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Effects of Semantic Anomalies in the Persian Language on Event-Related Potentials

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Abstract

Background: This study aimed to investigate the qualitative effects of semantic anomalies on event-related potentials (ERPs) in the context of Persian language processing. Comprehending sentences and integrating words in the correct order are crucial aspects of language processing. Understanding how the brain accomplishes this task during reading, writing, and listening is of great importance.

Methods: In this experiment, 10 healthy, right-handed, Persian-speaking participants (10 women, 10 men) aged 18-40 were included. Four types of sentences, including control conditions and semantic anomalies, were presented word-by-word on a monitor while EEG was recorded with a 64-channel system. The collected signals were analyzed, and the ERPs components were compared statistically.

Results: The presence of a semantic irregularity, specifically an incoherent verb at the end of a sentence, leads to the activation of the N400 component. This component is associated with symmetrical electrode distribution across the anterior, central, and parietal regions of the scalp. On the other hand, when the semantic irregularity in the form of an incoherent verb is positioned in the middle of the sentence, it elicits the production of the P600 component. The corresponding electrodes associated with the P600 component exhibit a distribution that is central, parietal, and left anterior.

Conclusion: The findings contribute to our understanding of the relationships between semantic processing and the N400 component, as well as between syntactic processing and the P600 component. The absence of N400 in the presence of semantic irregularities and the presence of P600 in the absence of semantic anomalies align with the dynamics of the language processing system, where distinct processing units interact and communicate independently.

Keywords: Sentence comprehension; Semantic processing; N400 wave; P600 wave; Semantic anomaly; Persian language; Event-related potentials.

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Introduction

The classical model of language processing focused on single-word processing, but recent neurobiological models have proposed a broader understanding of language processing beyond single words.[1] Overall, understanding the nature and functions of the human brain and language involves exploring neural mechanisms, plasticity, bilingual processing, early language experience, and genetic factors that contribute to language acquisition and processing.[2,3] A sentence is a continuous flow of information over time and a linear sequence of words. To understand the sentence, the reader or listener must correctly combine the words. How this human ability occurs in the moment is a fundamental and controversial challenge in the research on the psychology of language.[4] According to some experts, the distinction between meaning and syntax is at the heart of human language. Meaning and syntax in language are interdependent, but they may still be independent of each other. Neuroscientific evidence suggests that brain systems for syntax and semantics are separable in space (they comprise a subset of non-overlapping neural networks) and time (sequential neural computations). However, the precise contours of these networks, as well as their computations, are not specified.[5] One of the most common tools in neurolinguistic research is the event-related potential (ERP), which is used to study the neural responses associated with language processing.

The N400 and P600 components of the ERP waveform are commonly used to investigate semantic and syntactic processing, respectively.[6-9]

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Many studies have been conducted on the amplitude of distinct ERP waves, especially the two ERP components related to language tasks (the negative potential extracted in the interval 300 to 500 ms after the presentation of a word or phrase is N400, which is typically associated with semantic processing and is sensitive to semantic violations or incongruities in a sentence. When a semantic anomaly is present, such as an unexpected or implausible word, the N400 amplitude is larger compared to when the sentence is semantically congruent.[10-12] and the positive deflection in the ERP waveform interval 500 to 800 ms after stimulus presentation is P600. It is commonly associated with syntactic processing and is sensitive to syntactic violations or grammatical errors in a sentence. When a syntactic anomaly is present, such as a violation of grammatical rules or word order, the P600 amplitude is larger compared to when the sentence is syntactically correct.[6-8,11]

Although the correlations between the N400 and lexical meaning processing and the P600 and syntactic-lexical processing are well known, it should be noted that early studies of the N400 and P600 did not claim that these ERP effects are specific semantic or grammatical processes.[6,7] The presence of a semantic anomaly in a sentence can elicit both N400 and P600 effects, depending on the nature of the violation. If the anomaly is perceived as primarily syntactic in nature, it is more likely to elicit a P600 effect. Conversely, if the anomaly is perceived as primarily semantic or pragmatic, it is more likely to elicit an N400 effect [8]. In some situations, a P600 effect is caused by semantic irregularities, a phenomenon known as the semantic P600.[9,10] The P600 can be elicited by a violation of semantic structure, even in syntactically correct sentences. There has been much debate about the accuracy of the semantic P600, and several frameworks have been proposed to explain this phenomenon. For example, researchers have proposed the "semantic absorption" hypothesis.[11] Recent research has also shown that individual differences in cognitive abilities, such as verbal working memory capacity, can influence the magnitude of the N400 and P600 effects. Individuals with larger verbal working memory capacity tend to exhibit larger P600 amplitudes and smaller N400 amplitudes, suggesting a trade-off relationship between semantic and structural processing difficulty during language comprehension.[13] Given the importance of ERPs in providing evidence for reasonable explanations of language processing flows, the ambiguities and contradictory results in parallel research in different languages, and the limited research on Persian, our current study investigated the impact of semantic irregularities on extracted event-related potentials.

Materials and Methods

Research Methodology

The research employed a neurobiological methodology to examine language processing, with a specific emphasis on ERPs elicited by semantic anomalies. The experimental design involved delivering sentences under various conditions, with factors such as number (distinct versus identical) and acceptability (acceptable versus unacceptable) manipulated.

Study Participants

The study involved a sample of 20 individuals, equally divided by gender (10 males and 10 females), aged 18 to 40 years. The participants in the study were native Persian speakers residing in Tehran. They were assessed as strongly right-handed using the Edinburgh Handedness Inventory and had normal vision or corrected-to-normal vision. There was no documented evidence of any neurological disorders in the medical history.

Sample Selection and Sampling Method

Participants were selected according to specific criteria, including age, language proficiency, and handedness. The sampling technique employed in this study used convenience sampling, selecting individuals who met the inclusion criteria and expressed willingness to participate.

Setting and Study Time

The research was conducted in a controlled setting, using a high-resolution display, with participants seated comfortably. To minimize external stimuli, the testing room was kept at low light levels. The experimental sessions were conducted in complete silence to minimize potential distractions. The study for each participant lasted approximately 25 minutes.

Characteristics of the Studied Community

The surveyed population comprised native Persian-speaking residents of Tehran. The objective of including participants from diverse occupational and social backgrounds, as confirmed by a Likert-scale questionnaire, was to obtain a sample that accurately represents the population being studied.

Criteria for Inclusion and Exclusion

The inclusion criteria consisted of individuals aged 18 to 40 years who were native Persian speakers, strongly right-handed, and with normal or corrected-to-normal vision. The exclusion criteria encompassed individuals who had a documented history of neurological disorders or reading disabilities.

Methods and Materials

Based on the aim of this study, the neural processing of semantic anomalies and the basic conditions of semantic anomalies in Persian were analyzed. Since the frequency of use of the word, the length of the word, and the number of its syllables affect the characteristics of the waveform of ERPs, an attempt was made to use as many as possible all verbs with three or four letters and one segment, and all objects with one segment. In order to have a limited reference for the frequency of the target words, a large number of sentences and target words were included in a questionnaire with a Likert scale, and available to a large number of people in the age range of the statistical population of the research and with various occupational and social characteristics (except people participating in the experiment) were included. All the target words of the test were created from among the evaluated target words in the database and were selected by observing the same or close frequency of all the target words with each other. So that the gender of the subject does not create a semantic disturbance in the subject of the test and is not recognized as a new variable, all the subjects were used in the form of similar pronouns.

This experiment had two main control conditions: 1. sentences without irregularity (20 sentences) with the subject+object+letter+verb pattern is used as simple control sentences; 2. sentences without irregularity (20 sentences) with the subject+object1+letter+verb1+connecting letter+object2+letter+verb2 pattern are used as complex control sentences.

Also had two conditions with semantic anomaly: 1. anomaly at the last word of sentences (20 sentences), simple sentences. 2. semantic anomaly in the middle of sentences (20 sentences), complex sentences.

To prevent habituation and predictability of the main sentences of the experiment, filler sentences were used as many as the main sentences, with the elements of the sentence being mixed up. In total, 80 main sentences (in four conditions) and 80 filler sentences were used. Sample sentences are given in Table 1.

Procedure

This research was conducted using ERP. First, a special cap (INC) with 64 electrodes, based on the 10-20 system, was placed on the subject's head, with one electrode on the right earlobe as a reference. To record the movements of the eye muscles, two bipolar electro-oscillogram electrodes (EOG) were placed vertically, and two bipolar electrodes were placed horizontally above and below the left and right eyelids. The impedance was kept below 5, as per international standards. Also, the distance between the subject's eyes and the screen was set to 50 cm, the screen's color was (127/127/127), and after teaching the test procedure, the experimental stages of the test were conducted in complete silence and in a room with very little light. The subjects were asked not to take any drugs affecting the nervous system, sleep, or attention 24 hours before the test. Subjects were asked to read the sentences carefully to understand and determine whether each sentence was acceptable. Sentences were displayed in the center of a high-resolution screen, word by word, in black font on a gray background. The process of presenting the sentences and the experimental task is shown in Figure 1. This process was repeated for all main sentences and fillers. Each test session lasted for 25 minutes.

The independent component obtained over the appropriate time interval, from 100 milliseconds before to 1250 milliseconds after the application of stimulation (appearance of the word), has been separated from the EEG signal. The extracted parts, which are locked to the

Table 1. Sample sentences.

او نفت را ریخت. (She/He poured oil.)	**Control 1 Simple**
او شال را بافت. (She/He wove a scarf.)	
او گوشت را خورد. (She/He ate the meat)	
او نفت را ریخت و آن را سوزاند. (She/He poured oil and ignited it.)	**Control 2 Complex**
او شال را بافت و آن را فروخت. (She/He wove a scarf and sold it.)	
او گوشت را خورد و آن را بلعید. (She/He ate meat and swallowed it.)	
او دود را ریخت. (She/He poured the smoke.)	**Semantic anomaly- last word**
او خار را بافت. (She/He wove a thorn.)	
او یخ را پخت. (She/He cooked the ice.)	
او نفت را ریخت و را آن سوزاند. (She/He poured smells of oil and ignited it.)	**Semantic anomaly- middle word**
سیب کفش را دوخت و را آن فروخت. (She/He sewed an apple to a shoe and sold it.)	
داس نان را پخت و را آن بخشید. (She/He baked a kneading board of bread and distributed it.)	

moment of stimulus occurrence, are arranged below, and their average is calculated. For the four main-sentence conditions, a 3-digit code has been assigned to each word in each condition, and the average ERP for similar codes has been extracted separately. In this research, ERPs elicited by target words at the end of sentences (verbs) and in the middle of complex sentences were processed and statistically analyzed.

Data acquisition and analysis

All EEG signals were recorded from a gtec (HI.amp) device at 512 Hz, using a 64-channel cap with active electrodes referenced to A2. The experimental task was implemented in Psychtoolbox as a visually active task and presented to the participant while sitting on a comfortable seat.

In the preprocessing phase, a sequence of steps is applied to raw signals: (1) all signals are passed through a band-pass FIR filter with cut-off frequencies of 1 Hz to 30 Hz, to remove the low-frequency and high-frequency noises (including line noise), (2) Noisy signal windows were removed by visual inspection. (3) Artifact Rejection performed with the aid of the Independent Component Analysis (ICA) method. (4) After signal cleaning, an ERP wave is obtained by averaging the clean epochs for each channel signal separately.

All signal processing procedures were performed in MATLAB 2021b, and all preprocessing procedures used the EEGLAB 2020 toolbox. For statistical analysis, a post hoc repeated-measures ANOVA was performed using the Pingouin library in Python.

The behavioral data, including task reaction times and acceptability judgments for each sentence, were analyzed using GraphPad Prism 9. A one-way ANOVA was conducted to examine potential differences across the sentence conditions.

Results

Behavioural Results

The results indicated that there were no significant differences between the conditions [F (3, 63) = 0.7251, P = 0.54]. Table 2 and Figure 2 provide further details.

ERP Results

In comparing ERPs for correct verbs at the end of sentences versus in the middle of sentences, a clear pattern emerges. Correct verbs at the end of sentences tend to elicit a strong positive response, characterized by the production of the P600 wave. This response exhibits a relatively symmetrical distribution across the central, anterior, and parietal regions of the scalp (Figure 3A). On the other hand, correct verbs in the middle of sentences tend to evoke a negative response, manifested by the generation of the N400 wave. This negative response also displays a symmetrical distribution across the central, anterior, and parietal regions of the scalp (Figure 3B). The statistical analysis of this component across channels reveals significant differences between sentences with semantic anomalies and those without. The presence of a semantic anomaly in the form of an incoherent verb at the end of the sentence triggers the emergence of the N400 component. The corresponding electrodes associated with this component exhibit a symmetrical distribution across the anterior, central, and parietal regions of the scalp. When the semantic anomaly in the form of an incoherent verb is positioned in the middle of the sentence, it gives rise to the production of the P600 component. The corresponding electrodes associated with this component display a distribution that is central, parietal, and left anterior. In both conditions, the main effect of Condition has significance: Condition 1 (Stimulus at the end of sentences), $F(1,63) = -3.5$, $P < 0.0$; Condition 2(Stimulus in the middle of sentences), $F(1,63) = -1.9$, $P < 0.0$. Figure 3 and Tables 3 and 4 provide further details.

Discussion

Several studies have investigated the effects of semantic anomalies on event-related potentials (ERPs) and have provided valuable insights into the neural processing of semantic information.[14] In our research, the presentation of the correct verb in the middle of the sentence involves two categories of processes in the language processing system: processes related to composition—creating connections and integrating with previous words and context —and processes associated with ambiguity and neural anticipation. The next words are the completion of the understanding of the sentence. Comparing stimuli presented in the middle of a sentence with the same stimuli at the end of a sentence has yielded compelling evidence for enhancing our understanding of the interactions between the processes underlying the N400 and P600. Hagoort discussed the interaction between syntactic and semantic processing, suggesting that semantic and syntactic violation effects are non-additive.[7] Brouwer et al. presented a neurocomputational model of the N400 and P600 components, suggesting that the N400 reflects the retrieval of word meaning from semantic memory. At the same time, the P600 indexes the integration of this meaning into the unfolding utterance interpretation.[15] Overall, these studies demonstrate the utility of ERPs in investigating the effects of semantic anomalies on neural processing, shedding light on the time course and nature of semantic integration, syntactic processing, and the interplay between different levels of language processing. Hagoort investigated the effects of combined semantic and syntactic violations on ERPs,

showing that semantic integration is influenced by syntactic processing[7]. Schacht and Sommer Schacht & Sommer discussed the N400 component as an electrophysiological index of semantic processing,[16] Kim and Osterhout investigated the interaction between semantic and syntactic cues and observed that syntactic anomalies elicited a P600 effect, typically associated with syntactic processing, rather than the N400 effect associated with semantic anomalies.[8] Osterhout and Nicol Osterhout & Nicol evaluated the distinctiveness and independence of ERPs elicited by semantic and syntactic anomalies, revealing different ERP components associated with each type of anomaly.[17] Li et al. examined the detection of linguistic anomalies using language models. They found that different types of anomalies elicit distinct patterns of surprisal in the intermediate layers of the models.[18] Leckey and Federmeier (Leckey & Federmeier) discussed the positive contributions of the P600 component to language comprehension, highlighting its role in processing violations of semantic and syntactic structure.[19] These studies collectively contribute to our understanding of the effects of semantic anomalies on ERP components and shed light on the neural mechanisms underlying semantic processing in language comprehension. Gibson et al. discussed the traditional interpretation of the N400 and P600 components as indexing semantic and syntactic anomalies, respectively, but also noted P600 effects for materials with semantic incongruities.[6] Herten et al. observed P600 effects for implausible sentences, suggesting conflict monitoring during sentence perception.[20] Barber and Carreiras found that semantic violations typically produce a significant enhancement of the N400 component, associated with lexical-semantic integration processes.[21] However, some studies have reported P600 effects for certain types of semantic violations.[22] Hagoort (2003) investigated the effects of combined semantic and syntactic violations and observed that the N400 to semantic violations was larger when an additional syntactic violation was present, suggesting that semantic integration is influenced by syntactic processing. Brouwer et al. proposed a neurocomputational model that supports the existence of semantic P600 effects.[15] Tanner et al. Tanner et al. discussed the variability in ERP responses to semantic and syntactic violations, highlighting the presence of N400 effects for syntactic agreement violations and P600 effects for certain types of semantic violations.[23] Lau et al. Lau et al. discussed the semantic P600 effect as a response to highly implausible or impossible semantic anomalies encountered within semantically constraining contexts.[24] Other studies have also explored the semantic P600 effect in relation to syntactic processing difficulty and the influence of competing interpretations.[13,19,23,25] In our research, we observed a tendency towards negativity and the extraction of N400 waves when presenting the correct verb in the middle of the sentence. This indicates the expectation and the need to resolve ambiguity and achieve a complete understanding of the sentence. These findings help establish a relationship between these waves and processes associated with semantic comprehension. Conversely, the extraction of the N400 component after presenting a semantically and functionally inconsistent verb at the end of the sentence provides further evidence of the relationship between N400 and semantic processing, confirming previous research. In this research, the presence of a semantic anomaly and a functional verb in the middle of the sentence did not elicit the N400 component, in contrast to the impact of the same stimulus at the end of the sentence Examining the waveform pattern and observing a weak negative tendency within the N400 window range, the presence of a semantically inconsistent verb in the middle of the sentence continues to have a substantial impact on the activity level of semantic processing, as supported by relevant studies. However, the variable effect of its position in the middle of the sentence, which we have previously observed to produce a negative tendency even in conditions without irregularity, prevents the extraction of the N400 component from the inconsistent verb. Other research provides evidence of a relationship between the positive tendency of waves within the P600 window and processes related to the final review of structure, meaning coordination, and integration, as well as syntactic and semantic integration.[26,27] The extraction of the P600 component from the stimulus of the semantically irregular verb in the middle of the sentence can be seen as the language processing system's effort to reduce ambiguity. Considering that the semantic processing system is already engaged due to its position in the middle of the sentence, the brain relies more on the processing related to structural review and integration, which is associated with the P600 component. In other words, the relationship between the processes underlying the N400 and P600 components, while considered independent, can be seen as a dynamic compensatory mechanism for sentence comprehension. Even in the presence of a semantic problem and the expectation of intensified semantic processes and the extraction of the N400 component, the limited capacity to increase semantic processing leads to the utilization of processing capacity related to the P600 component to compensate for the gap in sentence understanding. These findings collectively suggest that the semantic P600 effect reflects the interplay between semantic and syntactic processes during language

comprehension.

One limitation of this report is that it focuses solely on the effect of semantic interventions on sentence comprehension, using the target words of the verb. This narrow focus limits the study's scope and may not provide a comprehensive understanding of linguistic processes in Persian.

To address this limitation and enhance the comprehensiveness of future research, it is recommended to incorporate experimental designs that simultaneously involve both syntactic and semantic interventions. By considering not only the verb but also other target words within the sentence, a more holistic understanding of linguistic processes can be achieved. This expanded approach would provide a more comprehensive analysis of how syntactic and semantic factors interact in sentence comprehension in Persian.

Conclusion

In conclusion, our findings contribute to understanding the relationships between semantic processing and the N400 component, as well as between syntactic processing and the P600 component. The absence of N400 in the presence of semantic irregularity and the presence of P600 in the absence of syntactic irregularity can be interpreted within the dynamics of the language processing system, where independent processing subunits interact and communicate with each other. Each subunit has its own limitations in terms of activity. Therefore, to maintain an optimal level of comprehension, if one subunit is not prone to increased activity, the other subunit compensates by increasing its own activity. This perspective offers a plausible explanation for the heterogeneous, sometimes contradictory observations across studies regarding the N400 and P600 components.

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Ethical consideration

The medical ethics committee approved the experimental design at Iran University of Medical Sciences, Tehran, Iran. Ethics code: IR.IUMS.REC.1396.0716.

Competing Interests

The authors declare no conflict of interest.

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