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Linguistic and emotional responses evoked by pseudoword presentation: An EEG and behavioral study

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ABSTRACT

When the semantic properties of words are turned off, such as in pseudowords, the grammatical properties of the stimuli indicated through suffixes may provide cues to the meaning. The application of electroencephalography (EEG), combined with the pseudoword paradigm, allows for evaluating the effects of verbs and nouns as linguistic categories within the time course of processing. To contribute to the ongoing discussion regarding the functional processing of words from different grammatical classes, we conducted an EEG experiment, followed by a behavioral lexical decision task (LDT). The EEG and LDT indicated different neural and behavioral reactions to the presented grammar classes, allowing for a deeper understanding of the neuro- and psycholinguistic dimensions of grammar.

1. Introduction

1.1. Language theories of social interaction and communication

Language, whether spoken or written, carries social, affective, or motivational information (for an overview, see Dunbar, 1996; Schunk & Usher, 2012; Carofiglio et al., 2009). However, social, emotional, or cognitive content is not only carried by the meaning of a word but is also conveyed in relation to word categories and grammar. Specifically, research has suggested that linguistic categories can communicate meaning beyond their semantic content (Fiedler, 2008; Formanowicz et al., 2017). For example, action verbs (e.g., *to smile*) in contrast to adjectives (e.g., *funny*) were found to prompt larger muscle activity of the zygomatic major muscle in healthy adults (Foroni & Semin, 2009). This may indicate that verbs related to action and motion have the exceptional potential to influence human behavior. However, several unresolved issues still exist regarding the processes behind this unique role of verbs in affecting cognition and behavior differently compared to other grammatical categories. This research contributes to the ongoing debate regarding the differences in the functional processing of words from different grammatical categories, such as verbs and nouns (for a review, see Vigliocco et al., 2011), as well as to the understanding of the nonsemantic effects of grammatical categories. Specifically, we examine whether differences in processing verbs versus nouns occur at the morphological level of a word. To tackle this problem, we apply electroencephalography as a methodology that allows for an understanding of the time course of stimulus processing (EEG; e.g., Yudes et al., 2016). Additionally, we examined the neural and behavioral differences between the processing of verbs and nouns by employing a behavioral lexical decision task (LDT) and a pseudoword-based grammar class recognition paradigm, an approach for grammar class identification in neurolinguistic studies (Pulvermüller, 2010; Pulvermüller & Shtyrov, 2003). Using pseudowords with a suffix indicating their grammar class allows the reader to distinguish between verbs and nouns. Investigating the time course of this spontaneous processing by means of event-related brain potential (ERP) correlates of syntactic or semantic processing will unravel at which stages of stimulus processing, differences between pseudoverbs and pseudonouns will occur.

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1.1.1. Previous empirical Evidence: Neurophysiological and behavioral stages of lexical processing

In line with prominent theories on grammatical class processing (see Section 1.2), most empirical EEG-ERP studies suggest that early ERPs such as the P200 potential elicited in a time window prior to 250 ms after stimulus onset can indicate the processing of grammatical category information through morphological suffix identification at the orthographic level (Brown et al., 1999; Yudes et al., 2016). In contrast, the lexico-semantic effects of word processing occur at about 300 ms (e.g., Grainger & Holcomb, 2009), and indicate the beginning of structural- and semantic-related encoding of the presented words. These processes may be followed by a prominent EEG-ERP component that reflects semantic and conceptual processing (N400). Occasionally, depending on the paradigm, a left anterior negativity (LAN) component can occur, as it is sensitive to the grammatical features of natural language (Krott et al., 2006; Penke et al., 1997; Yudes et al., 2016). EEG-ERP recordings in line with theoretical models of word processing can therefore inform us about the stages at which word processing takes place (e.g., orthographic, lexico-semantic, syntactic, emotional, etc.).

Importantly, EEG methodology has already been used in investigating differences between verb and noun processing. For example, a comparison of acoustic stimuli of unambiguous nouns, unambiguous verbs, ambiguous words with noun-biased semantics, and ambiguous words with verb-biased semantics revealed differences in the processing of nouns and verbs (Zhao et al., 2017). The noun–verb dissociation was detected between 150 and 250 ms after stimulus onset over occipital electrode sites and between 380 and 450 ms over frontal electrodes covering the motor cortex (Zhao et al., 2017). These results indicate that processing differences between nouns and verbs are based on semantic rather than grammatical processing. However, grammatical class recognition is evident (Federmeier et al., 2000) in the modulation of an event-related component peaking at about 200 ms over frontal electrode sites when an ambiguous word is presented with an auxiliary word "the" for nouns and "to" for verbs (Lee & Federmeier, 2008). This shows that, when words have the same visual form, additional support is needed from other linguistic components to make their grammar class distinct and clearly recognizable by the reader. It should be noted, however, that auxiliary words blur the distinction between grammar classes (Vigliocco et al., 2011), because words become entangled in syntactic relationships and the difference between them is determined by an additional linguistic element.

In a series of EEG studies, Pulvermüller et al. (1996) found that verbs elicit stronger responses over motor regions of the brain, whereas nouns evoke stronger activity changes in the occipital lobes. Although these differences in neural responses might reflect the differing activation of motor and visual areas by verbs and nouns, the question remains whether these differences also occur when semantic differences between nouns and verbs are controlled. This controversy was addressed by Yudes et al. (2016), who observed several differences between nouns and verbs across the time course of information processing implicated by the differential modulation of the amplitude of early and late language-realted ERPs. In this EEG-ERP study (Yudes et al., 2016), which compared shared-stem nouns and verbs (e.g., *patinar* "to skate" and *patinaje* "skating"), differences were found as early as 200 ms after stimulus onset in anterior parts of the brain, as it was shown in Pulvermüller (1999). These differences continued to be visible in other time windows and ERPs, including the LAN (left anterior negativity), an indicator of grammar processing (e.g. Grey, 2022), and the N400, an indicator of semantic processing (e.g., Barber et al., 2010). Thus, Yudes et al.'s (2016) results support the assumption that different neural pathways are activated for processing nouns versus verbs and, hence, for words matched on semantics but differing in a grammatical category in a real-word paradigm. However, questions about the neurophysiological impact of grammar class exponent standing alone, are still not answered.

In line with neurophysiological research, behavioral studies focusing on noun and verb processing have shown that grammatical categories are processed differently (Azimi et al., 2020; Salmazo-Silva et al., 2017). Most of this evidence comes from studies using the LDT as an experimental paradigm. Findings from behavioral studies using the LDT converge on slower reaction times for verbs than for nouns (Cordier et al., 2013). This holds true in designs in which words are compared regarding their linguistic dimensions, including formal features (number of letters, syllables, homographs, and orthographic neighbors, and frequency and age of acquisition) and semantic features (imagery, number and strength of associations, number of meanings, and context dependency). In hemifield designs, where words are presented to either the left or the right visual hemisphere, the LDT elicits faster responses for verbs when they are presented to the right visual field (left hemisphere) as opposed to the left visual field (right hemisphere), supporting theoretical assumptions of left-hemisphere dominance in the distinction between grammatical word categories.[2] However, when controlling semantic and abstract features, such as the imageability of a word (Clark & Paivio, 2004; Paivio et al., 1968), the differences between nouns and verbs in visual field presentations seem to disappear (Chiarello et al., 2002). Accordingly, behavioral results alone do not allow conclusive evidence that mental representations of verbs and nouns as distinct grammatical word categories differ per se from each other or that word versus nonword decisions that are thought to require at least some semantic processing differ as a function of grammatical class, that is, whether nouns or verbs are presented.

1.1.2. Noun and verb Processing—Theoretical Approaches, social consequences

As indicated above, the empirical results for grammar class processing are mixed, likely due to a variety of paradigms and method used. Similarly theoretical accounts propose several established standpoints with respect to lexical categories processing. Specifically, three theoretical views currently exist (for an overview, see Vigliocco et al., 2011). The first theoretical view proposes that grammar and semantics are different processes and that grammar plays a role in sentence production and sentence comprehension because meaningful language use requires connected speech (Levelt, 1989; Pickering & Branigan, 1998). This theoretical position, called lexicalism (e.g., Bresnan, 2001; Kaplan & Bresnan, 1982), suggests that processing differences attributable to differences in grammatical class are preexisting entities of language that can and should best be studied at the sentence level (Levelt et al., 1999). Consistent with the lexicalist view (e.g., Bresnan, 2001; Kaplan & Bresnan, 1982), neural networks, when processing words from two different conceptual domains, are fractionated during grammar class encoding. According to this point of view, nouns engage the left temporal areas, and verb processing engages the left inferior frontal areas (Damasio & Tranel, 1993; Daniele et al., 1994).

The second theoretical view refers to a combinatorial approach according to which morpho-syntactic rules that apply to nouns and verbs, not word forms per se, are processed in partially separate brain networks and are activated during language processing (Tyler & Marslen-Wilson, 2008). Again, this approach suggests that differences between grammatical word categories exist and are elicited in tasks involving phrases and sentences but not in tasks using single words. Shapiro et al.'s (2006) research shows that left temporal areas (including the fusiform gyrus) integrate nouns into phrases and that verbs are integrated into phrases within the left inferior and middle frontal areas.

The third theoretical point of view suggests that the proposed grammatical processing differences between word categories (as suggested by the other two views) do not exist on their own but arise

[2] Faster reaction times for verbs were also observed in behavioral tasks other than LDT. In an Implicit Association Test, Weis and colleagues (2022) has shown that verbs vs. nouns are processed faster when paired with self-related vs. other-related pronouns. These studies were based on an assumption that verbs through their relation to activity are processed faster than nouns.

through an interaction of different linguistic processes that include but are not restricted to grammar and semantics. Crucially, this latter emergentist point of view assumes that no separate processes or neural networks for grammar class processing exist. Instead, differences between grammatical word categories are driven by conceptual processes (object-related for nouns vs. action-oriented for verbs), and these conceptual differences determine separability in word processing, regardless of the words' grammar class (Burgess & Lund, 1997; Elman, 2004). A shared neural network is engaged in both noun and verb processing and depends on morpho-syntactic processes. From this stance, lexico-semantic information is placed bilaterally in temporal lobe structures, visible especially in superior and middle temporal gyrus activation, while computing morpho-syntactic information is strictly left lateralized and activates superior temporal and inferior frontal areas during the processing of words from divergent grammar classes (Tyler & Marslen-Wilson, 2008). Tyler et al. (2004) proposed an approach according to which the differences in grammar class perception are caused by morphological differences in noun and verb structures. In functional magnetic resonance studies (Longe et al., 2007), differences between inflected nouns and verbs resulted in stronger left inferior frontal gyrus (LIFG) activation while processing regularly inflected verbs (e.g., *hitting*) than regularly inflected nouns (e.g., *dogs*). The same situation occurs when inflected forms of verbs (*hears*) are presented. Verbs provide stronger activation of the left fronto-temporal brain region than inflected nouns (*snails*) do, and additionally, no difference can be found when a stem (*hear* and *snail*) is presented (Longe et al., 2007). According to Tyler et al. (2004), a feasible hypothesis is that uninflected nouns and verbs share the neural network, but when morphological operations are performed, the LIFG is more strongly engaged in grammatical class processing.

One promising empirical approach that could help solve the questions raised by the different psycholinguistic theoretical viewpoints and the previous empirical research using words are studies that use pseudowords instead of real words as linguistic stimuli. In a study conducted by Vigliocco et al. (2011), participants were asked to evaluate pseudowords referring to a noun or verb grammar class embedded in the context (*a wug*, *many wugs*, *he wugs*, *they wug*). The results showed that people took differences in grammar class into consideration when making their judgments. Pseudowords with noun prepositions were rated as linked with an object 84% of the time, whereas verbs were associated with an action 83% of the time. This result indicates that pseudowords can be classified by grammatical appearance.

Furthermore, a recent study by Formanowicz et al. (2017) demonstrated that pseudoverbs are evaluated as more agentic than pseudonouns or pseudoadjectives (Studies 2–4). This finding is interesting, as it suggests that morphological cues make people allocate cognitive concepts to individual parts of speech, especially verbs, which have the unique function of indicating action. In line with this pragmatic language view, supralinguistic dimensions, such as the social relevance or the emotional meaning of a word have been proposed to modulate word processing and its time course: this has been shown in several studies using nouns, adjectives or verbs (for an overview see for example Herbert et al., 2018; Citron, 2011) based on the results of EEG studies investigating modulation of early and late event-related brain potentials. Moreover studies that compared the spatio-temporal processing of real words with and without emotional meaning (e.g., high positively arousing – nouns, high negatively arousing nouns and neutral nouns) with the spatio-temporal processing of pseudowords based on the real words created within each emotion or neutral category mentioned before or compared with letter strings devoid of any meaning or orthographical information revealed several differences across the time course of lexical processing (Kissler & Herbert, 2013). The results point toward temporal and spatial differentiation between words with and without meaning that occurs at prelexical, lexical, and postlexical processing levels. Additionally, the results indicate word versus nonword differentiation associated with emotion processing by involving posterior structures engaged in emotion processing and right lateralization of emotion effect. Crucially, effects that indicate early differentiation of words according to their meaning and relevance for the perceiver are not restricted to emotional words but have been observed also for auditory and visually presented self-related words, i.e. pronouns signaling first person agency and ownership (Blume & Herbert, 2014; Herbert et al., 2018), also when these are presented as pronoun–noun combinations (Herbert, Herbert, Ethofer & Pauli., 2011; Herbert, Herbert & Pauli, 2011; Herbert, Pauli & Herbert 2011) or embedded within sentences (Holt et al., 2009; Esslen et al., 2008).

Thus, in summary, different theoretical viewpoints concerning differences in the processing between the two word classes of nouns and verbs exists. Concurrent empirical evidence and studies investigating words without sentence context allow so far no firm conclusion of whether differences in the processing of nouns and verbs are lexical or derive from semantic or even supralinguistic differences between verbs and nouns such as their differential embodied meaning or socioemotional relevance.

1.2. Aim of the present study

Our study builds upon previous evidence (outlined above) that suggests that, in addition to traditional linguistic dimensions (grammar, syntax, semantics), can also impact word and socioemotional processing and contribute to the distinct processing of grammatical word classes, such as nouns and verbs. In line with this evidence, the present study aimed to test whether word class (noun or verb) affects neuronal processing of words differently when the lexical stimuli are devoid of meaning. To do so, pseudowords were used as stimuli that carried the grammatical class exponent but no semantic meaning. Our study therefore can shed light on whether the limitations of semantic information can highlight the distinction of concepts assigned to the grammar-related properties of words (noun and verb differentiation). To discover whether a difference exists between nouns and verbs, understood as separate grammar categories, pseudowords were taken from inflectional language (Polish), and electrophysiological and behavioral markers were assessed in native speakers of the Polish language.

1.3. Hypotheses

By creating a link between morphological features of the pseudowords and cognition, we investigated how language use can affect human responses at the behavioral and neuronal levels. The application of the EEG methodology, particularly the modulation of ERPs, in combination with the pseudoword paradigm and reaction time measures, allowed us to evaluate the effects of verbs as a linguistic category and contribute to the ongoing discussion regarding the differential functional processing of words from different grammatical classes (Vigliocco et al., 2011; Xia and Peng, 2022).

1.3.1. Hypotheses: Grammar class processing differences in linguistic ERPs

First, we hypothesized that the difference in pseudonoun and pseudoverb processing would appear at an early stage of stimulus processing, showing differences in the P200, indicating morphological complexity processing of verbal stimuli (Yudes et al, 2016). Second, if a common metasemantic social grammar effect exists, this would be indicated by a LAN, which would occur for word category violations and would indicate syntactic processing (Brown et al., 1999; Yudes et al., 2016). Third, we hypothesized that pseudoverbs and pseudonouns would differ in the N400 component time window, reflecting "late" semantic and conceptual processing. The difference between pseudonoun and pseudoverb processing was expected to also be shown in temporally later time windows, of the P600 event-related potential, due to the presentation of gender-inducing cues in pseudonouns (Misersky et al., 2019). On the behavioral level, we hypothesized that pseudoverbs would elicit faster responses than pseudonouns in line with previous observations

(Bradley, 2009; Citron et al., 2013).

2. Methods

2.1. Participants

Students and working professionals were recruited online via announcements placed on social media and academic e-mail systems. In total, we recruited 42 people. Of these, one participant was excluded because of uncorrected vision during the study, and one was excluded because of the reported language-related difficulties. This resulted in a final sample size of 40 participants ($M_{age} = 23.23$, $SD_{age} = 3.42$, $range_{age} = 18–33$, 22 women and 18 men). All participants were right-handed and native Polish speakers. All participants provided written informed consent and were paid 120 PLN for taking part in the experiment. All procedures performed in studies involving human participants were approved by the ethical committee, and references to the participants have been anonymized.

2.2. Procedure and tasks

Before participating in the EEG task, participants were asked to provide basic demographic information, such as age, education, and diagnosed language-processing disorders (e.g., dyslexia). Participants also provided information about possible visual and hearing impairments and whether they had normal or corrected-to-normal vision. Participants were then seated in a room and asked to take part in two experimental procedures: a passive-reading EEG task (as in Yudes et al., 2016) and a behavioral LDT. Overall, the study took about 40 min to complete.

In the EEG task, stimuli were presented using PsychoPy 3 (https://www.psychopy.org/) in white font on a gray background. Each participant was asked to sit in front of the screen and read pseudowords silently with full attention. The EEG task consisted of four 5-minute sessions. Each session contained 40 pseudonouns and 40 pseudoverbs trials presented in randomized order. Each trial started with a fixation cross (which was displayed for 1000 ms) followed by a blank screen (200 ms), after which a pseudoword appeared on the screen (900 ms). Next, a blank screen was displayed (1000 ms plus a jitter, i.e., a random number sampled from log-normal distribution using Python's *random.lognormvariate* function, $\mu = 0$, $\sigma = 0.3$). The single trial duration was 3100 ms plus the jitter (see Fig. 1a).

Participants then engaged in 160 trials of the classic LDT (e.g., Cordier et al., 2013), in which they decided whether a presented pseudoword resembled more a noun or a verb. Before the task, the experimenter instructed participants that they will see words like in the EEG study and they should press the keyboard button as soon as they see the word presented on the screen. Stimulus presentation and data collection were designed in OpenSesame software for Windows (Mathôt et al., 2012). Pseudowords were presented in lowercase type in white font in the center of a gray background. Each trial consisted of a 500 ms fixation cross that was immediately followed by a target word (a pseudonoun or a pseudoverb; see Fig. 1B). Target words were presented until the participant categorized the word as a noun or a verb. The noun/verb response keys were located at the left and right ends of the bottom row of the keyboard ("M" and "Z" keyboard keys). The experiment contained two blocks. In the first block (Block A), the verb response key was assigned to the "Z" key; in the second block (Block B), the verb response was assigned to the "M" key (see Fig. 1B).

2.3. Stimuli

To generate 415 pseudowords, we used a Python-based pipeline in line with e.g., (Dołżycka et al., 2022) based on the Wuggy algorithm (Keuleers & Brysbaert, 2010). From the SketchEngine Web Corpus (Engine Polish Web, 2012; plTenTen12 corpora, RFTagger; Kilgarriff et al., 2004), the 20,000 most frequent words were extracted. These high-frequency words were used as inputs for the Wuggy program for generating verbs in their infinitive forms and common nouns with unambiguous inflections of feminine and masculine suffixes. Aimed to obtain pseudoword pairs that differed only in their suffixes to extract grammar class indicators in Polish. In Polish, as in other inflectional languages, grammar classes can be distinguished by typical word endings belonging to each grammar class, for example, -Ø, -k, -g, –ch, -anin for masculine nouns, -a, -ka, ga, -cha for feminine nouns, and -ć, -ać, -ować, -nąć, -ić, yć, -ywać, -iwać, -ąć for the infinitive forms of verbs. As an output, pseudowords generated by matching subsyllabic elements compliant with the phonotactic restrictions of the Polish language. Words that contained characters that are not included in the Polish alphabet were removed. Only stems that had been jointly assigned with at least one noun-indicating suffix and at least one verb-indicating suffix were considered. For each pseudoword stem, there was a list of phonologically and orthographically plausible ultimate syllables that could be added to it. Using the Grammatical Dictionary of Polish (Saloni

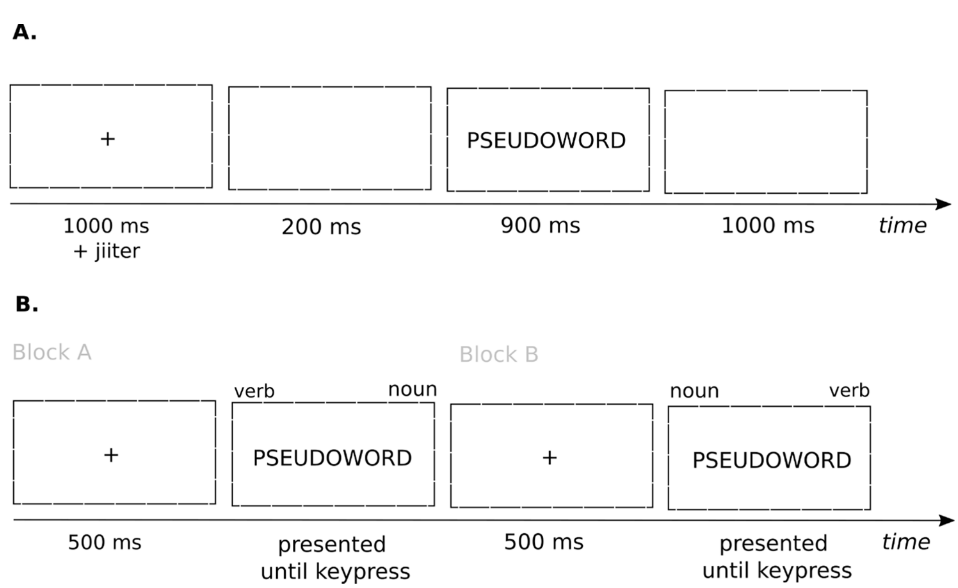

Fig. 1. Trial Structure Design Note. A: Passive reading task - EEG study; B: Lexical decision task.

et al., 2015), pseudowords identified as real words after the last syllable addition were removed. For the unifying stimuli list, only words that contained 7–9 characters were kept. For all generated pseudowords, the Levenshtein distance value (OLD20; Yarkoni et al., 2008) was computed. To ensure that words were not too similar to or too distant from real words, we chose only pseudonouns and pseudoverbs with an OLD20 value between 2.0 and 3.5. Furthermore, the measurement for the difference between the pseudoverb and pseudonoun OLD20 was kept at$<$0.5. To ensure pseudoword pairs are detached from the semantic meaning for the EEG experiment, created an online study an online study was conducted. We asked 312 participants about the possibility that the presented pseudoword could be a real Polish word in terms of orthographic and phonological accuracy (answers ranged from 0 [not at all] to 4 [very much]) and about the similarity of the presented pseudoword to any word existing in the Polish language (answer ranges were the same as in the first question). Additionally, people chose grammar class of the presented pseudoword (participants were able to choose one of the presented options: "verb," "noun," "adjective," "other," or "I don't know"). To choose the proper stimuli grammar class we applied the following criteria: correct grammar class identification criterion (above 80%) for nouns and verbs, the significance of evaluation as not similar to Polish existing words, and assessment as possible in terms of Polish language rules. Next, using the Hungarian algorithm (Kuhn, 1955) pseudonouns and pseudoverbs were paired to form shared-stem pseudoword pairs with similar OLD20 values. From the 121 pseudoword list we chose pseudoword pairs, 40 pairs were selected. The list of stimuli contained 40 pseudoverbs in the infinitive form and 40 pseudonouns divided equally by grammatical gender category (feminine and masculine). This method allowed us to obtain a balanced pseudoword pair (nouns: firdazja, bażlałek; verbs: frdawić, bażlawić*)* for an EEG and behavioral study. The properties of the 80 pseudoword set used in the EEG and behavioral study (for a full list, please see Supplementary Online Material) are presented in Table 1.

2.4. Apparatus

Participants were seated in a quiet room in a chair approximately 200 cm away from a Dell high-definition monitor 1920 × 1200 px, with a refresh rate of 60 Hz. Continuous EEG data were recorded at a sampling frequency of 1000 Hz using a BrainVision BrainAmp DC amplifier (Brain Products GmbH, Munich, Germany), with a 64-channel EEG actiCAP arranged according to the international 10–20 system. During signal registration, all EEG channels were set at a default placement of 10–20 electrodes. The electrodes' impedance was kept below 15 kΩ. Behavioral LDT participants were seated in the same room. For stimuli and procedure presentation, an ASUS ZenBook UX410UA was used. Participants submitted answers via a laptop-embedded keyboard.

2.5. Nested regression Analysis: Behavioral effect of grammar class exposition

For LDT data analysis, a nested regression analysis of the obtained reaction times was conducted. The analysis was conducted using MPlus (Muthén & Muthén, 2017). Our aim was to examine whether verbs are categorized faster than feminine and masculine nouns. It is important to note that participants rated multiple words and may have tended to respond more quickly or slowly to some types of words. Therefore, we nested ratings in participants to obtain a robust standard error estimation, and reaction times were entered as dependent variables. To determine whether nouns with different grammatical genders were differently processed than verbs as predictors, we used two dummy coded variables: one comparing verbs and feminine nouns and the other comparing verbs and masculine nouns (verbs coded as 0, nouns as 1). Additionally, the session was included as a control variable.

Table 1
Properties of Pseudoword Stimuli Set.

Properties	Pseudonouns	Pseudoverbs
Resemblance to real words	1.70 (0.49)	1.65 (0.58)
Possibility of being a real word	1.43 (0.49)	1.41 (0.66)
Correct identification (%)	90.81 (0.93)	90.99 (0.86)
Orthographic neighbors (OLD20)	2.81 (0.55)	2.81 (0.53)

Note. Depicted values are arithmetic means with standard deviations in parentheses. OLD20 = Levenshtein distance value.

2.6. EEG data preprocessing

Using Brain Vision Analyzer 2 (Brain Vision Analyzer, Version 2.2.2, Brain Products GmbH, Giltching, Germany), the raw 1000 Hz EEG signal was down-sampled to 256 Hz. We used IIR filters with low (0.15 Hz) and high (40 Hz) half-amplitude cutoffs and a notch filter (50 Hz) with a 12 dB/octave slope. Next, ocular correction with a common reference was performed using the Gratton & Coles algorithms implemented in Brain Vision Analyzer software. Due to the lack of specific electrodes for eye blink or eye-movement control, we used an ocular correction function for an ocular artifact template in the Fp1 (set as VEOG) and Fp2 (set as HEOG) channels (for details see: Plank, 2013; Cheval et al., 2019; Lins et al., 1993), automatically marked as an artifact of eye-movement patterns (blinks and horizontal eye movements). The eye-movement patterns were corrected across the dataset. Next, the brain signal was re-referenced to the TP9 and TP10 electrodes. Before artifact rejection, bad channels were reconstructed from adjacent electrodes using triangulation and linear interpolation. Interpolated electrodes varied from 1 to 13 of 64 channels across participants ($M = 2.90$, $SD = 2.89$; calculated from analyzed data of 40 participants). Segmentation started 200 ms before and ended 1800 ms after stimulus onset. Large-movement artifacts were rejected manually. Independent component analysis (ICA) and reversed ICA were additionally conducted for eye-blink detection and atypical signal power spectrum rejection using the algorithm implemented in the Brain Vision Analyzer 2 software. Next, the signal was epoched for three groups of presented stimuli: a group of (1) verbs (verb) and subgroups of the noun condition, (2) feminine (fem) and (3) masculine (masc), with a baseline correction of 200 ms before stimulus onset. The data from the averaged segments were exported for peak detection for further statistical analysis. From 40 recordings, 8 datasets were rejected from the analysis due to a high signal-to-noise ratio (SNR; SNR $<$ 1). EEG recordings from 32 participants were involved in the grand average analysis ($M_{\text{age}} = 23.50$, $SD_{\text{age}} = 3.62$, $range_{\text{age}} = 18$–33, 16 male).

2.7. Spatio-Temporal cluster ANOVA: Grammar class effect in pseudowords

To examine the effect of grammar class during silent reading of a random sequence of verbs and feminine and masculine nouns, we conducted one-way repeated-measures analyses of variance (ANOVAs) for each ERP separately (e.g., see Kissler et al., 2009) using the Python-based statistical analysis package pingouin.py 0.5.2 (Vallat, 2018)

To detect language-related event-related potentials, five main time windows were selected: 1) 100–190 ms, 2) 190–290 ms, 3) 300–450 ms, 4) 410–580 ms, and 5) 600–900 ms. These time windows covered the peaks of the P100, P200, LAN, and P600, respectively. To check bioelectrical activity patterns, we distinguished the general regions of interest (ROIs). As, for example, in Kissler et al. (2009), we assigned a particular ROI and time window to each event-related potential. P100, EPN, P300, LPC, and P600, respectively and these were quantified at the posterior electrodes (O1, O2, P3, P5, P7, P4, P6, P8, PO3, PO7, PO4, and PO8). The P200, N100, and LAN components were assigned to the frontal electrodes (AF3, AF4, F1, F3, F5, FC1, FC3, F2, F4, F6, FC2, and FC4). The selection of electrodes was based on previous literature concerning lexical processing and visually evoked potentials and similar sensor nets with 32–64 electrodes (e.g., Herbert et al., 2006). Analyses for all mentioned ERPs were conducted separately within the left and right hemispheres. Statistical analysis was based on the maximum negative (for the EPN, N100, and LAN components) and positive (for P100, P200, P300, LPC, and P600) values of the ERP amplitude extracted via the peak detection algorithm of the analysis software. The topographic and ERP illustrations of the epoch for each selected condition are presented in Figs. 2 and 3.

For each time window, we conducted the following analyses: first for pseudoverbs contrasted with pseudonouns altogether, second for pseudoverbs and pseudonouns in masculine form and feminine form separately. The first analysis was a 2x2 ANOVA with two factors: hemisphere (two levels: left and right hemisphere) and condition (grammar class with two levels: pseudoverbs and pseudonouns: PV-PN). Additionally, we conducted a more specific analysis, i.e., an ANOVA with the main factor of grammar class, which contained three levels: verb, feminine noun, masculine noun ($PV\text{-}PN_{fem}\text{-}PN_{masc}$) calculated within hemisphere (left and right).

3. Results

3.1. Statistical analysis of the behavioral lexical decision task (LDT)

The accuracy rate for correct answers was calculated for all trials presented in the study (M = 96 %; the average accuracy across participants was M = 96.04%; SD = 3.42% with values ranging from 85.60% to 100%). We recoded into missing data, words that were incorrectly classified (4% of all responses)[3], as well as responses slower than 2500 ms (additional 2.4%). As a sensitivity analysis, we also included a second measure of reaction times (RT_sensitivity), of which responses slower than 1500 ms were excluded (additional 7.2%). As shown in Table 2, the regression analysis of reaction times obtained during the LDT, when pseudonouns and pseudoverbs were presented as target stimuli, showed a clear pattern of pseudonouns being processed more slowly than pseudoverbs.

3.2. Statistical analysis of Event-Related potentials

3.2.1. P100 and N100: Time window 100–190 ms

To discover whether pseudowords belonging to different grammar classes evoke different brain responses in early time windows of about 100–190 ms, we conducted a repeated-measures ANOVA within the P100 and N100 ROIs. The 2x2 PV-PN ANOVA with condition (pseudoverbs, PV, and pseudonouns, PN) and hemisphere (left vs right electrode cluster) as an additional factor showed that for the P100 amplitude there was no significant difference between pseudoverbs and pseudonouns ($F_{(1,31)}$ = 0.13, p =.72, η_g^2 < 0.01), however, there was a significant difference between hemispheres ($F_{(1,31)}$ = 9.82, p =.004, η_g^2 = 0.04; M_{left} = 5.59 μV, M_{right} = 2.65 μV). The interaction between hemisphere and *PV-PN* condition was not significant ($F_{(1,31)}$ = 0.48, p =.50, η_g^2 < 0.01).

Further analyses of the effects of condition (pseudoverbs, PV, and pseudonouns feminine, pseudonous masculine) were conducted separately within the left or right hemisphere. The ANOVA comparing pseudonouns with feminine or masculine forms and pseudoverbs $PV\text{-}PN_{fem}\text{-}PN_{masc}$ within hemispheres showed that in the left hemisphere, the amplitude peak of the P100 differed significantly between the three categories ($F_{(2,62)}$ = 4.15, p =.02, η_g^2 = 0.01; Fig. 3). Post-hoc Tukey Test for pairwise comparisons showed that there was a difference between pseudoverbs and feminine pseudonouns (p =.03), but not between pseudoverbs and masculine pseudonouns (p =.39) or the two types of pseudonouns (p =.40). Within the right hemisphere, the difference between pseudoverbs, pseudonouns_{fem} or $\text{pseudonouns}_{masc}$ was not significant ($F_{(2,62)}$ = 2.13, p =.13, η_g^2 = 0.06). The direction of the effects is illustrated in Table 3.

The 2x2 PV-PN ANOVA with hemisphere as an additional factor of N100 component showed that there is no significant difference between pseudoverbs and pseudonouns *PV-PN* condition ($F_{(1,31)}$ = 0.85, p =.37, η_g^2 < 0.01) and also between hemispheres ($F_{(1,31)}$ = 0.63, p =.44, η_g^2 < 0.01; M_{left} = 1.72 μV, M_{right} = 1.42 μV). The interaction between hemisphere and condition was not significant ($F_{(1,31)}$ = 0.02, p =.97, η_g^2 < 0.01).

The ANOVA comparing pseudonouns with feminine or masculine forms and pseudoverbs $PV\text{-}PN_{fem}\text{-}PN_{masc}$ within hemispheres showed that in the left hemisphere, showed a nonsignificant effect ($F_{(2,62)}$ = 1.08, p =.17, η_g^2 < 0.01). The results for the right hemisphere were also not significant ($F_{(2,62)}$ = 2.31p =.11, η_g^2 < 0.01). The mean amplitude and latency for the described ERPs are presented in Table 3.

3.2.2. P200 and EPN: Time window 190–290 ms

In the P200 region of interest repeated-measures PV-PN ANOVA analysis showed no significant main effects of condition - pseudoverbs and pseudonouns ($F_{(1,31)}$ = 0.15, p =.70, η_g^2 < 0.01). There was a significant main effect of hemisphere ($F_{(1,31)}$ = 13.55, p =.001, η_g^2 = 0.02; M_{left} = 3.41 μV, M_{right} = 2.88 μV). The interaction between PN-PV condition and hemisphere was not significant ($F_{(1,31)}$ = 1.45, p =.24, η_g^2 < 0.01).

In the left hemisphere, the $PV\text{-}PN_{fem}\text{-}PN_{masc}$ ANOVA showed that a frontal P200 difference within the condition was significant ($F_{(2,62)}$ = 3.18, p =.05, η_g^2 = 0.09). Post-hoc Tukey Test for pairwise mean comparisons showed that there was a difference between pseudoverbs and feminine pseudonouns (p =.04) and in pseudoverbs and masculine pseudonouns (p =.03), but there was no significant difference between the two types of pseudonouns (p =.99). The $PV\text{-}PN_{fem}\text{-}PN_{masc}$ ANOVA was not significant within the right hemisphere ($F_{(2,62)}$ = 2.04, p =.14, η_g^2 = 0.06).

In the EPN region of interest, repeated-measures PV-PN ANOVA with hemisphere as a second factor showed no significant main effect of condition, ($F_{(1,31)}$ = 0.07, p =.79, η_g^2 < 0.01). There was a significant hemisphere main effect ($F_{(1,31)}$ = 48.80, p <.001, η_g^2 = 0.11; M_{left} = -1.89 μV, M_{right} = 0.07 μV). The interaction between *PN-PV* condition and hemisphere was not significant ($F_{(1,31)}$ = 2.20, p =.15, η_g^2 = 0.001).

Within the left hemisphere, the ANOVA comparing PV, PN_{fem} and PN_{masc} was not significant ($F_{(2,62)}$ = 2.81, p <.07, η_g^2 = 0.01), however within the right hemisphere significant differences emerged ($F_{(2,62)}$ = 5.19, p <.01, η_g^2 < 0.01). A Post-hoc Tukey Test for pairwise mean comparisons showed a difference between pseudoverbs and feminine pseudonouns (p =.012), but not between pseudoverbs and masculine pseudonouns (p <.26), and no significant difference between the two types of pseudonouns (p =.40). The mean amplitude and latency values for the P200 and EPN ERPs are presented in Table 4.

3.2.3. P300 and N400: Time window 350–450 ms

PV-PN ANOVA with hemisphere as an additional factor showed no significant main effects of N400 PV-PN condition ($F_{(1,31)}$ = 1.16, p =.29, η_g^2 < 0.01) nor hemisphere ($F_{(1,31)}$ = 0.94p =.34, η_g^2 < 0.01). The interaction between PN-PV condition and hemisphere was not significant ($F_{(1,31)}$ = 1.19, p =.28, η_g^2 < 0.01).

The analysis of $N400PV\text{-}PN_{fem}\text{-}PN_{masc}$ showed significant differences in grammar class within both the left ($F_{(2,62)}$ = 4.97, p =.012, η_g^2 = 0.14) and right ($F_{(2,62)}$ = 8.43, p =.001, η_g^2 = 0.21) hemispheres (Fig. 3). Post-hoc Tukey Test for pairwise mean comparisons in the left hemisphere showed that there was a difference between pseudoverbs and feminine pseudonouns (p =.001) and in pseudoverbs and masculine pseudonouns (p =.001), but there was no significant difference between the two types

[3] Please note that of the 4% incorrectly classified words 50.4% were verbs (M_{RT} = 1086.77, SD_{RT} = 835.60) and 49.6% were nouns (M_{RT} = 1099.33, SD_{RT} = 852.28). If nouns are considered with respect to their grammatical gender there were 16.9% incorrectly classified feminine nouns (M_{RT} = 1102.84, SD_{RT} = 896.03) and 32.7% incorrectly classified masculine nouns (M_{RT} = 1097.51, SD_{RT} = 834.30).

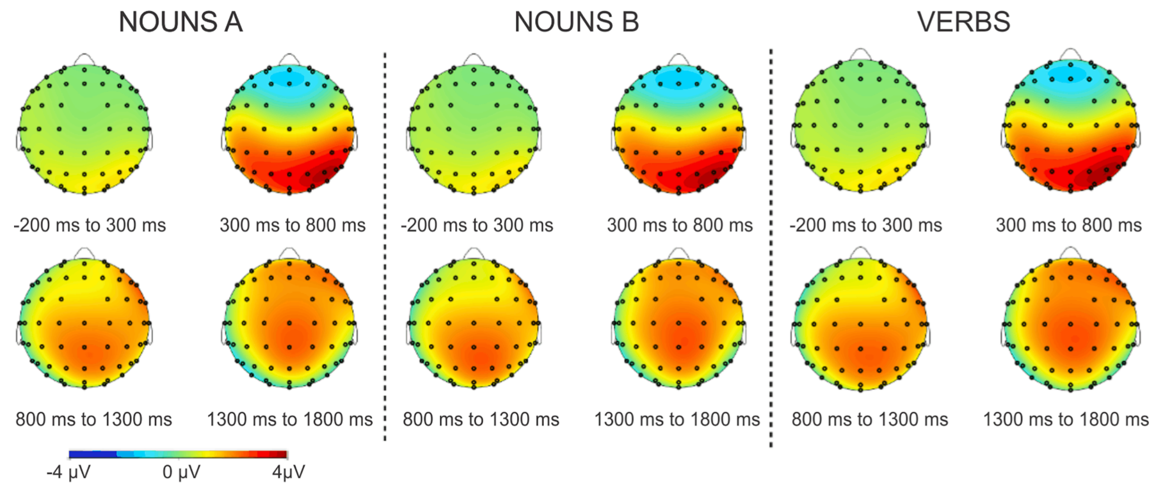

Fig. 2. Topographic representation of epoched brain activity (-200 ms to 1800 ms) Note. The time course starts with the baseline correction 200 ms before the pseudoword presentation. NOUNS A = feminine nouns; NOUNS B = masculine nouns; VERBS = all verbs.

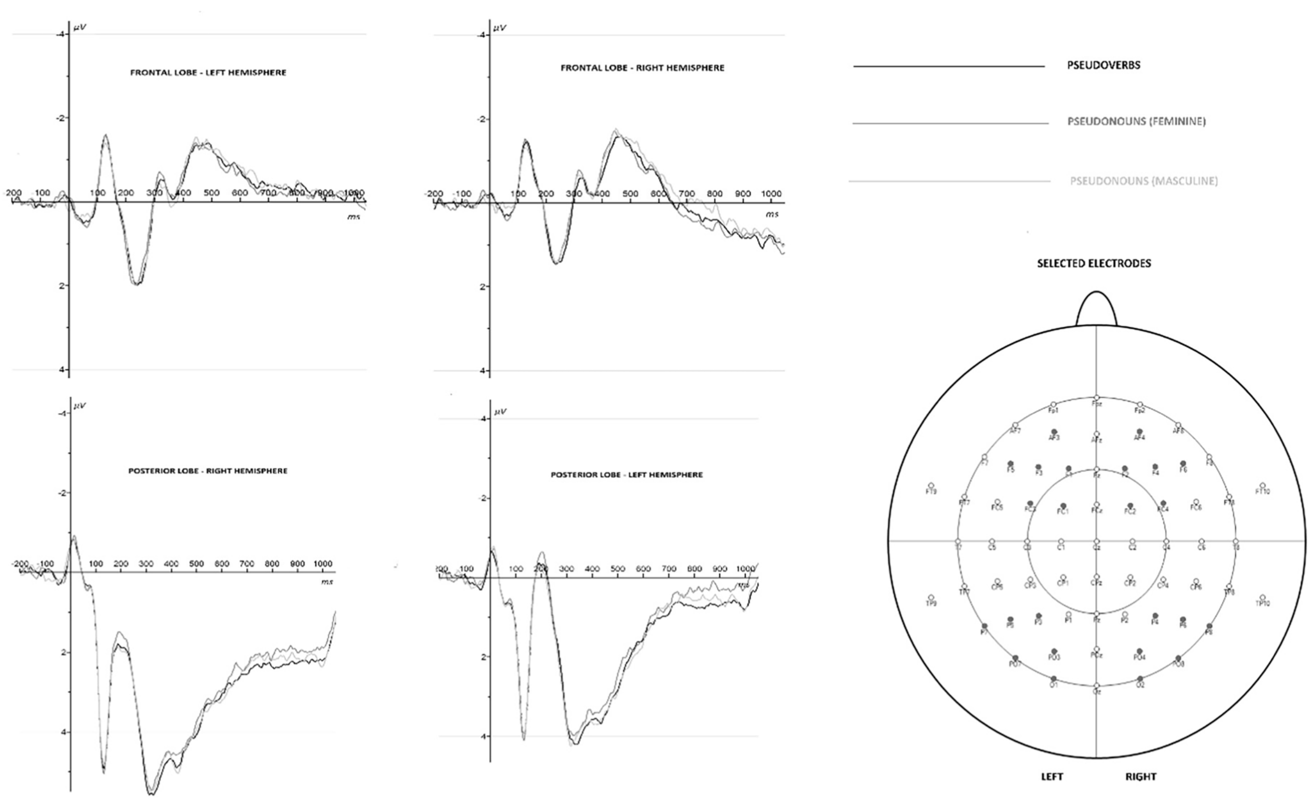

Fig. 3. ERP Illustration of ERP's and electrode selection.

Table 2
Regression Coefficients for the Two Analyses Conducted.

Variable	RT		RT_sensitivity	
	B	*SE*	*B*	*SE*
Intercept	885.18***	40.18	786.01***	25.34
Verbs (0) vs. Feminine Nouns (1)	47.58**	14.71	37.91***	8.08
Verbs (0) vs. Masculine Nouns (1)	75.19***	18.05	50.77***	8.97
Session	−141.35 ***	24.90	−94.00***	14.81
R^2	0.04**		0.04***	

Note. B represents unstandardized coefficients and SE stands for standard error. * *p* <.05.** p <.01. *** *p* <.001.

of pseudonouns (p =.99). For the right hemisphere the results of the Tukey Test were very similar, with p <.001, p <.001, and p =.97, respectively.

For the P300, the PV-PN ANOVA with hemisphere as an additional factor showed no significant main effect of condition - pseudoverbs and pseudonouns ($F_{(1,31)} = 0.38$, p =.55, $\eta_g^2 < 0.01$), but a significant main effect of hemisphere ($F_{(1,31)} = 9.43 p = .004$, $\eta_g^2 < 0.001$; $M_{left} = 5.15$ μV, $M_{right} = 6.44$ μV). The interaction between PN-PV condition and hemisphere was not significant ($F_{(1,31)} < 0.001$, p =.99, $\eta_g^2 < 0.01$). The analyses comparing the two types of pseudonouns (PN_{fem}-PN_{masc}) with verbs (PV) revealed no significant differences neither within the left ($F_{(2,62)} = 1.82$, p =.17, $\eta_g^2 = 0.87$) nor right ($F_{(2,62)} = 2.81$, p =.07, $\eta_g^2 <$ 0.01) hemisphere. The mean amplitude and latency values are presented

Table 3
Mean amplitude and latency of components analyzed in 100–190 ms time window.

Unit	Left hemisphere			Right hemisphere		
	$noun_{fem}$	$noun_{masc}$	verb	$noun_{fem}$	$noun_{masc}$	verb
posterior P100						
μV	5.99	5.78	5.55	6.98	6.83	6.65
ms	138	140	140	140	143	141
frontal N100						
μV	−3.03	−3.05	−2.80	−3.16	−3.10	−2.87
ms	137	138	137	141	140	139

Note. ROI = region of interest; $noun_{fem}$ = feminine nouns; $noun_{masc}$ = masculine nouns.

Table 4
Mean amplitude and latency of components analyzed in 190–290 ms time window.

Unit	Left hemisphere			Right hemisphere		
	$noun_{fem}$	$noun_{masc}$	verb	$noun_{fem}$	$noun_{masc}$	verb
frontal P200						
μV	3.74	3.75	3.42	3.22	3.14	2.92
ms	238	241	239	238	240	240
posterior EPN						
μV	−2.25	−1.98	−1.92	0. 12	−0.35	−0.14
ms	219	220	218	225	226	224

Note. ROI = region of interest; $noun_{fem}$ = feminine nouns; $noun_{masc}$ = masculine nouns.

in Table 5.

3.2.4. LPC and LAN: Time window 410–580 ms

For the LPC component, the PV-PN ANOVA with hemisphere as an additional factor showed no significant main effect of condition - pseudoverbs and pseudonouns ($F_{(1,31)} = 0.13$, $p = .72$, $\eta^2_g < 0.01$). There was a significant main effect of hemisphere ($F_{(1,31)} = 10.42 p = .003$, $\eta^2_g = 0.07$; $M_{left} = 4.63$ μV, $M_{right} = 5.95$ μV). The interaction between *PN-PV* condition and hemisphere was not significant ($F_{(1,31)} = 0.15$, $p = .70$, $\eta^2_g < 0.01$).

Within the left hemisphere, the PV-PN_{fem}-PN_{masc} ANOVA showed significant differences ($F_{(2,62)} = 3,10$, $p = .05$, $\eta^2_g = 0.01$). Post-hoc Tukey Test for pairwise mean comparisons showed that there was a difference between pseudoverbs and masculine pseudonouns ($p < .01$), but not between pseudoverbs and feminine pseudonouns ($p = .24$), and no significant difference between two types of pseudonouns ($p = .12$). The PV-PN_{fem}-PN_{masc} effects were significant also within the right hemisphere ($F_{(2,62)} = 4.67$, $p = .013$ $\eta^2_g = 0.01$) (Fig. 3). Results of the Tukey Test were significant for pseudoverbs and masculine pseudonouns comparison ($p < .001$), but not significant in feminine nouns and verbs ($p = .43$). Comparison of both types of pseudonouns showed a significant result ($p = .04$).

The analysis of the frontal (LAN-assigned) regions in PV-PN ANOVA with hemisphere as an additional factor showed no significant main effects of condition - pseudoverbs and pseudonouns ($F_{(1,31)} = 0.01$, $p = .91$, $\eta^2_g < 0.01$) nor hemisphere ($F_{(1,31)} = .22 p = .64$, $\eta^2_g < 0.01$). The interaction between the *PN-PV* condition and hemisphere was not significant ($F_{(1,31)} = 0.16$, $p = .69$, $\eta^2_g < 0.01$),

The more detailed grammar class ANOVA (PV-PN_{fem}-PN_{masc}) showed significant differences, in both the left ($F_{(2,62)} = 7.46$, $p = .001$, $\eta^2_g = 0.19$) and right ($F_{(2,62)} = 7.64$, $p = .001$, $\eta^2_g = 0.20$) hemispheres (Fig. 3). Post-hoc Tukey Test for pairwise mean comparisons in the left hemisphere showed that there was a difference between pseudoverbs and $pseudonouns_{fem}$ ($p = .001$) and in pseudoverbs and $pseudonouns_{masc}$ ($p < .001$), but there was no significant difference between the two types of pseudonouns ($p = .57$). In the right hemisphere, results of the Tukey Test showed the same pattern, with $p = .001$, $p < .001$, and $p = .69$, respectively. The mean amplitude and latency values for ERPs observed in this time window are presented in Table 6.

3.2.5. P600: Time window 600–900 ms

The analysis of the posterior P600-related regions in PV-PN ANOVA with hemisphere as an additional factor showed no significant main effects of condition - pseudoverbs and pseudonouns ($F_{(1,31)} = 2.08$, $p = .16$, $\eta^2_g = 0.002$), but there was hemisphere ($F_{(1,31)} = 18.74$, $p < .001$, $\eta^2_g = 0.16$; $M_{left} = 2.66$ μV, $M_{right} = 4.28$ μV) main effect. The interaction between the *PN-PV* condition and hemisphere was not significant ($F_{(1,31)} = 0.02$, $p = .90$, $\eta^2_g < 0.01$).

The ANOVA comparing pseudonouns with feminine or masculine forms and pseudoverbs PV-PN_{fem}-PN_{masc} within hemispheres showed significant effect in the left ($F_{(2,62)} = 5.65$, $p = .006$, $\eta^2_g = 0.15$) and right ($F_{(2,62)} = 4.23$, $p = .02$, $\eta^2_g = 0.13$) hemispheres. Post-hoc Tukey Test for pairwise mean comparisons conducted for significant effect of condition in the left hemisphere showed that there was a difference between pseudoverbs and feminine pseudonouns ($p = .01$) and between pseudoverbs and masculine pseudonouns ($p < .001$), but there is no significant difference between the two types of pseudonouns ($p = .45$). The same was true for the analysis within the right hemisphere, with $p = 0.02$, $p = .001$, and $p = .71$, respectively. The mean amplitude and latency values for the P600 are presented in Table 7.

4. Discussion

The current study aimed to determine the neural and behavioral correlates that drive distinctive grammar class processing during processing of pseudowords devoid of semantic meaning derived from Polish verbs and nouns. In particular, we investigated whether pseudonouns and pseudoverbs elicit different electrophysiological responses when presented in passive-reading paradigm. Next, in a behavioral LDT, we

Table 5
Mean amplitude and latency of components analyzed in 350–450 ms time window.

Unit	Left hemisphere			Right hemisphere		
	$noun_{fem}$	$noun_{masc}$	verb	$noun_{fem}$	$noun_{masc}$	verb
frontal FN400						
μV	−2.72	−2.71	−2.22	−2.94	−2.91	−2.34
ms	414	418	416	415	419	419
posterior P300						
μV	1.55	1.75	2.21	6.61	6.91	6.50
ms	392	396	394	393	397	401

Note. ROI = region of interest; $noun_{fem}$ = feminine nouns; $noun_{masc}$ = masculine nouns.

Table 6
Mean amplitude and latency of components analyzed in 410–580 ms time window.

Unit	Left hemisphere			Right hemisphere		
	$noun_{fem}$	$noun_{masc}$	verb	$noun_{fem}$	$noun_{masc}$	verb
frontal LAN						
μV	−3.32	−3.46	−2.84	−3.39	−3.50	−2.91
ms	485	488	489	477	484	485
posterior LPC						
μV	0.30	0.52	0.86	6.18	6.59	5.97
ms	495	499	497	503	492	502

Note. ROI = region of interest; $noun_{fem}$ = feminine nouns; $noun_{masc}$ = masculine nouns.

Table 7
Mean amplitude and latency of components analyzed in 600–900 ms time window.

Unit	Left hemisphere			Right hemisphere		
	$noun_{fem}$	$noun_{masc}$	verb	$noun_{fem}$	$noun_{masc}$	verb
posterior P600						
μV	3.15	3.31	2.77	4.75	4.87	3.56
ms	713	712	710	721	715	712

Note. ROI = region of interest; $noun_{fem}$ = feminine nouns; $noun_{masc}$ = masculine nouns.

examined reaction times for the presented pseudowords. Taken together, the results indicate that a difference between grammar class processing can be observed at both the neuronal level and the behavioral level. In the EEG, processing differences between the presented grammar classes related to pseudonouns and pseudoverbs were reflected by amplitude modulation of early as well as late language- and attention-related ERPs. In the behavioral task, lexical decisions elicited differential reaction times for pseudonouns and pseudoverbs.

Interestingly, the analysis comparing the processing of pseudoverbs with pseudonouns did not show any significant differences in the different time windows of early and late ERP component but significant main effects of the factor hemisphere. This is indicating overall differences in the amplitude modulations of the different ERPs of interest in the left and right hemisphere, however did not differ between pseudonouns and pseudoverbs as reflected by insignificant interaction effects between the factors “condition” and “hemisphere”. However, when modulation of ERP amplitudes was compared between the three grammatical pseudoword classes (pseudonouns feminine, masculine and pseudoverbs) within each hemisphere separately there were significant differences. These differences were observed already in very early time windows starting in the P100 time window indicating perceptual processing of lexical features (see below) and continuing into the P200 and EPN time windows indicative of different stages of word processing associated with orthographical and lexico-semantic processing.

4.1. Modulation of P200, N400, LAN and P600 by gender-related pseudonouns and infinitive forms of pseudoverbs

As far as differences in the P200 time window are concerned, one explanation for this result is that pseudonouns in an inflected language like Polish show a greater variety in the suffixes of the presented pseudowords. In the present study, pseudonouns had grammatical gender distinction compared to pseudoverbs which were presented only in the infinitive form, with one inflectional ending (-ć). Additionally, pseudoverbs, through their suffixes indicate dynamics, which however is not associated with a reference point, such as a body part or object (e.g., the verb *kopać* [to kick] implies that somebody is doing something dynamically using legs, hands, or a tools using hands, while the pseudoverb *firdawić* [*to firdaw*] implies only a dynamic or static action. In the case of nouns, morphological cues delineating the concreteness and imageability (Paivio, 1978) of pseudonouns (by indicating a grammatical gender suffix) make them more demanding for neural responses in terms of language-related time windows and ROIs. We therefore assume that pseudonouns, as they are more object-oriented and related to memory updating (imageable), elicited more pronounced amplitude modulations in the P200 time window compared to pseudoverbs. This result is similar to Kounios and Holcomb’s (1994) finding that concrete words elicited stronger peaks than abstract words; our pseudoword stimuli set showed a similar pattern of results, where pseudonouns elicited a more positive P200 amplitude. Second, this result is consistent with Yudes et al. (2016), who found differences between grammar classes; nouns and action-nouns elicited a more positive peak in the P200 time window than action and non-action verbs. In our study, pseudonouns also evoked a more positive P200 amplitude than pseudoverbs.

A second possible explanation for the result in the frontal P200 is that it reflects early semantic top-down processes on word recognition and a time window of access to mental lexicon, Hauk and Pulvermüeller (2004), whereas posterior effects in the same time window as the frontal P200 occuring within the first 250 ms such as the EPN might be more sensitive to bottom-up driven early semantic processing (Kissler et al., 2009). In the present study, grammatical gender indicators might facilitate these kinds of mental operations by assigning an object-related concept. In the presented stimulus set, pseudonouns were more morphologically complex than pseudoverbs and elicited stronger electrophysiological responses. However, in the LDT, where participants were asked to decide whether the presented pseudoword was a noun or verb, the results from the correct trials showed that pseudoverbs were classified more quickly than pseudonouns. Therefore, it can be concluded that gender inflectional endings that induce (object-related) cues in the mental image of nouns and a variety of suffixes hinder processing by delaying the reaction time in the response to nouns and require more electrophysiological processing demands.

We observed more frontal negativity for the N400. A similar effect was found by Imbir et al. (2018), in which the morphological complexity of the stimulus modulated ERP amplitudes. As mentioned previously, inflectional endings of nouns present greater diversity than verbs in the infinitive form. Thus, we interpret the pseudonoun stimuli in the present study as more complex and hence more demanding during word processing. Suffixes presented in nouns assign gender; thus, they also refer to semantics by indicating imageable (specific) grammar class concepts. On the other hand, while binding N400 component with other cognitive processes, like predictive coding (Friston 2018) we can interpret that pseudoverbs elicited less prominent amplitude, thereby facilitated processing costs in the human brain (Bornkessel-Schlesewsky and Schlesewsky, 2019). We also found differences between grammatical classes in the topography and time window corresponding to the LAN component. Pseudonouns elicit larger amplitudes than pseudoverbs. Although LAN differences usually occur in sentence-based paradigms as predictors of the difficulty level of sentence elements’ integration (Canseco-Gonzalez, 2000), we obtained this result in the single-word presentation paradigm. According to the results of our study, the presence of the LAN component might highlight the nonsemantic differences between pseudonouns and pseudoverbs. The LAN component presented here can be a marker of morpho-syntactic manipulation in shared-stem pseudowords in serial order presentation. The lack of real meaning may emphasize the differences resulting from belonging to different grammar classes. Focusing attention on the morphological indicators of grammar suggests that LAN event-related potential may be applicable when investigating the morphological aspects of linguistic knowledge. Interestingly these effects denoted by the gender suffix remained and were also observed in the N400 time window from 350 to 450 ms after stimulus presentation.

In the time window related to the P600 (600–900 ms), we observed differences over the right posterior region. Most studies investigating the P600 focus on syntactic and semantic dependencies related to the reanalysis of sentence consistency. For example, the P600 can be a sign of demands on working memory while linking long-distance structural dependencies related to prediction of a *wh-* phrase (Gouvea et al., 2010), which is an indicator of non-verb–related parts of the sentence based on *wh-* questions (*what*, *why*, *where*, *which*, *who*, or *how*). The P600 can be observed at the verb position while reading the sentence, especially when the direct object of the *wh-* phrase appears before the verb (Kaan & Swaab, 2003). According to previous studies, this is a sign of difficulty in syntactic integration (Gibson, 1998). The presence of the P600 in the present EEG experiment may suggest that grammar-related dependencies can be narrowed down to the word level by revealing an affiliation with a grammatical class, for example, through gender suffixes in pseudonouns. It could be possible that parsing also takes place at the lower levels of the language, such as morphology. This leads to the assumption that theoretical approaches can be widened by considering dependencies within constituent parts of words, not just sentences. Our experiment provides evidence that this late language-related ERP can also be obtained by presenting a single-word paradigm and that pseudonouns provide discrete information concerning activation *wh*-knowledge by eliciting stronger neural responses. Although the P600 is commonly observed in syntactic tasks, following Kissler and Herbert (2013), we observed differences in its modulation within grammar class conditions that might not occur independent from the effects observed in earlier time windows including attention-related ERPs.

4.2. Modulation of P100, EPN and LPC by gender-related pseudonouns and infinitive forms of pseudoverbs

Besides the above reported effects (P200, LAN and N400), we additionally observed very early effects in the time window of P100 amplitude. According to previous studies, the hemispheric distribution of event-related potentials shows that pseudowords elicit similar results as real words and pictures, which evoke more positive peaks. Regarding linguistical processing, the peak of P100 was greater in the left hemisphere than in the right showing mirrored hemispheric pattern of activity shown in studies related to word and picture processing (Compton et al., 1991; Kounios et al., 1994; Neville et al., 1982). This result also suggests that while presenting sets of words assigned to two different grammatical classes, grammatical class exponent is a crucial factor for hemispheric processing. Pseudonouns and pseudoverbs indicate different modulations of early ERP components when activating lexical access (Kissler & Herbert, 2013). Scott et al. (2009) observed reduced P100 amplitude after negative words were presented. This kind of neural activity was interpreted as a prelexical perceptual defense mechanism. The pseudoverbs presented in this study showed a similar pattern of influencing brain activity. By measuring the early brain component as P100, we revealed that, as in the case of negative words, morphological cues of verbs can herald neural operationalization, for example, a threat with dynamic properties.

As in previous research (Herbert et al., 2008; Kissler & Herbert, 2013), pseudowords in our study elicited differential modulation in the time window of the EPN component, that is, a component typically driven by the emotional content of a word. We found a similar pattern of brain activity—the difference between grammar classes was significant, within the right hemisphere, which is confirming that there is difference in grammatical class perception., As it was shown in the previous literature evidences, lexical processing is modulating emotion-related responses (Kissler & Herbert, 2013).

Pseudowords elicited sustained attention-related responses in later time windows related to the LPC, a brain potential akin to the EPN shown to be driven by the emotional content of the word and by sustained attention. The LPC component was shown around 460 ms after stimulus presentation, and it was modulated by the grammar class. This parietal effect, according to Curran (2000), is associated with recollection. Previous literature has also shown the binding of the LP component with the FN400 ERP (Smith & Guster, 1993). However, these findings do not support the thesis about a qualitative distinction between brain areas engaged in feeling and familiarity processing and those areas that are responsible for conscious recollection. Taking this into account, pseudowords are a kind of stimuli that can force the differentiation of the concepts of verb and noun.

5. Conclusion

Taken together, the present results strengthen the existing evidence that different aspects of language and different linguistic dimensions of words can affect brain activity and behavior, even during the processing of words devoid of meaning, such as pseudoverbs and pseudonouns. Based on our results, we assume that the grammar-related factors of pseudowords affect human brain activity and behavior by incorporating morphological cues in linguistic-related stimuli while retrieving mental lexicon items in terms of grammar. In the case of nouns, the ERP and behavioral results suggest that instantiating an object designated by this grammatical class requires greater linguistic processing demands, which is reflected in higher linguistic-evoked potentials and longer reaction times. The situation changes when we consider attention-related and emotion-related ERPs. As for verbs, the results indicate behavioral and attention-related early neural effects (P100), which are triggered more by the grammar class of pseudoverbs than by pseudonouns, that is also reflected in reaction-time.

6. Limitations of the study and future outlook

Future research should consider the limitations of the current work. The experiment trial lasted about 3100 ms. Future studies could test if the difference between pseudoverbs and pseudonouns could appear with shorter trial durations. Additionally, future studies could investigate differences of the ERP components latency in relation to behavioral measures to test whether there is a relation between the latency measures on the neural level and reaction time on the behavioral level. Moreover, it could be of interest to investigate between-blocks differences in the amplitudes of the ERP components in future studies, because it will add additional information about how pseudoverbs and pseudonouns are processed across several runs of repeated presentation. Particularly, this would link this study to the literature on novel word learning.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data available on request for scientific use only.

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