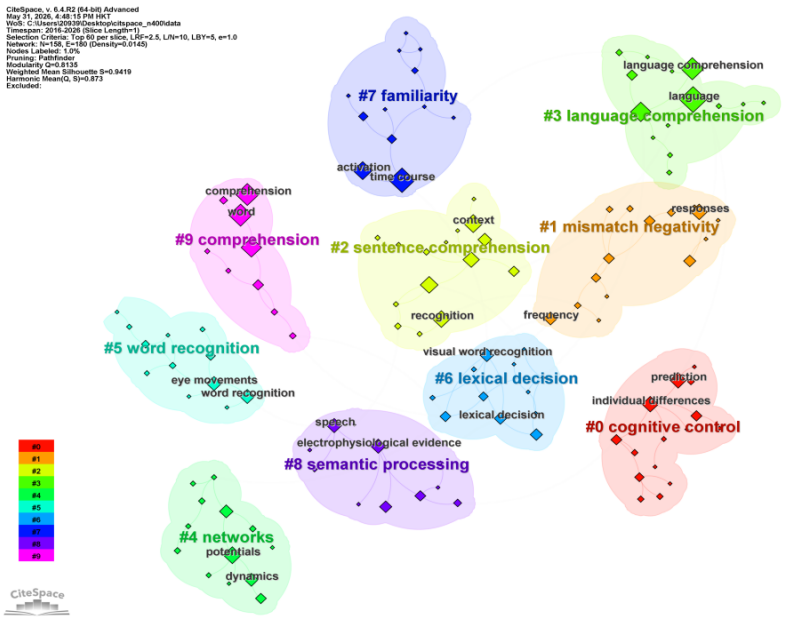

Figure 3. Keyword clustering network.

It can be observed that ten major clusters are identified, namely cognitive control, mismatch negativity, sentence comprehension, language comprehension,

networks, word recognition, lexical decision, familiarity, semantic processing, and comprehension. Accordingly, N400 research from 2016 to May 2026 is closely associated with cognitive control, language comprehension, semantic processing, word recognition and brain network mechanisms, forming a complete and logically coherent research framework.

When sorting the ten keyword clusters by research content, we can inductively divide these published thematic lines into three broad thematic categories for interpretive convenience: foundational neural mechanism studies, core linguistic application research, and extended frontier explorations. This categorical grouping is a subjective inductive summary of bibliometric clustering outputs, not an empirically validated structural framework of N400 cognitive function. The basic mechanism layer consists of Cluster #0 (cognitive control), Cluster #4 (networks) and Cluster #1 (mismatch negativity). It focuses on fundamental mechanisms of neural cognition, brain networks and ERP components, laying theoretical and technical foundations for the entire field. The core application layer includes Cluster #3 (language comprehension), Cluster #2 (sentence comprehension), Cluster #5 (word recognition), Cluster #6 (lexical decision), Cluster #8 (semantic processing) and Cluster #9 (comprehension). It centers on application scenarios covering the whole process of linguistic cognition and represents the core focus of N400 research. The in-depth extension layer is represented by Cluster #7 (familiarity), which explores influencing factors and regulatory mechanisms of the N400 effect. This research branch also expands continuously to cross-language studies, population differences and multimodal integration, reflecting the cutting-edge development trends of this field.

2.4. Keyword Burst Analysis

Keyword burst indicators identify terms with dramatic changes in occurrence frequency, which helps to explore the research frontiers of N400 studies. Standardized data were imported into CiteSpace, with the time range set from January 2016 to May 2026. The top 60 high-frequency items were retained for each time slice, and keywords were selected as the analysis unit. Burst detection was conducted based on the keyword co-occurrence map to generate the visualization of the top 25 burst keywords in N400 research from 2016 to 2026.

The figure shows that semantic integration had the highest burst strength of 8.96 during 2018 to 2020, followed by word frequency with a burst strength of 8.27 from 2023 to 2026. The term mismatch negativity (MMN) maintained a burst duration of six years from 2017 to 2022, indicating long-term and sustained academic attention to this research topic.

In terms of chronological evolution, violations emerged as the earliest research hotspot between 2016 and 2017. Studies in this period mainly focused on N400 responses to semantic violations, establishing fundamental experimental paradigms for subsequent research on semantic processing. From 2018 to 2020, semantic integration, upcoming words and speech perception became successive burst key-

words. Researchers began to investigate the effects of contextual prediction and verbal input on the N400 effect, shifting the research focus from isolated semantic conflicts to dynamic semantic processing. Between 2021 and 2023, new burst keywords including older adults, syntax and concreteness appeared. Research extended to different populations and linguistic structural features, with particular attention paid to cognitive aging among the elderly and the interaction between syntactic and semantic processing. From 2023 to 2026, word frequency, age, Chinese and network became newly emerging hotspots. It demonstrates that N400 research has expanded from traditional Indo-European languages to logographic writing systems such as Chinese. Combined with brain network analysis and individual developmental differences, the field has achieved progress in both research breadth and depth.

According to the temporal distribution and research content of burst keywords, current frontiers of N400 research mainly include semantic processing mechanisms across languages (especially Chinese), the regulatory effects of word frequency and linguistic experience, dynamic characteristics of brain networks, and linguistic cognitive differences among older adults. These emerging hotspots provide clear directions for future research (See Figure 4).

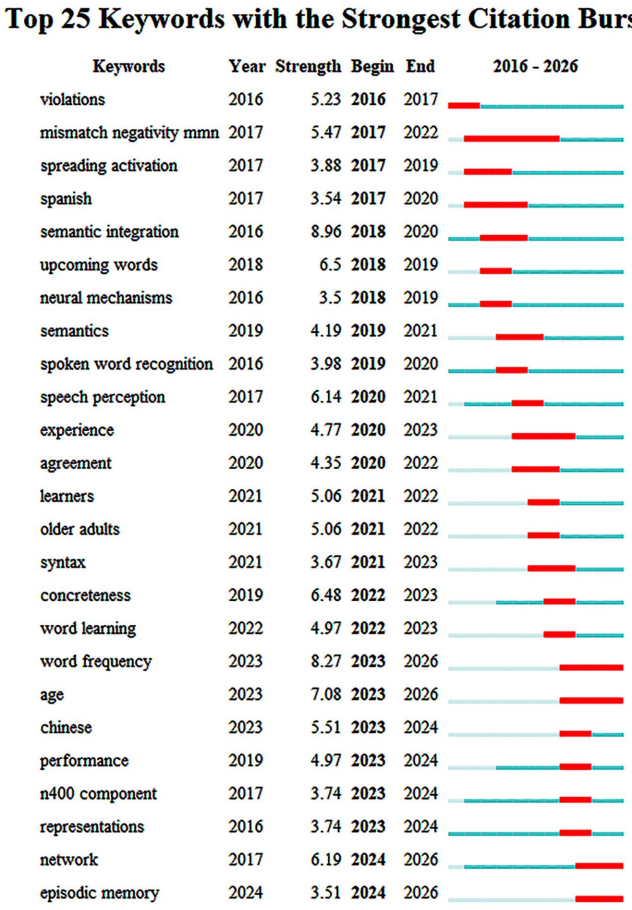

Figure 4. Keyword burst plot.

2.5. Thematic Evolution Analysis

Timeline maps adopt horizontal bands ordered by time to present the intellectual trajectory of research evolution. They clearly illustrate the distribution, evolutionary paths and developmental trends of research hotspots, enabling researchers to accurately grasp the latest advances in a given field. In CiteSpace, keyword timeline maps arrange keywords chronologically from left to right. The size of circular nodes is positively correlated with keyword frequency; larger nodes represent higher research popularity and more abundant research outputs.

This study analyzed the evolution of research hotspots using CiteSpace. The time span was set to 2016-2026 (up to May) with a one-year time slice. The top 60 high-frequency keywords were retained for each time slice, and keywords were selected as the node type. The generated keyword cluster timeline map is presented below. The map contains 158 nodes and 180 links. The modularity value Q = 0.8135 indicates significant cluster structures and reasonable classification of research topics. The weighted mean silhouette value S = 0.9419 verifies the high reliability of clustering results, which can effectively reflect the evolutionary characteristics of N400 research (See Figure 5).

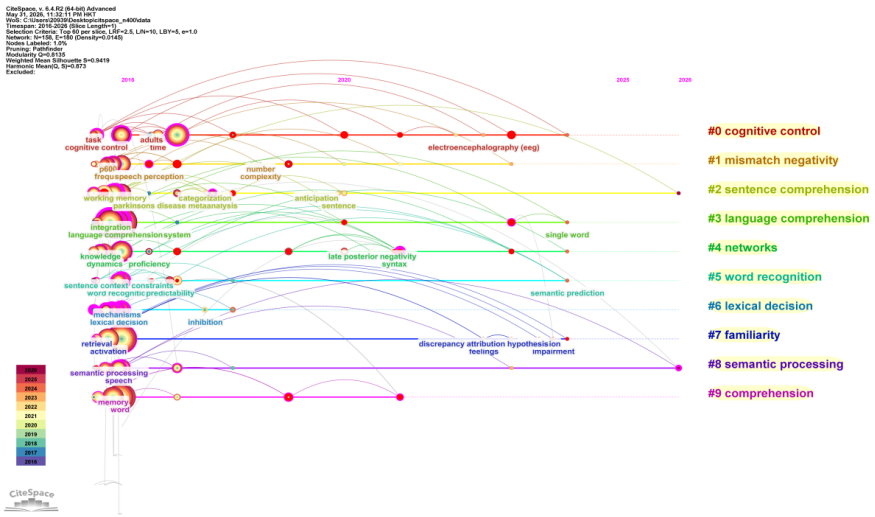

Figure 5. Keyword timeline map.

From an overall perspective of the map, the evolution of keywords along the timeline shows a shift from a focus on fundamental topics to diverse research directions. The total number of nodes increases over time, indicating growing research interest and a continuously refined research system in the field of N400. Besides the core terms N400 and event-related potential (ERP), nodes for brain potentials, language comprehension and semantic integration are relatively large. These topics have remained stable research hotspots over the years, which also demonstrates the close links between N400 research and language comprehension, semantic processing, as well as basic electrophysiological studies. These themes form the core research framework and underpin the overall development of N400-related studies.

On the right side of the map are labels for ten keyword clusters: #0 cognitive control, #1 mismatch negativity, #2 sentence comprehension, #3 language comprehension, #4 networks, #5 word recognition, #6 lexical decision, #7 familiarity, #8 semantic processing, and #9 comprehension. These clusters follow a clear evolutionary pattern on the timeline. Early research centered on clusters related to basic mechanisms, such as #0 cognitive control and #1 mismatch negativity, which explored the neural regulatory mechanisms of N400 and fundamental properties of ERP components. In the middle stage, research gradually expanded to clusters concerning language processing, including #2 sentence comprehension and #5 word recognition, covering language comprehension at lexical and sentential levels. In the later period, studies extended to brain networks, cross-language research and individual differences. Clusters such as #4 networks and #7 familiarity remained active from 2023 to 2026, revealing a general trend that research has evolved from single-component analysis to multi-dimensional and interdisciplinary integration. Dense connections within each cluster reflect strong internal relevance and the gradual enrichment of relevant knowledge systems. Cross-temporal and cross-topic connections between different clusters also highlight the interdisciplinary integration of N400 research, which jointly drives the sustained progress of this field.

3. Conclusions

Based on 2166 N400-related publications retrieved from the Web of Science Core Collection between 2016 and 2026, this study conducted a bibliometric and visual analysis using CiteSpace. We systematically summarized the current status, core themes and research frontiers of N400 studies from the perspectives of publication trends, keyword co-occurrence, clustering structure, keyword bursts and timeline mapping. The main conclusions are presented as follows.

First, research interest in the N400 has shown a fluctuating upward trend with promising development prospects. From 2016 to 2025, annual publications can be divided into three phases: a period of steady development (2016-2018), a phase of rapid growth (2019-2020) that formed the first research peak, and a stage of high-level fluctuation and renewed growth (2021-2025), which reached the maximum output of 241 publications in 2025. These trends indicate that global academic attention to N400 research keeps rising, and this field maintains strong academic vitality and sound development momentum.

Second, keyword co-occurrence and clustering visualizations allow us to inductively categorize existing N400 publications into three broad thematic dimensions for interpretive convenience: foundational neural mechanism explorations, core linguistic application paradigms, and extended frontier topics on individual and cross-language variation. The core-intermediate-periphery hierarchical pattern only describes the distribution characteristics of keywords in the bibliometric network, which is an interpretive summary of published research themes rather than an established structural property of N400-mediated semantic processing. The

core layer is anchored by fundamental technical terms such as event-related potential (ERP) and brain potentials. The middle layer is dominated by keywords of linguistic cognition, demonstrating that major applications of N400 research focus on semantic cognition. The peripheral layer centers on individual differences and multi-dimensional analyses, representing emerging research directions. Clustering analysis further categorized all research topics into ten major clusters (Q = 0.8135, S = 0.9419), including cognitive control, mismatch negativity (MMN), sentence comprehension, language comprehension, networks, word recognition, lexical decision, familiarity, semantic processing and comprehension, which together constitute a complete research system.

Third, research hotspots have evolved dynamically and become increasingly diversified. Keyword burst analysis illustrates the temporal changes of research focuses. In the early stage (2016-2020), studies mainly explored semantic violations and semantic integration, concentrating on semantic conflict, dynamic semantic integration and verbal input processing. Since 2021, researchers have paid more attention to cognitive differences across age groups. After 2023, research frontiers have further concentrated on semantic processing mechanisms across languages (especially Chinese), the regulatory effects of word frequency and linguistic experience, and dynamic features of brain networks. Meanwhile, explorations on linguistic cognitive differences among older adults have continued. Semantic processing and language comprehension remain the core of N400 research. In recent years, this field has expanded toward brain network mechanisms, individual differences and cross-language processing, creating a research landscape where classic topics are continuously advanced and new research directions constantly emerge.

Fourth, N400 research follows a clear evolutionary path and presents an obvious trend of multi-dimensional integration. The timeline map shows that the field has developed sequentially from basic mechanism exploration to core application research and then to diversified extensions. Early studies focused on basic mechanisms such as cognitive control and mismatch negativity. Mid-stage research expanded to practical scenarios of language processing, including sentence comprehension, word recognition and lexical decision. Recent work has extended to brain networks, familiarity, cross-language research and individual differences. Dense internal links within each cluster and cross-temporal and cross-topic connections between different clusters indicate that N400 research is evolving from single ERP component analysis toward multi-dimensional, interdisciplinary and multimodal integration, with an increasingly sophisticated and integrated knowledge system.

This study conducted a knowledge map analysis of 2166 N400-related papers using CiteSpace based on the Web of Science Core Collection, systematically mapping research hotspots, core clusters, and frontier trends in the field from 2016 to May 2026. Nevertheless, several limitations should be considered when interpreting the findings.

First, this study relies on a single database (the Web of Science Core Collection).

Although this database is broadly representative of scholarly literature, it may omit important works indexed in Scopus, PubMed, or other regional databases, potentially affecting the comprehensiveness of the resulting maps. Second, CiteSpace's keyword co-occurrence analysis draws on both Author Keywords and Keywords Plus, which differ in their semantic origins—the former reflecting authors' subjective indexing and the latter being automatically extracted from titles by Web of Science. This heterogeneous mixing may assign different labels to conceptually similar topics, thereby affecting the accuracy of cluster interpretation. Third, during manual exclusion of off-target disciplines, we removed not only clearly irrelevant fields but also certain engineering categories and the Biotechnology Applied Microbiology category. While this step was necessary to maintain thematic focus on cognitive and linguistic research, it may have inadvertently excluded a small number of studies applying the N400 paradigm to emerging interdisciplinary topics such as neuroengineering, biosensing, or language-related crossover work at the periphery, thus introducing selection bias. We maintained consistent decision rules throughout the screening to mitigate this risk, but the possibility of unintended omission cannot be fully ruled out.

Future studies can adopt multi-database and multi-parameter sensitivity analyses to verify the robustness of present findings. Future N400 research should prioritize semantic integration in logographic languages (e.g., Chinese) [17] [18], interactions between brain network connectivity and developmental differences [19] [20], aging-related language-cognitive changes [21] [22], and neural correlates of multimodal semantic processing under natural paradigms [23].

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Data Availability

All data and materials used in this study are available from the corresponding author upon reasonable request (Email: yuanxing.dou@zjnu.edu.cn).

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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