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Emotional word processing in bilinguals: An oscillatory cascade from perception to regulation in the second language

Iga Krzysik[1], Marcin Naranowicz[1,2], Olivia Molina-Nieto[3], Guillaume Thierry[3] and Rafał Jończyk[1,2]

[1]Faculty of English, Adam Mickiewicz University, Poznań, Poland; [2]Cognitive Neuroscience Center, Adam Mickiewicz University, Poznań, Poland and [3]School of Psychology and Sport Science, Bangor University, Bangor, UK

Research Article

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Corresponding author:
Iga Krzysik;
Email: iga.krzysik@amu.edu.pl

G.T. and R.J. contributed equally.

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Abstract

Processing emotionally negative words in a second language (L2) feels less vivid and more cognitively demanding than in the first language (L1), yet the neural mechanisms underlying this difference remain poorly understood. Using single-trial modelling of event-related potentials (ERPs) and event-related spectral perturbations (ERSPs), we examined attention allocation to negative versus neutral words in highly proficient late Polish–English bilinguals performing a semantic categorisation task in a modified oddball paradigm. Valence and language modulated early posterior negativity (EPN) and P300, but not the N400. Mass-univariate analysis detected valence modulations in the N400 range, highlighting limitations of classic ERP approaches. Time–frequency analysis further revealed Language × Valence interactions: negative L2 words selectively elicited a cascade of delta, theta and alpha synchronisation from posterior to frontal regions across 59–641 ms, consistent with successive perceptual, lexical-semantic and regulatory processing stages. Emotional processing in L2 is thus qualitatively distinct, more effortful and regulated rather than simply being less efficient.

Highlights

- Late bilinguals show more effortful, regulated processing of negative words in L2.
- EPN and P300 were modulated by valence and language.
- Negative L2 words elicited delta, theta and alpha synchronisation across 59–641 ms.
- L2 emotional processing is qualitatively distinct, not merely less efficient than L1.

1. Introduction

The ability to express and comprehend emotions through language constitutes one of the building blocks of human verbal communication, enabling the regulation of social interactions and shaping daily experiences. Previous research has shown that processing of emotional words differs significantly from that of neutral words (e.g., Kissler et al., 2006; Kissler & Herbert, 2013; Recio et al., 2014). This may be due to greater perceptual salience, the triggering of the limbic system into action, the activation of a broader network of semantic connections or a combination of these (Citron, 2012).

Emotional language processing may even be more complex in the case of bilinguals who may have an imbalanced experience with emotional words in their first language (L1) and their second language (L2). Bilinguals have been found to exhibit reduced sensitivity to L2 emotional content (e.g., Caldwell-Harris, 2014; Colbeck & Bowers, 2012; Toivo & Scheepers, 2019). In late sequential bilinguals, who generally have acquired their L2 after the age of 12, such differences can be linked to contextual differences between acquisition of L1 (early age of acquisition, naturalistic, immersive, emotion-rich) and L2 (later age of acquisition, formal, structured, detached; Pavlenko, 2006; Caldwell-Harris, 2014). Emotional language processing is also modulated by differences in the development of affective experience embodiment. Indeed, delayed and indirect embodiment in L2 (Pavlenko, 2006; Wei et al. 2024, but see Wei & Thierry, 2025), particularly of negative L2 content (Sheikh & Titone, 2016), is thought to result in semantic dampening in L2 (Jończyk, 2016) possibly underpinned by inhibition of covert lexical access to L1 (Wu & Thierry, 2012). Such differences, however, tend to shrink with increasing language proficiency or immersion in the L2 environment (Conrad et al., 2011; Imbault et al., 2021; Ponari et al., 2015; but see, Jończyk, 2016).

Self-reports have suggested that L2 emotional words are perceived as less emotionally intense than equivalent L1 words with swear words and love confessions carrying more significant

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emotional weight in the L1 (Dewaele, 2004, 2008). Psychophysiological measures, as indexed by facial motor resonance, grip force, skin conductance, pupil dilation or brain activation, have shown that bilinguals respond less to L2 than L1 emotional words and written narratives (Baumeister et al., 2017; Del Maschio et al., 2024; Harris, 2004; Iacozza et al., 2017; Jankowiak & Korpal, 2018; Toivo & Scheepers, 2019; Thoma et al., 2023). Conversely, eye-tracking studies have suggested a processing advantage for L2 positive words (Sheikh & Titone, 2016) in addition to a disadvantage for L2 negative words (Tang & Ding, 2024).

Using event-related potentials (ERPs), Conrad et al. (2011) and Opitz and Degner (2012) observed comparable early posterior negativity (EPN) amplitudes and late positive potential (LPP) effects in L1 and L2 but observed a delay in L2 processing manifested as a peak latency difference. While emotional words are thought to engage similar neural mechanisms in L1 and L2, they do so with reduced efficiency in L2. Chen et al. (2015) found that positive words elicit a larger EPN and a smaller LPP than neutral words in L1, with a trend for positive L2 words to elicit reduced N400 amplitudes (compared to neutral words). Bilinguals further exhibit reduced sensitivity to L2 negative words in a sentence context and even to L2 sentences that include moral violations (Jończyk, 2016; Szczypek et al., 2026; but see Aldariz et al., 2026). In a S1–S2 anticipation paradigm, Jończyk et al. (2019) reported increased neurophysiological anticipation of emotional pictures following a negative relative to a neutral word cue in L1 Polish, with no such anticipation effect reached significance in L2 English. In a language production paradigm, Jończyk et al. (2024) also found reduced N400 amplitudes, along with increased LPP amplitudes, for L2 negative words when participants were required to orally translate words from L2 to L1 (i.e., oral production of negative words in L1) as compared to L1-to-L2 translation. The authors interpreted this effect as stemming from the inhibitory effect of L2 negative words on language non-selective lexical access proposed by Wu and Thierry (2012). Bilinguals typically activate native language translation equivalents automatically and unconsciously when reading or listening to L2 words; yet when words carry negative emotional valence, such parallel activation is suppressed, implying the existence of inhibitory mechanisms. This effect has been shown to apply with a delay (Zhang et al., 2023) and was more recently extended to the non-verbal domain since it can also be triggered by negatively valenced pictures (Zhang et al., 2025).

ERPs have provided key insights into the temporal dynamics of language processing for several decades. However, traditional averaging approaches rely heavily on phase-locked (evoked) activity, discarding non-phase-locked (induced) oscillatory dynamics that carry meaningful information (Cohen, 2014; Makeig et al., 2004). A complementary approach entails analysing variations of time–frequency spectra across electrodes time-locked to an event. Event-related spectral perturbations (ERSPs) quantify changes in oscillatory power across both time and frequency domains, and capture both evoked and induced components of the neurophysiological response (Delorme & Makeig, 2004). Rossi et al. (2023) recently recommended supplementing traditional ERP measures with time–frequency analyses to better capture the complexity of language-related neural dynamics in language and bilingualism research.

Seminal studies introducing time–frequency analysis have established links between classical ERP components and power variations in specific frequency bands. P300 modulation, for instance, has been linked to changes in delta power (1–4 Hz), consequently interpreted as reflecting the updating of attentional context models in response to novel or task-relevant stimuli. The N400 has been associated with theta increases (4–8 Hz), suggesting that variations in theta power index lexical-semantic retrieval and memory network activation (Bastiaansen & Hagoort, 2003). Increases in theta power (event-related synchronisation, ERS) have also been observed for emotional relative to neutral pictures or faces (Balconi & Pozzoli, 2009; Knyazev, 2012; Petro et al., 2025; Sulpizio et al., 2021). Alpha (8–12 Hz) oscillations are commonly linked to inhibition of task-irrelevant neural activity, with power increases reflecting cortical idling or functional suppression of task-irrelevant pathways, i.e., the gating-by-inhibition hypothesis (Engel et al., 2001; Foxe & Snyder, 2011; Jensen & Mazaheri, 2010; Jensen et al., 2012; Klimesch et al., 2007; Klimesch et al., 2011; Knyazev, 2007; 2012). Conversely, alpha power decreases (event-related desynchronisation [ERD]) are thought to reflect the release of inhibition and heightened cortical excitability. In paradigms involving emotional stimuli, alpha ERD has been associated with the engagement of motivational systems in response to, or in anticipation of, highly arousing stimuli (Keil et al., 2001; Schubring & Schupp, 2019, 2021). Consistent with this proposal, Wang and Bastiaansen (2014) observed alpha ERD for emotionally valenced words (both positive and negative) relative to neutral words, suggesting that affectively salient stimuli induce cortical excitement and reduce inhibition. In the language domain, left-lateralised alpha ERD, like theta ERS, has been linked to lexical-semantic access and memory retrieval (Bastiaansen & Hagoort, 2006; Klimesch, 1999).

Little is known, however, about how L1 and L2 emotional words direct attention in bilinguals – a critical gap given the increasingly bi- and multilingual nature of global communication. Monolingual studies have indicated that emotional language modulates attention early (e.g., Hofman et al., 2009, Zhao et al., 2018); however, it remains unresolved whether emotional words capture attention differently depending on whether they are encountered in a speaker's L1 or L2. Given that bilinguals process emotional content with reduced automaticity and may experience weaker affective resonance in L2 than L1, it is possible that L2 emotion words fail to capture their attention to the same extent as their L1 equivalents. It could be also that attention capture is no different between L1 and L2, but that L2 words entail less effective lexical access and/or semantic activation mechanisms, whether due to reduced connectivity and efficiency or to inhibition. The present study employed mass-univariate hierarchical linear modelling (LIMO, Pernet et al. 2011) of EEG data recorded during a semantic categorisation task in a modified oddball paradigm to examine the neural dynamics of attention orientation to emotional words in bilinguals.

The oddball paradigm is a common framework to study attention modulations based on the detection of novel (infrequent) stimuli (i.e., deviants) within a stream of highly repeated (frequent) stimuli (i.e., standards). Stimuli are presented sequentially as a stream of standards sporadically interrupted by a deviant (Carbajal & Malmierca, 2018). Deviants classically modulate the amplitude of the P300 component, a positive-going ERP wave maximal over centroparietal electrodes and peaking at around 300–400 ms (Polich, 2007). Emotional valence has been successfully manipulated in both visual and auditory oddball paradigms (Schlüter & Bermeitinger, 2017), with negative-valenced deviant words eliciting increased EPN, P300 and LPP amplitudes (Imbir et al., 2015; Ishida et al., 2018).

2. The present study

Here, we examined neural correlates of attention capture by negative words in L1 and L2 during a semantic categorisation task within an oddball paradigm. Polish–English bilinguals were

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presented with a stream of neutral words varying in meaning (standards) sporadically interrupted by negative words (deviants). This design departs from the traditional oddball paradigm typically presenting a low variance (often identical) stimulus repeatedly as the standard; instead, we used semantically diverse words whose standard status was based on their sharing of the same neutral valence. In addition to the P300 indexing attention capture, we analysed three components sensitive to emotional valence: EPN and N400 (e.g., Citron, 2012; Gibbons et al., 2022; Schindler & Kissler, 2016). We hypothesised that (i) EPN would be larger for negative than neutral words (Opitz & Degner, 2012; Zhang et al. 2014); (ii) P300 amplitude would be reduced for negative words in English (L2) compared to their Polish (L1) equivalents; and (iii) given that participants were engaged in a semantic categorisation task, we anticipated larger N400 amplitudes for negative words, since they were presented at a lower frequency than neutral ones, thereby making them less expected from a semantic viewpoint. Based on prior findings (Jończyk et al., 2016, 2024; Wu & Thierry, 2012; Zhang et al., 2023), negative words were expected to elicit reduced N400 amplitudes in L2 compared to L1 possibly involving inhibitory mechanisms. Finally, motivated by an assumption that oscillatory dynamics can reveal aspects of language processing that are undetectable in conventional amplitude measures, we employed an exploratory, data-driven analysis of ERSPs in the 3–25 Hz frequency range (delta–to–beta) bands, to characterise the time–frequency dynamics of language-specific emotional processing effects.

3. Methods

3.1. Participants

We analysed 37 EEG datasets from Polish (L1)–English (L2) bilingual speakers (26 female, 10 male, 1 non-binary) aged 19–33 (M = 23.97, 95% CI [22.77, 25.17]). All participants were students and graduates of the Faculty of English, Adam Mickiewicz University, Poznań, Poland. Sample size was determined based on heuristics informed by financial constraints and prior ERP research on emotion processing in bilinguals (e.g., Jończyk et al., 2024; Szczypek et al., 2026), following recommendations by Lakens (2022). Consistent with de Groot (2011), participants were classified as highly proficient unbalanced late bilinguals who had not lived in the L2 (English) environment and had acquired their L2 in an instructional yet immersive learning context (see Supplementary Table S1). This classification was further supported by LexTALE (Lemhöfer & Broersma, 2012) scores (M = 88.83, 95% CI [86.58, 91.08], range = 75.00–100.00), indicating upper and lower advanced L2 English proficiency in the group (C1–C2 CEFR levels). All participants had normal/corrected-to-normal vision and no language or neurological disorders. The study was approved by the Ethics Committee for Research Involving Human Participants at Adam Mickiewicz University, Poznań, Poland (#23/2021/2022). Informed consents were obtained from all participants, who received compensation for participation in the form of a gift card (100 PLN).

3.2. Materials

The experimental stimuli comprised 173 Polish and 173 English words, with 36 negative (e.g., grave, victim, death) and 137 neutral (e.g., vehicle, tailor, dimension) nouns in each language. Polysemous words, Polish–English cognates and interlanguage homonyms and homographs were excluded. To ensure that respective concepts were similarly represented by the selected words in both languages, we included Polish–English translation equivalents of all selected words, doubling the number of the experimental stimuli. Translation was completed by a qualified team member holding a degree in English Linguistics and postgraduate qualifications in written translation.

Negative and neutral words were matched across languages in terms of their critical lexico-semantic characteristics: word frequency, valence, arousal, concreteness as well as the number of letters and syllables (see Supplementary Table S2). These ratings were drawn from established normative databases: Imbir (2016) for Polish stimuli and Warriner et al. (2013) for English stimuli. Word frequency values were obtained from SUBTLEX-PL (Mandera et al., 2015) and SUBTLEX-UK (van Heuven et al., 2014). Concreteness ratings were based on Imbir (2016) for Polish and Brysbaert et al. (2014) for English. Unequal variances (Welch two-sample) t-test was used to compare respective mean scores between negative and neutral words. Consistent with prior studies (e.g., Jończyk et al., 2024; Naranowicz et al., 2023; Opitz & Degner, 2012), the analysis revealed smaller valence and greater arousal scores for negative than neutral words in both Polish, $t_{Valence}(43.81) = -27.71$, $p < .001$; $t_{Arousal}(42.19) = 14.58$, $p < .001$, and English, $t_{Valence}(48.93) = -27.72$, $p < .001$; $t_{Arousal}(48.63) = 12.73$, $p < .001$. Additionally, we compared mean valence and arousal scores between Polish and English separately for each word type to ensure comparability across the two languages. The analysis showed no between-language differences in valence scores for both negative, $t(69.77) < .01$, $p = 1.00$, and neutral words, $t(265.18) = -1.54$, $p = .125$. Also, there were no between-language differences in physiological arousal scores for both negative, $t(69.98) = -.51$, $p = .612$, and neutral words, $t(251.85) = 1.80$, $p = .074$.

3.3. Procedure

Participants were first pre-screened online by means of an in-house medical history questionnaire, LexTALE (Lemhöfer & Broersma, 2012), Edinburgh Handedness Questionnaire (Oldfield, 1971) and Multidimensional Assessment of Interoceptive Awareness (Mehling et al., 2018). The experiment was carried out in the Psychophysiology of Language and Affect Laboratory (PoLA) at Adam Mickiewicz University, Poznań, Poland. Participants were seated in a dimly lit and quiet booth, 75 cm away from a LED monitor with a screen resolution of 1280 × 1024 pixels. Participants completed the Language History Questionnaire (Li et al., 2020) during EEG cap preparation. Also, as recent studies have shown that participants' mood may affect emotional language processing in bilinguals (e.g., Naranowicz et al., 2023), participants rated their current emotional state by means of the Polish version of Positive and Negative Affect Schedule (PANAS; Watson et al., 1988, as adopted to Polish by Fajkowska & Marszał-Wiśniewska [2009]).

In the experiment proper, participants performed a semantic categorisation task, wherein they were asked to read single words presented one-by-one and monitor words belonging to specific semantic categories (i.e., fruits, flowers, clothes, furniture and animals) not overlapping with the categories present in the neutral word set. Participants were instructed to memorise the last word belonging to a targeted category and type it in at the end of each block. Participants completed two Polish and two English blocks (in a counterbalanced order), each comprising one block of originally selected and one of translated stimuli. In each block, participants were asked to focus on a different semantic category. To keep

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the overall number of neutral words at 140 in one block, we included 134–137 neutral experimental stimuli and 3–6 neutral target words from one of the specific semantic categories drawn from outside the experimental neutral word list. To put participants in a desired language mode, they completed practice trials in the language of the forthcoming block. In total, participants were presented with 704 words, including 144 negative and 560 neutral words (including targets) in each language across four blocks.

The design of the experiment was inspired by the classic P300 oddball paradigm, which involves the presentation of repetitive, frequent stimuli (standards) interspersed with infrequent stimuli (deviants; e.g., Chung-Fat-Yim et al., 2023; Harwood et al., 2022; Squires et al., 1975). In the current study, however, the paradigm differed from the classic P300 paradigm: Instead of repeating the exact same standard stimulus several times (3–5) in a row, standard words were different words sharing a neutral valence. This resulted in an inherently variable baseline which could be perceived as the standard condition only with respect to emotional valence. Negative words serving as deviants differed from standards in terms of valence. The surface semantic categorisation task was implemented to ensure participants processed every stimulus for meaning.

In each block, neutral words were the standards presented in sequences of three, four or five followed by a single deviant negative word. Additionally, there was a sequence that included five standard words with one word from the target category (fruits, flowers, clothing, furniture and animals), replacing the deviant word. While the presentation of word type (standard versus deviant versus target) was fixed within each sequence, the selected words were randomised. Words were displayed in black Arial font, size 24, on a light grey background. The display resolution was set to 1024 × 720 pixels.

Each block was preceded by a resting state fixation of 5000 ms. The presentation duration of each word was randomised, ranging between 600 and 700 ms in increments of 20 ms. The interstimulus interval ranged from 100 to 200 ms, also varying in increments of 20 ms. Such variability was introduced to prevent participants from predicting the onset of the next word, thereby maintaining attention and engagement throughout the experiment.

3.4. Data recording

SurveyMonkey (SurveyMonkey Inc., San Mateo, California, USA) was used to collect self-report data (i.e., the background questionnaires). E-Prime 3.0 (Psychology Software Tools, Pittsburgh, USA) was used to present stimuli and collect the PANAS ratings. The EEG signal was acquired at a sampling rate of 1024 Hz from 64 Ag/AgCl electrodes placed according to the International 10–20 positions with a BioSemi ActiveTwo amplifier, using the ActiView software (BioSemi B.V., Amsterdam, the Netherlands). Electrode impedance was kept below 5 kΩ.

3.5. Data analysis

EEG data analyses were performed using EEGLAB (Delorme & Makeig, 2004, version 2025) in MATLAB R2024b (The MathWorks, Inc.). Offline continuous EEG data were down-sampled to 512 Hz, high-pass filtered at .5 Hz and low-pass filtered at 20 Hz using the Hamming-windowed sinc finite impulse response filter (pop_eegfiltnew in EEGLAB, Delorme, 2023). Unsystematic artefacts in continuous EEG data were manually detected and removed. Bad channels were identified using three complementary criteria applied in EEGLAB, closely following recommendations in the HAPPE preprocessing pipeline (Gabard-Durnam et al., 2018). First, channels were evaluated based on spectral properties using *pop_rejchan.m*, with normalised spectra computed over 1–100 Hz and channels exceeding a threshold of [−5, 2.5] standard deviations (SDs) flagged for rejection. Second, channels were evaluated based on probability of the signal distribution, with normalised scores and the same threshold of [−5, 2.5] SDs. Third, channels were evaluated using the *clean_rawdata* plugin (Mullen et al., 2015; channel correlation criterion = .485). A channel was rejected if it was flagged by any of these three methods (M = 1.78, SD = 2.03). Next, data were re-referenced to the activity of all channels (global average reference). Continuous data were subjected to Adaptive Mixture Independent Component Analysis (AMICA; Palmer et al., 2008) implemented in EEGLAB. The resulting AMICA decomposition was inspected using IClabel (Pion-Tonachini et al., 2019). Independent components containing ocular artefacts were removed from the data (M = 2.08, SD = .36). Then, data were epoched from −200 to 650 ms surrounding each trial (time-locked to word onset). Epochs were further pruned for non-stereotypical artefacts using the EEGLAB function *pop_jointprob.m*. Epochs with absolute values exceeding 6 SDs at a single electrode and 3 SDs at all electrodes were rejected (M = 15.89; SD = 7.64).

Epochs were then imported into the STUDY structure in EEGLAB. ERPs were computed with a 200 ms baseline over a time window of −200 to 650 ms. ERSPs were computed using a bigger epoch (−1000 ms to 1200 ms) in the 3–25 Hz frequency range and baselined between −400 and −100 ms relative to stimulus onset. Subsequent ERP and ERSP analyses were performed in the LIMO EEG toolbox (Pernet et al., 2011).

A hierarchical general LIMO approach was used in LIMO EEG to account for both within-subject variance (single-trial level) and between-subject variance (group level). At first-level analysis, a generalised linear model (GLM) was specified for each participant with factors Language (Polish, English), Valence (negative, neutral) and their interaction. Single-trial data were analysed automatically across the −50–650 ms time window (Bellec et al., 2012). Parameter estimates were obtained using trial-wise weighted least squares (Pernet et al., 2022), providing robust estimates of condition effects at each electrode and time point. At the second level, effects of Language, Valence and their interaction were assessed across participants using a robust 2 × 2 repeated-measures ANOVA applied channel by channel and frame by frame. For ERPs and ERSPs, significance was determined via cluster-based permutation testing (Maris & Oostenveld, 2007). When significant main effects or interactions were detected, post-hoc pairwise contrasts were performed with multiple-comparison correction (cluster-based permutation at α = .05). Note that Hotelling t-tests are used in these models to account for the covariance between measures; thus, there is no need to adjust for sphericity in the ERP data (Pernet et al., 2011). Effect sizes were calculated using the *limo_get_effect_size.m* function, which outputs an effect size tailored for the analysis type – in this case the multivariate and boundless Mahalanobis Distance D, computed as $D = T^2$_Hotelling/N (Pernet et al., 2011). D is the multivariate analogue of Cohen's D^2 and can be interpreted across topographical space. Following Cohen (1988) conventions for D, effects were classified as small (D = .25), medium (D = .50) or large (D = 1.00).

To ensure the comparability of the negative and neutral conditions, we included in the analyses only the neutral words that

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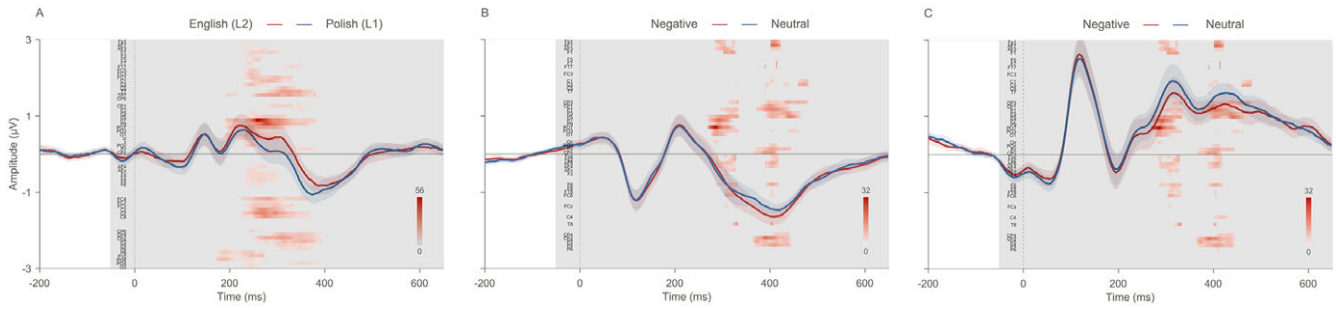


Figure 1. ERPs plotted as linear derivations of a priori selected electrodes for P300 (A), N400 (B) and EPN (C), with point-by-point mass-univariate GLM results displayed as *F*-value heat maps in the background. Shaded grey areas indicate the time window submitted to LIMO analysis (−50 to 650 ms); shaded bands around ERP waveforms represent 95% confidence intervals. The colour bar represents *F*-values. (A) P300, derived from six centroparietal electrodes (CP1, CPz, CP2, P1, Pz, P2), for the main effect of Language. The effect was significant over one cluster spanning 172–395 ms, with a broadly distributed topography (Fp1, AF7, AF3, F5, F7, FT7, C1, C3, C5, T7, CP3, CP1, P1, P3, P5, PO3, POz, Pz, CPz, Fpz, Fp2, AF8, AF4, F6, FT8, FC6, C4, T8, CP4, CP2, P2, P4, P6). (B) N400, derived from nine frontocentral-parietal electrodes (FC1, FCz, FC2, C1, Cz, C2, CP1, CPz, CP2), for the main effect of Valence. (C) EPN, derived from 10 parieto-occipital electrodes (O1, PO3, P3, P5, P7, O2, PO4, P4, P6, P8), for the main effect of Valence. The main effect of Valence (B–C) was significant over two clusters: (1) 270–334 ms, broadly distributed (Fp1, AF7, AF3, F5, F7, FT7, C1, C3, C5, T7, CP3, CP1, P1, P3, P5, PO3, POz, Pz, CPz, Fpz, Fp2, AF8, AF4, F6, FT8, FC6, C4, T8, CP4, CP2, P2, P4, P6) and (2) 365–480 ms, also broadly distributed (Fp1, AF7, AF3, F1, FC3, C3, CP3, P1, P3, P5, P7, P9, PO7, PO3, O1, Oz, Fpz, Fp2, AF8, AF4, AFz, Fz, F6, F8, FT8, FC6, FCz, T8).

preceded negative words (i.e., super standards), resulting in comparable numbers of items across conditions.

4. Results

4.1. Event-related potentials

Mean amplitude analysis revealed a main effect of Language ($F_{(1,36)}$ = 25.51, $p < .001$; $\eta_p^2 = .42$) and a main effect of Valence ($F_{(1,36)} = 6.72$, $p = .014$, $\eta_p^2 = .16$) in the EPN range with more negative amplitudes for English (L2) than Polish (L1) and for negative than neutral words. We found a main effect of Language ($F_{(1,36)} = 10.73$, $p = .002$, $\eta_p^2 = .23$) and Valence ($F_{(1,36)} = 4.77$, $p = .036$, $\eta_p^2 = .12$) in the P300 range, with more positive amplitudes for English (L2) than Polish (L1) and neutral than negative words. There was no main effect of Language ($p = .243$) or Valence ($p = .061$) or their interaction ($p = .740$) on the N400 mean amplitude.

Mass-univariate GLM analysis[1] revealed a significant main effect of Language over one cluster between 172–395 ms across most of the scalp including frontal, central and parietal regions ($F_{mean} = 10.65$, $F_{min} = 4.11$, $F_{max} = 55.98$; effect sizes $D_{mean} = .64$; $D_{min} = .25$, $D_{max} = 3.4$), coinciding with the P300 effect, showing greater amplitudes to L2 than L1 words (see Figure 1A). A main effect of Valence was also significant over two clusters. The first cluster was significant between 270–334 ms and widely distributed with a focus over the parietal region ($F_{mean} = 8.36$, $F_{min} = 4.12$, $F_{max} = 20.8$; effect sizes $D_{mean} = .51$; $D_{min} = .25$, $D_{max} = 1.26$), coinciding with the EPN, and showed larger amplitudes to negative than neutral words (see Figure 1C). The second cluster showed a broad scalp effect of greater amplitudes to negative than neutral words between 365–480 ms ($F_{mean} = 8.36$, $F_{min} = 4.12$, $F_{max} = 21$; effect sizes $D_{mean} = .51$; $D_{min} = .25$, $D_{max} = 1.92$), coinciding broadly with the N400 time window (see Figure 1B).

[1]Following comments from anonymous reviewers, we also analysed ERPs with a less stringent 0.1 Hz high-pass filter. This analysis showed a main effect of Language, but no main effect of Valence or the interaction between Language and Valence. This is likely due to greater variance in single-trial EEG data that is expected to be reduced by 0.5 Hz high-pass filter. The result of the analysis can be found on the project's OSF website.

4.2. Event-related spectral perturbations

Given the absence of a Language × Valence interaction in any of the windows analysed with traditional or data-driven ERP amplitude approaches, we explored possible interactions by modelling single-trial ERSPs in the 3–25 Hz frequency band and 0–650 ms time window, across all 64 electrodes. Six interaction clusters reached significance. To interpret these, four *post-hoc* contrasts were examined: negative English versus neutral English (1–1 0 0), negative Polish versus neutral Polish (0 0 1–1), negative English versus negative Polish (1 0–1 0) and neutral English versus neutral Polish (0 1 0–1). We discuss only those *post-hoc* contrasts that overlap in latency, frequency and topography with the interaction clusters.[2] The significant interaction clusters and the *post-hoc* contrast clusters are described below, organised around the two contrasts that yielded interpretable effects.

4.2.1. Negative English versus neutral English

Three interaction clusters (clusters 1, 2 and 3) were driven, in whole or in part, by a valence effect specific to English, that is, greater ERS for negative than neutral words in the L2. These are shown together in Figure 2.

[2]One interaction cluster (number 4 in the original LIMO output) spanned 336–504 ms in the lower alpha range (7.5–10.2 Hz) over a centroparietal region (CP1, P1, P3, POz, Pz, CPz, CP2, P2; $F_{mean} = 6.82$, $F_{min} = 4.11$, $F_{max} = 19.70$). Unlike the clusters described above, however, no single *post-hoc* contrast produced a cluster satisfying all three criteria for a driver – channel containment, latency overlap and frequency overlap – simultaneously. The negative English versus neutral English contrast produced a matching channel set and latency, but in the delta/theta range (3.0–5.1 Hz) rather than the alpha range of the interaction. The negative Polish versus neutral Polish contrast produced a matching channel set and frequency range (8.4–16.6 Hz), but its latency window (553–641 ms) did not overlap with the interaction cluster (336–504 ms). This interaction cluster therefore appears to reflect a convergence of valence-related activity across both language conditions – a centroparietal alpha modulation that reaches significance only under the interaction correction, with neither language contrast alone sufficient to produce a cluster in this precise time–frequency window. This may indicate a genuine Language × Valence interaction in the alpha band over parietal regions.

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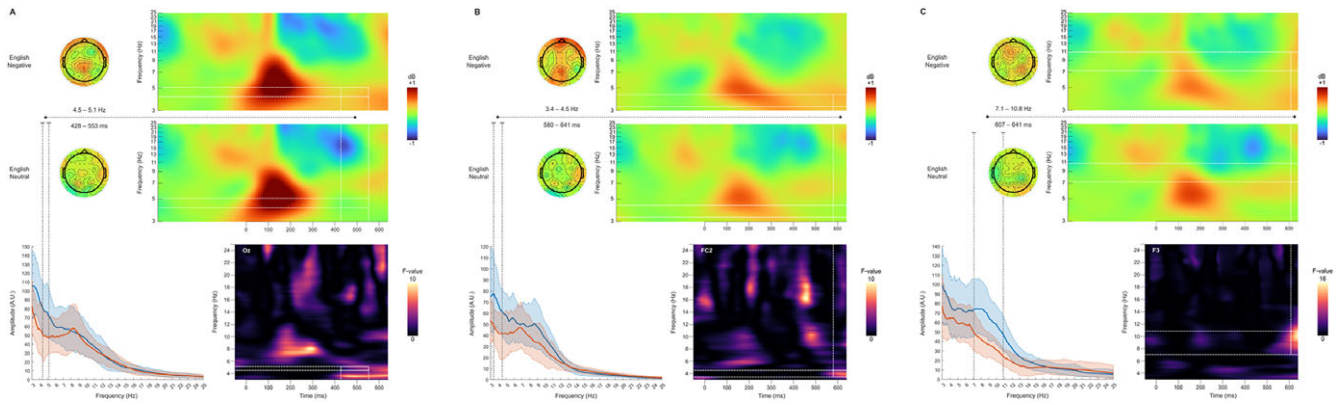


Figure 2. ERSP results showing critical clusters for the difference between negative and neutral words in English. (A) Post-hoc cluster driving the interaction cluster 2. Top left panel: scalp topographies in the 4.5–5.1 Hz and 428–553 ms time window for English negative and English neutral words; top right panel: ERSPs showing a linear derivation of channels where the interaction cluster was significant (O1, Oz, POz, O2); bottom left panel: beta values at the time of maximal difference at electrode Oz plotted across frequencies (blue = English negative; red = English neutral); bottom right panel: *F*-values shown as heat maps for electrode Oz where the effect was maximal. (B) Post-hoc cluster driving the interaction cluster 5. Top left panel: scalp topographies in the 3.4–4.5 Hz and 580–641 ms time window for English negative and English neutral words; top right panel: ERSPs showing a linear derivation of channels where the interaction cluster was significant (C1, CPz, FC4, FC2, FCz, Cz, C2); bottom left panel: beta values at the time of maximal difference at electrode FC2 plotted across frequencies (blue = English negative; red = English neutral); bottom right panel: *F*-values shown as heat maps for electrode FC2 where the effect was maximal. (C) Post-hoc cluster driving the interaction cluster 6. Top left panel: scalp topographies in the 7.1–10.8 Hz and 607–641 ms time window for English negative and English neutral words; top right panel: ERSPs showing a linear derivation of channels where the interaction cluster was significant (AF3, F1, F3, FC1, C1, AFz, Fz, Cz); bottom left panel: beta values at the time of maximal difference at electrode F3 plotted across frequencies (blue = English negative; red = English neutral); bottom right panel: *F*-values shown as heat maps for electrode F3 where the effect was maximal. Shaded areas denote the 95% Bayesian Highest Density Interval. A.U. = arbitrary units.

Interaction cluster 1 spanned 428–553 ms in the theta range (4.5–5.1 Hz) over an occipital region (O1, Oz, POz, O2; $F_{mean} = 6.53$, $F_{min} = 4.12$, $F_{max} = 11.28$). The post-hoc contrast between negative and neutral English yielded a large, sustained cluster between 352–641 ms in the 3.0–5.1 Hz range over a broad centroparieto-occipital region ($F_{mean} = 7.02$, $F_{min} = 4.11$, $F_{max} = 20.37$), characterised by small–to–large effect sizes ($D_{mean} = .43$; $D_{min} = .25$; $D_{max} = 1.24$). This cluster reflects greater delta/theta ERS for negative than neutral words in English in the late theta range over occipital regions. Interaction cluster 2 was observed late in the epoch, from 580 to 641 ms, in the delta range (3.4–4.5 Hz) over a frontocentral region (C1, CPz, FC4, FC2, FCz, Cz, C2; $F_{mean} = 7.08$, $F_{min} = 4.12$, $F_{max} = 13.43$). The same post-hoc cluster also drove this interaction, reflecting a late, valence-modulated delta ERS that is specific to English. Finally, Interaction cluster 3 was confined to the final 130 ms of the epoch (510–641 ms) in the lower alpha range (6.5–10.6 Hz) over a frontal region (AF3, F1, F3, FC1, Fpz, AF4, AFz, Fz, F2, FC2, FCz, Cz; $F_{mean} = 6.69$, $F_{min} = 4.11$, $F_{max} = 16.01$). It was driven by a *post-hoc* cluster spanning 553–641 ms in the lower alpha range (7.1–11.3 Hz) over a frontocentral region ($F_{mean} = 6.19$, $F_{min} = 4.11$, $F_{max} = 16.11$) and characterised by small–to–large effect sizes ($D_{mean} = .38$; $D_{min} = .25$; $D_{max} = .98$). This *post-hoc* cluster reflects a late, valence-driven alpha ERS over frontal regions, indicating greater alpha synchronisation for negative than neutral English words.

4.2.2. Negative English versus negative Polish

Three interaction clusters (4, 5 and 3) were driven by differences in the processing of negative words across the two languages. These are shown together in Figure 3.

Interaction cluster 4 was observed early in the epoch, from 59 to 184 ms, in the theta range (5.5–7.7 Hz), over an occipital region (PO3, O1, Iz, Oz, POz, O2; $F_{mean} = 5.97$, $F_{min} = 4.12$, $F_{max} = 9.22$). This cluster was driven by the post-hoc contrast between negative English and negative Polish, which revealed greater theta ERS (3.88–7.53 Hz) for negative English than negative Polish words between 31–510 ms, encompassing a widespread bilateral occipito-temporal and parietal region ($F_{mean} = 6.13$, $F_{min} = 4.11$, $F_{max} = 13.57$) and showing small–to–large effect sizes ($D_{mean} = .37$; $D_{min} = .25$; $D_{max} = .82$). This early effect therefore reflects a language-direction difference in the initial cortical response to negative stimuli, already apparent in the first 200 ms of processing.

Interaction cluster 5 spanned 336–455 ms in the theta range (4.1–6.2 Hz) over a right temporal–parietal region (FT8, FC6, C6, T8, TP8, CP6, CP4, P6, P10; $F_{mean} = 6.22$, $F_{min} = 4.12$, $F_{max} = 15.72$). The post-hoc contrast between negative English and negative Polish revealed greater theta ERS for negative English than negative Polish words (post-hoc cluster 1, described above). This result indicates an increase in right temporal–parietal theta ERS for negative English relative to negative Polish words in the 336–455 ms window, consistent with a language-specific modulation of emotional word processing coinciding with the N400 time range.

Finally, interaction cluster 3 presented previously was also driven by the negative English versus negative Polish *post-hoc* contrast. Significance in this *post-hoc* cluster spanned 510–641 ms in the lower alpha range (6.5–10.6 Hz) over a frontal region (AF3, F1, F3, FC1, Fpz, AF4, AFz, Fz, F2, FC2, FCz, Cz; $F_{mean} = 6.69$, $F_{min} = 4.11$, $F_{max} = 16.02$), and was characterised by small–to–large effect sizes ($D_{mean} = .41$; $D_{min} = .25$; $D_{max} = .97$). This late frontal alpha modulation thus reflects not only a valence effect specific to English (greater alpha ERS for negative than neutral English words) but also a language difference for the processing of negative stimuli (greater alpha ERS for negative English than negative Polish words). The convergence of *post-hoc* contrasts for this cluster suggests that the 510–641 ms alpha synchronisation over frontal regions indexes an effect that is simultaneously valence-sensitive and language-dependent.

5. Discussion

Here, we leveraged insights from LIMO of single-trial ERPs and ERSPs to explore the neural dynamics of attention allocation to

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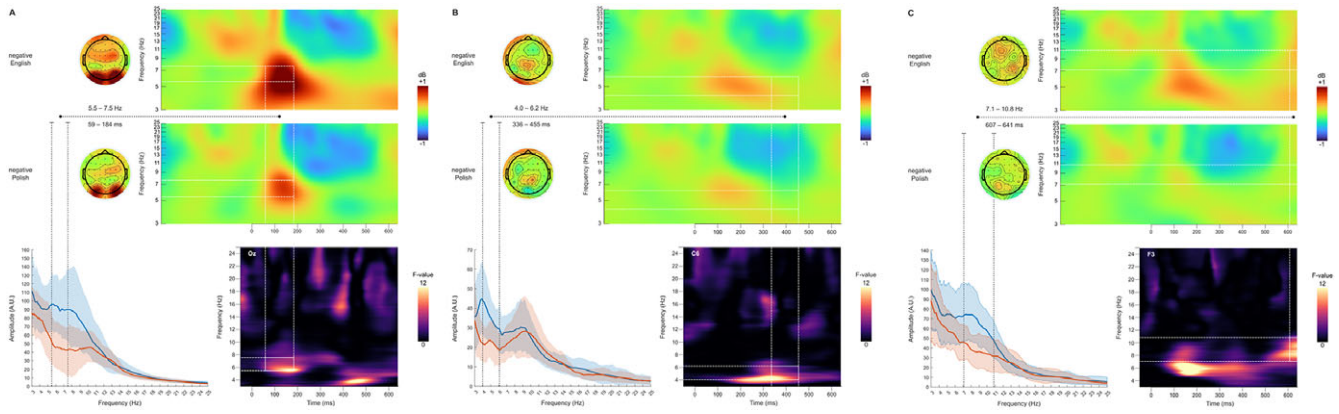


Figure 3. ERSP results showing critical clusters for the difference between negative English and negative Polish words. (A) Post-hoc cluster driving the interaction cluster 3. Top left panel: scalp topographies in the 5.5–7.5 Hz and 59–184 ms time window for negative English and negative Polish words; top right panel: ERSPs showing a linear derivation of channels where the interaction cluster was significant (PO3, O1, Iz, Oz, POz, O2); bottom left panel: beta values at the time of maximal difference at electrode Oz plotted across frequencies (blue = English negative; red = Polish negative); bottom right panel: *F*-values shown as heat maps for electrode Oz where the effect was maximal. (B) Post-hoc cluster driving the interaction cluster 1. Top left panel: scalp topographies in the 4–6.2 Hz and 336–455 ms time window for negative English and negative Polish words; top right panel: ERSPs showing a linear derivation of channels where the interaction cluster was significant (FT8, FC6, C6, T8, TP8, CP6, CP4, P6, P10); bottom left panel: beta values at the time of maximal difference at electrode C6 plotted across frequencies (blue = English negative; red = Polish negative); bottom right panel: *F*-values shown as heat maps for electrode C6 where the effect was maximal. (C) Post-hoc cluster driving the interaction cluster 6. Top left panel: scalp topographies in the 7.1–10.8 Hz and 607–641 ms time window for English negative and English neutral words; top right panel: ERSPs showing a linear derivation of channels where the interaction cluster was significant (AF3, F1, F3, FC1, C1, AFz, Fz, Cz); bottom left panel: beta values at the time of maximal difference at electrode F3 plotted across frequencies (blue = English negative; red = Polish negative); bottom right panel: *F*-values shown as heat maps for electrode F3 where the effect was maximal. A.U. = arbitrary units.

negative versus neutral words in highly proficient Polish–English bilinguals. Our design combined a modified oddball paradigm with a semantic categorisation task, in which a baseline of neutral words (standards) was interrupted by emotionally negative words (deviants). Mainstream ERP analyses revealed more negative EPN amplitude for negative than neutral words and for L2 English than L1 Polish words in the absence of an interaction. In the P300 window, more positive amplitudes were registered for neutral than negative words, and for L2 than L1 words. Again, no interaction was found. Analysis of N400 mean amplitude yielded no significant effects of either valence or language of operation. While main effects can provide meaningful insights in within-subject designs such as those employed here, they do not allow drawing inferences to compare emotion processing across languages.

Mass-univariate GLM analysis of single-trial data broadly converged with more traditional ERP amplitude analyses, revealing Language effects between 172–395 ms (encompassing both EPN and P300 effects), Valence effects between 270–334 ms (coinciding with the EPN window) but also between 365–480 ms (coinciding with the N400 window), which had failed to significantly modulate ERP mean amplitudes based on a priori electrode selections.

In the absence of critical Language × Valence interactions in the amplitude domain, we turned to exploratory time–frequency analyses of single-trial EEG data in order to detect subtle interactions that may exist within specific frequency bands and that may have been missed by amplitude-based approaches. The time–frequency analysis revealed five main clusters where a Language × Valence interaction reached significance. Differences between negative and neutral words in English drove interactions in the (1) theta range (428–553 ms, posterior), (2) delta range (580–641 ms, central) and (3) lower alpha range (510–641 ms, frontal). Differences between negative words in English and Polish drove Language × Valence interactions in the (4 and 5) theta range (59–184 ms, posterior and 336–455 ms, centroparietal) and (3 again) lower alpha range (510–641 ms, frontal).

Enhanced EPN amplitudes for negative compared to neutral words between 200–300 ms are consistent with modulation of early attention by emotional content (e.g., Citron et al., 2013; Kissler & Bromberek-Dyzman, 2021; Kissler et al., 2009; Opitz & Degner, 2012; Palazova et al., 2011; Rohr & Abdel Rahman, 2018). The main effect of language of operation on EPN amplitude, however, is not readily consistent with previous studies (Kissler & Bromberek-Dyzman, 2021; Opitz & Degner, 2012), and some studies reported a main effect in the opposite direction (Vélez-Uribe & Rosselli, 2021). Any interpretation of EPN modulation by language of operation is difficult in the absence of an interaction with valence and could be driven by differences in perceptual processing and categorisation or word familiarity idiosyncratic to the experimental design used. It is noteworthy, however, that the EPN time window overlaps with early stages of visual word form processing, and thus, greater EPN negativity for L2 than L1 may reflect differences in the automaticity of orthographic and lexical access between languages.

The P300 component, indexing explicit attentional control and cognitive resource allocation (Polich, 2007), showed main effects of both language of operation and valence. The language effect, with larger amplitudes for L2 than L1 words, is consistent with increased demands on context updating and stimulus evaluation associated with processing words in the non-dominant language (Moreno & Kutas, 2005), reflecting non-specific amplification of evaluative processing driven by reduced lexical automaticity rather than differential emotional engagement. Note that this interpretation converges with the explanation offered above for the L2 > L1 EPN effect (Hahne, 2001; Silverberg & Samuel, 2004). The valence effect corresponding to larger amplitudes for neutral than negative words, is counterintuitive only if the design is considered as a standard oddball. In the present paradigm, valence and stimulus probability pulled in opposite directions: negative words should elicit larger P300s by virtue of their emotional salience, yet progressively smaller ones as participants learn that negative words constitute the deviant category and the novelty signal associated with them

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diminishes across the experiment. Neutral words, as the dominant category actively monitored for meaning in the semantic categorisation task, may paradoxically come to drive larger P300 amplitudes as the task-relevant categorisation target (cf. Duncan-Johnson & Donchin, 1977; Mars et al., 2008). This interpretation is further complicated by the variable-standard design we implemented, in which neutral words differed on every trial, potentially elevating P300 to neutral standards by increasing the working memory demands of tracking the standard category boundary. Finally, the neutral > negative contrast in the P300 window may partly reflect the leading edge of an N400-like negativity for negative words encroaching on and suppressing apparent P300 amplitude for negative stimuli – which is not implausible given that mass-univariate analysis revealed valence effects as early as 270 ms, which points to a limitation of the mean amplitude approach.

The mean amplitude analysis of the N400 window yielded no significant effects of Language or Valence, standing in contrast to the previous findings of studies using tasks that required semantic engagement with word meaning (Jończyk et al., 2016, 2024; Wu & Thierry, 2012; Zhang et al., 2023). We contend that this relates to the nature of the semantic categorisation task employed here, which required participants to detect target category members (emotional valence was task-irrelevant) and this may have attenuated the extended valence-related semantic processing typically associated with robust N400 modulation. Critically, however, the apparent null result conceals effects obscured by conventional amplitude averaging. Mass-univariate GLM analysis of the same data revealed valence effects in two distinct time windows: one broadly overlapping with the EPN-to-P300 transition and one coinciding with the N400 range, indicating that negative words did elicit differential neural responses during semantic processing. These effects were not captured by mean amplitude analysis, which is likely attributable to their spatial distribution across a broad scalp topography that did not align with the frontocentral electrode selection conventionally used to measure the N400 (Kutas & Federmeier, 2011), again highlighting the sensitivity advantage of data-driven spatiotemporal approaches over *a priori* component windows.

The direction of the valence effect in the N400 window – greater amplitudes for negative than neutral words – is consistent with the idea that emotional words have richer and more densely interconnected semantic representations and therefore require greater neural resources during meaning-level integration (Kissler et al., 2009; Kousta et al., 2011; Vigliocco et al., 2014). Notably, the absence of a language modulation in the N400 window stands in contrast to the sustained L2 > L1 differences observed in the earlier EPN and P300 windows. This may suggest that once lexical-semantic access is sufficiently underway, processing becomes more aligned across languages in this highly proficient group, with emotional content modulating meaning-level processing similarly regardless of language of operation, consistent with the view that late semantic integration is less sensitive to language dominance at advanced proficiency levels than earlier stages of orthographic and lexical access.

The time–frequency analysis revealed a consistent pattern of enhanced oscillatory activity for negative relative to neutral words in L2 English with distinct effects emerging across delta, theta and alpha bands at different latencies and topographies – a pattern suggesting a multistage cascade of increased cognitive and regulatory engagement during emotional processing in the L2.

The observation of greater delta/theta synchronisation for negative than neutral words in English (L2) – but not in Polish (L1) – is consistent with the view that processing emotionally negative content in L2 recruits additional cognitive and regulatory resources. Theta oscillations, particularly over frontal regions, have been associated with emotional regulation processes including cognitive reappraisal and the resolution of emotional conflict (Ertl et al., 2013; Zouaoui et al., 2023). The enhanced frontal theta observed here for negative L2 words may therefore reflect the active engagement of regulatory mechanisms as bilinguals deal with the emotional content of L2 words. Crucially, however, this pattern should not be interpreted as straightforward evidence of a stronger emotional reaction to L2 negative words. Rather, it may reflect greater effort required to fully extract the affective meaning of L2 words, involving more sustained and resource-demanding processing. This interpretation is consistent with a body of literature demonstrating that L2 emotional processing is less automatic, less embodied and more cognitively mediated than L1 processing (see Aguilar et al., 2024; Caldwell-Harris, 2014; Jończyk, 2016; Pavlenko, 2006 for reviews).

Building on this mid-epoch theta modulation, a late (510–641 ms) alpha power modulation emerged with a dominant frontal topography, characterised by increased alpha synchronisation for English (L2) negative words relative to both English (L2) neutral and Polish (L1) negative words. This temporal succession – from mid-latency theta to late alpha – is consistent with a processing cascade in which initial effort-related engagement is followed by regulatory control mechanisms operating on the products of that earlier processing. This pattern indicates that the effect is jointly driven by emotional valence and language of operation. Increased frontal alpha synchronisation has been commonly linked to top-down inhibitory control mechanisms that gate or suppress task-irrelevant or potentially disruptive information (e.g., Foxe & Snyder, 2011; Jensen & Mazaheri, 2010; Klimesch et al., 2007). Within this framework, the observed effect may reflect enhanced inhibitory demands when processing emotionally salient content in L2, possibly related to the need to regulate competing linguistic or affective representations. At the same time, within an emotion regulation framework, alpha synchronisation may index the down-regulation of affective responses, including relatively automatic or implicit forms of control (e.g., Knyazev, 2007; Ochsner & Gross, 2005; Uusberg et al., 2013). From this perspective, the enhanced alpha synchronisation for English (L2) negative words observed here may reflect the engagement of regulatory processes that modulate the impact of negative emotional content during L2 processing, with inhibitory control and emotion regulation converging on the same observed effect rather than representing mutually exclusive explanations.

Viewed as a whole, the sequence of interaction clusters identified in the time–frequency analysis traces a coherent spatiotemporal trajectory that maps onto successive stages of emotional word processing in L2. The earliest effect – greater theta synchronisation for negative English than negative Polish words as early as 59–184 ms over posterior occipital regions – suggests that the divergence between L1 and L2 processing of negative stimuli begins at or near the stage of visual word form and orthographic processing, preceding full lexical-semantic access. This is followed by a mid-latency theta effect over right temporal–parietal regions (336–455 ms), coinciding with the N400 window and consistent with greater demands on lexical-semantic integration for negative words in L2. A further valence-specific posterior theta/delta effect (428–553 ms) suggests that emotional differentiation in L2 remains anchored in posterior regions at this stage, possibly reflecting delayed or more effortful perceptual-affective integration compared to L1. Finally, activity migrates anteriorly, culminating in the late frontocentral delta (580–641 ms) and frontal alpha (510–641 ms) modulations discussed above. This posterior-to-frontal progression across time,

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accompanied by a shift from theta to alpha frequency, is consistent with a processing architecture in which early perceptual and orthographic differences between L1 and L2 cascade forward through lexical-semantic integration and ultimately engage frontal regulatory and inhibitory control mechanisms. That this full cascade is observed for negative but not neutral words in L2, and is largely absent for L1, speaks to the particular demands that emotionally valenced content places on the bilingual language system when processed in the non-dominant language – demands that are met not by a failure of emotional processing but by a more effortful, sustained and regulated route to achieving it.

6. Limitations and future directions

Several limitations of the current study warrant consideration when interpreting our findings. First, the modified oddball paradigm employed here deviates substantially from the classical design in ways that complicate component-level interpretation. By using a different neutral word on every trial rather than a repeated identical standard, we established a valence-defined rather than item-specific baseline, which introduces inherent variability into the standard condition and likely contributed to the atypical P300 pattern observed – specifically the neutral > negative amplitude reversal discussed above. While this design choice was motivated by the need to avoid lexical repetition effects and to ensure meaning-level processing of every stimulus, it represents a trade-off that limits the comparability of our P300 findings with the classical oddball literature.

Second, the semantic categorisation task, while effective in ensuring engagement with word meaning, rendered emotional valence task-irrelevant. This may have attenuated valence-related effects – particularly in the N400 window – and likely constrained the conditions under which language differences in emotional processing could emerge. The absence of a Language × Valence interaction in the ERP amplitude domain may partly reflect this task constraint rather than a genuine equivalence of emotional processing across languages.

Third, the time–frequency analysis, while revealing a rich and theoretically interpretable pattern of oscillatory interactions, was exploratory in nature and was conducted in the absence of a priori hypotheses regarding specific frequency bands, latencies or topographies. The six significant interaction clusters were identified through cluster-based permutation testing, which controls family-wise error rate but does not protect against the possibility that some clusters reflect noise, particularly given the large number of comparisons implicit in a whole-scalp, whole-epoch, multi-frequency analysis. The theoretical accounts offered for the delta, theta and alpha modulations – while consistent with existing literature – should therefore be treated as hypothesis-generating rather than confirmatory and require replication with designs that include a priori frequency-band and topographic predictions.

Fourth, the sample, while adequate for ERP research and consistent with prior work in this area, comprised a relatively homogeneous group of highly proficient late bilinguals with instructional L2 acquisition and no immersive L2 experience. This limits generalisation to bilinguals with different acquisition histories, proficiency levels or language use patterns. Future work should systematically vary proficiency and immersion experience to examine how these factors modulate the oscillatory cascade identified here, and whether the posterior-to-frontal, theta-to-alpha progression observed for L2 negative words approximates L1 patterns as a function of increasing automaticity. Finally, the use of isolated words limits ecological validity; investigating these effects at the sentence or discourse level would allow examination of whether the delayed and effortful affective integration observed here for L2 negative words accumulates or is resolved in richer linguistic contexts.

7. Conclusion

This study investigated the neural dynamics of emotional word processing in highly proficient Polish–English bilinguals using single-trial ERP and time–frequency analyses within a modified oddball paradigm. Mainstream ERP analyses revealed main effects of language and valence across EPN and P300 windows but no Language × Valence interaction – a pattern that, taken at face value, might suggest emotional processing proceeds similarly across L1 and L2 at high proficiency. Mass-univariate GLM analysis complicated this picture, revealing valence effects in the N400 window invisible to conventional mean amplitude analysis and underscoring the sensitivity advantage of data-driven approaches.

Most critically, time–frequency analysis revealed a Language × Valence interaction entirely absent from the amplitude domain: negative words in L2 but not L1 elicited a systematic cascade of enhanced delta, theta and alpha oscillatory activity tracing a coherent posterior-to-frontal trajectory across 59–641 ms, reflecting successive stages of perceptual, lexical-semantic and regulatory processing. That this cascade was valence-specific and language-dependent demonstrates that the bilingual emotional processing disadvantage is not a general cost of L2 processing but reflects a qualitatively different route to achieving comparable emotional categorisation. Future confirmatory work varying proficiency levels and linguistic context will be needed to establish the generality and boundary conditions of this oscillatory cascade. These findings may potentially carry broader implications for real-world L2 communication, as the oscillatory activity elicited by negative words in L2 suggests that emotionally charged language places greater demands on L2 users than behavioural performance alone would indicate. This could be particularly relevant in contexts where accurate processing of emotional content is consequential (such as clinical interviews or counselling conducted in an L2).

Supplementary material. The supplementary material for this article can be found at http://doi.org/10.1017/S1366728926101709.

Data availability statement. The data that support the findings of this study are openly available in OSF (https://tinyurl.com/LateBilingN4).

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Author contribution. Conceptualisation: I.K., M.N., O.M.-N., G.T., R.J.; Data curation: M.N.; Formal analysis: I.K., M.N., R.J.; Funding acquisition: G.T., R.J.; Investigation: I.K., M.N.; Methodology: I.K., M.N., O.M.-N., G.T., R.J.; Project administration: G.T.; Visualisation: G.T., R.J.; Writing – original draft: I.K., M.N., O.M.-N., G.T., R.J.

Competing interests. None.

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