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REGULAR ARTICLE

Neural signatures of perceptual closure and top-down feedback in lexical access: an ERP study

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ABSTRACT
Perceptual Closure, the ability to recognise incomplete stimuli by integrating prior knowledge, has been well-studied in object perception but remains largely unexplored in language research. We examined how lexical feedback (word frequency) interacts with bottom-up visual processing when word stimuli are incomplete. Using event-related potentials (ERPs), participants performed a lexical decision task with high – and low-frequency words in complete or incomplete (top-only) formats. Behavioural results showed additive effects of word frequency and completeness. ERP analyses revealed that completeness affected early perceptual components (P100, N170) and closure-related responses (VAN, P300), while word frequency modulated later lexical-semantic processing (N400). Crucially, word frequency effects emerged earlier for incomplete (350–450 ms) than complete words (450–600 ms), suggesting lexical feedback helps disambiguate perceptually difficult stimuli. Overall, these findings provide insights into the interplay between visual and linguistic information, linking models of word recognition and reading with broader cognitive and neural mechanisms of perception.

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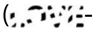
1. Introduction

Often, when we walk down the streets and see a weathered poster with some features of the letters faded, we can still readily recognise the words. Similarly, we can identify the brand name SAMSUNG even though the letter **A** is not fully represented in its logotype, again suggesting that the absence of some letter features does not prevent the recognition of the words. These are demonstrations of the principle of Perceptual Closure, first studied by Gestalt psychologists in the early decades of the twentieth century, which proposes that individuals can identify familiar patterns even when they are fragmented due to their perceptual learning experience (see Snodgrass & Kinjo, 1998, for review). This Gestalt principle suggests that our cognitive system fills in the missing information not only for words but for general incomplete stimuli, explaining why fragmented images are later remembered as complete (Foley et al., 1997).

A number of behavioural studies have examined the Perceptual Closure effect of incomplete words by removing the lower or upper half of words (e.g. ; ). In masked priming experiments in the Roman alphabet, a prime that only keeps its upper part is quite effective at producing repetition priming effects (-METRO faster than -METRO), to a greater degree than a prime that only keeps its lower part (-METRO vs. -METRO; Perea et al., 2012a; see also Perea et al., 2012b, for evidence with a delayed-letter technique). This advantage for the upper part of words, which has also been found in other writing systems (e.g. Chinese: Tsao & Wang, 1983; Korean Hangul: Pae et al., 2021), is explained by the fact that the upper part of letters contains less ambiguity than the lower part. For instance, the upper part of the letter “r” is unique to that letter, whereas its lower part is visually confusable with “f”, “i”, “l” (see Tejero et al., 2014, for discussion). Indeed, Hebrew words show the opposite pattern because the lower part of Hebrew letters tends to be more disambiguating than their upper part (see Shimron & Navon, 1981).

In the present experiment, we directly tested the electrophysiological signature of the Perceptual Closure effect during visual word recognition by comparing words that were displayed either in their complete form or in their top-part-only form while ensuring the letters composing the stimuli remained unambiguous. Specifically, all letters in the stimuli were unambiguous in their upper parts, as any letters that could be visually

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confusable from the top (e.g. i and j) were discarded. This manipulation differs from the above-cited behavioural studies in three main aspects. First, the main aim of previous behavioural studies was to determine whether the top-only part enabled lexical access faster than the bottom-only part of words. Here, we focus on the Perceptual Closure phenomenon elicited by comparing the top-only part of linguistic stimuli to the complete stimuli. Second, in the behavioural studies, there was no perfect control over the degree of potential ambiguity in the upper versus lower half of the letters in the words due to restrictions in word selection (but see Tejero et al., 2014, for an exception, via newly created words). In the present experiment, we achieved this control by discarding words that contained ambiguous letters in the upper part (e.g. i and j), ensuring that the upper portion uniquely identified each letter (e.g.  for the Spanish word *masa* [dough]). Lastly, to obtain a continuous measure of the underlying processes during partial and complete stimuli recognition, we registered the participants' electrophysiological signature and obtained the Event-Related Potentials (ERPs). This technique provides an average of electrical activity that is both time – and phase-locked to specific events (Maurer & McCandliss, 2008), thus offering continuous information rather than a response at the end of lexical access – as occurs with behavioural experiments.

Importantly, previous studies on object recognition have tracked the electrophysiological signature of the Perceptual Closure effect. The most common manipulations compare EEG responses to scrambled or incomplete object images () vs. complete stimuli (). The Visual Awareness Negativity component (VAN), the Negativity Closure (NcL), and the N350 components have been proposed to reflect the phenomena of Perceptual Closure (Förster et al., 2020; Schendan & Kutas, 2002). The VAN, a negative potential peaking around 200–300 ms post-stimulus, is elicited only by stimuli that reach conscious perception in visual awareness studies, regardless of their relevance for the task (Förster et al., 2020; Pitts et al., 2014). The topographic distribution of this component is not well established due to high variability in the EEG reference used across studies (for a review, see Koivisto & Revonsuo, 2010). For example, Wilenius-Emet et al. (2004) reported larger negative amplitudes for scrambled line-drawing objects than for complete ones in frontal and central scalp electrodes, using a mastoid average offline reference.

The VAN has been strongly associated with another component known as NcL (Negativity Closure) in studies on the Perceptual Closure phenomenon (Förster et al., 2020). In fact, some studies suggest that the VAN and NcL components may overlap or even represent the same process (Förster et al., 2020). Like the VAN, the NcL peaks around 250–300 ms after stimulus onset. This potential is typically distributed over occipital-temporal scalp areas when the nose is used as the reference electrode. The NcL amplitude increases as a function of perceptual completeness, as shown in a study on different degrees of fragmented object pictures (Doniger et al., 2000). Hence, the NcL is associated with pre-recognition processes of incomplete information and is thought to reflect a series of computations until a threshold is reached, and the stimulus is recognised. Notably, its relation to the Closure phenomenon is well-established because: (1) it has been observed regardless of object categories, including pictures of faces, buildings, or line drawings (Azadmehr et al., 2013; Doniger et al., 2000, 2001; Liu et al., 2020), and (2) it is dissociated from the amount of sensory information, as its modulation by progressively less fragmented pictures (which contain less sensory information than complete stimuli) does not correlate with preceding effects in the P100 or N1 components.

The VAN and NcL components may be followed by a widespread frontal-parietal positivity: the P300. However, while these earlier negativities have been strongly associated with perceptual awareness (and are task-independent), the P300 occurs only for task-relevant stimuli. Consequently, it is thought to reflect post-perceptual processes related to comparing the current percept with the target held in working memory for decision-making (Förster et al., 2020; Koivisto & Grassini, 2016; Schröder et al., 2021). For instance, it is elicited by unaware task-relevant conditions but not by aware task-irrelevant conditions (Pitts et al., 2014). Therefore, the P300 may not reflect Perceptual Closure per se but rather be a consequence of conscious perception. Finally, other studies on scrambled stimuli have also reported an effect in the frontal N350 ERP, where unidentified stimuli elicit larger voltage negativities than identified stimuli (Pietrowsky et al., 1996; Schendan & Kutas, 2002). Thus, the N350 amplitude may reflect the process of searching for a stored image that matches the perceived one.

In sum, an extensive body of literature has shown that visual awareness effects – associated with the Perceptual Closure phenomenon of incomplete stimuli – occur between 200 and 350 ms post-stimulus onset. Different nomenclatures have been proposed for these components, depending on their exact time window, topographic source, and polarity deflection. We propose that all these components may reflect common underlying processes and that their apparent differences are likely due to variations in experimental paradigms and EEG analysis methods across studies.

Notably, while all these studies used line drawings, objects, or faces as stimuli, none have explored the electrophysiological signature of Perceptual Closure effect for incomplete visual word-forms – a gap our study seeks to address. Like objects, visual words are composed of specific visual features (i.e. letters) which combine to form their identity. These letters, in turn, are built from specific fragments defined by contrast and orientation (Dehaene et al., 2005). Therefore, as in object recognition, the visual system must extract the relevant information to recognise orthographic stimuli (McCandliss et al., 2003). Given that visual word recognition also relies on the extraction and integration of letter-level features, it is reasonable to expect that Closure mechanisms similar to those involved in object processing () may also be engaged when orthographic stimuli are degraded (metro).

Notably, in the object recognition literature, Perceptual Closure has been associated with top-down mechanisms that facilitate the reconstruction of fragmented stimuli, particularly when bottom-up input alone is insufficient for recognition (Doniger et al., 2000; Schendan & Kutas, 2002). A similar interpretation may extend to the domain of word recognition, especially when only partial visual information is available. Consistent with this, previous behavioural research using partial primes in a lexical decision task showed that the advantage for the upper half of letters over the lower half was specific to word stimuli, but not to pseudowords (Perea et al., 2012b). This dissociation suggests the involvement of lexical-level top-down feedback that supports the identification of real words from partial input. In contrast, such top-down would be absent for pseudowords, as they do not activate stored lexical representations. This pattern is consistent with interactive proposals of visual word recognition (McClelland & Rumelhart, 1981; see Carreiras et al., 2014, for review) and fits well with previous electroencephalography (EEG) and neuroimage (fMRI) studies on the top-down influence of higher-level linguistic information on perceptually ambiguous words. For instance, when words are difficult to read (e.g. alliance), high-frequency words show a distinct brain signature compared to low-frequency words early in processing (N170), while easy handwritten and typed words do not show frequency effects until 250 ms post-stimulus (Vergara-Martínez et al., 2021); this pattern has been associated with engaging attentional networks to resolve letter feature ambiguities (see Qiao et al., 2010). In line with this, fMRI research reveals non-standard word formats (e.g. rotated, peripheral, or difficult handwritten words) increase parietal activation during processing (Qiao et al., 2010; Cohen et al., 2008; see Mayall et al., 2001; Pammer et al., 2006). Thus, visual ambiguous stimuli prompt greater reliance on lexical top-down processes, which enhance attentional engagement to resolve letter identification (Barnhart & Goldinger, 2010; Qiao et al., 2010).

Importantly, the extent to which top-down feedback influences orthographic encoding depends on stimulus legibility. For instance, in the EEG study by Vergara-Martínez et al. (2021), an early frequency effect emerged only for difficult handwritten words – not for easy handwritten or typed stimuli. These difficult handwritten words were the least legible, showing poor separation between letters and high variability in letter shape. As such, the early frequency effect was interpreted as an index of increased attentional demands required to resolve the identity of individual letters.

However, as no previous electroencephalography studies have characterised the Perceptual Closure phenomena during the processing of incomplete words, it is still unknown the role that lexical top-down information may exert in their identification.

In the context of the present experiment, the top-only words serve as relevant stimuli for investigating top-down engagement. Notably, although these stimuli display only the upper portion of the original word form, they retain clear and distinctive letter features that support identification – unlike the highly ambiguous handwritten stimuli used by Vergara-Martínez et al. (2021). Therefore, if the letter features preserved in the upper part of words are sufficient to activate their corresponding letter receptors in a purely feedforward manner, early lexical top-down effects (e.g. word frequency), as observed in Vergara-Martínez et al. (2021), would not be expected. Examining the time course of the frequency effect in response to top-only words is thus essential to test this hypothesis.

To sum up, the main goal of the present study was to characterise the Perceptual Closure effect in the context of orthographically unambiguous stimuli. Second, it examines the role of higher-level lexical processing during the Closure phenomenon, specifically focusing on the influence of word frequency. We aimed to analyse whether detectors for letter fragments operate in a purely bottom-up manner or whether lexical feedback also plays a role in this process. To achieve this, we recorded participants' electrophysiological responses alongside their behavioural data (response times and accuracy) during a lexical decision task, a widely employed paradigm in word recognition experiments (see Krakauer et al., 2017, for a discussion on the importance of integrating behavioural and neural measures).

At the behavioural level, a previous masked priming study (Perea et al., 2012b) examined the effects of word frequency and presentation format, using complete words as targets while manipulating the format of the primes (complete words, top-only words, or bottom-only words). Masked repetition priming effects were sizeable and similar in magnitude for complete and top-only primes, regardless of word frequency, whereas they were smaller for bottom-only primes. However, since this was a priming experiment with complete words, it remains unclear how processing unfolds in the absence of priming. More directly relevant to the present study, an eye movement study on silent sentence reading (Perea, 2012) found greater reading costs – indexed by longer.

fixation durations and more progressive fixations – for top-only sentences compared to intact sentences. These reading costs were even more pronounced for bottom-only sentences. At the local level of target words (either high – or low-frequency) embedded in the sentences, the type of text interacted with word frequency in total reading times. This interaction was driven mainly by the very large word-frequency effect for bottom-only words (185 ms), whereas the word-frequency effect was considerably smaller for top-only and complete words (99 and 70 ms, respectively). Based on these findings and given our use of an unprimed lexical decision task, we expect longer response times for top-only words compared to complete words, with the word-frequency effect being similar for intact and top-only words, or slightly larger for top-only words.

At the electrophysiological level, the visual presentation of orthographic stimuli elicits a series of ERPs that provide critical measures of the neural processes underlying recognition (i.e. perceptual, categorisation, and lexical-semantic selection).

First, the P100 and N170 components are associated with overall stimulus visibility and orthographic word processing, respectively (Maurer et al., 2005). Given that perceptual information differs between partial and complete conditions, we expect main effects of stimulus format in these early ERPs, with top-only stimuli eliciting larger amplitudes and longer latencies than complete stimuli, consistent with previous findings (see Goffaux et al., 2003; Maurer et al., 2005; Tanaka, 2020; Winsler et al., 2022). Confirmatory analysis of these components will assess whether such amplitude differences reliably emerge, providing further evidence for early perceptual sensitivity to stimulus format.

Second, we anticipate differences between partial and complete words in ERPs associated with Closure phenomena (VAN, NcL, N350) and post-perceptual processing (P300). To our knowledge, this is the first study to examine Closure effects in the processing of top-only orthographic stimuli. Hence, we adopt an exploratory approach to characterise the electrophysiological signature of Perceptual Closure in visual word recognition.

Third, word frequency influences both the rate at which information accumulates from a word stimulus and the speed with which lexical representations are activated (Ratcliff et al., 2004). Consequently, word-frequency effects are expected to emerge as soon as whole-word representations are accessed (Grainger et al., 2012). It is well established that the strongest word frequency effects, typically manifesting as larger negativities for low frequency compared to high frequency words, occur in the N400 time window (approximately 350–500 ms), an ERP component associated with lexical-semantic retrieval (Dufau et al., 2015; Hauk et al., 2006; Vergara-Martínez et al., 2021; see also reviews in Laszlo & Federmeier, 2014 and Vergara-Martínez et al., 2020a).

However, several studies have also reported word-frequency effects in earlier time windows. For instance, Hauk et al. (2006, 2009) found word-frequency effects in ERP components between 100–200 ms when using standard printed stimuli. Notably, these effects emerged under very rapid stimulus presentation (100 ms), a factor known to influence the dynamics of word processing. Supporting this, Dambacher et al. (2012) observed that the latency of word-frequency effects decreased systematically as the rate of word presentation increased. Taken together, these findings suggest that taxing attentional resources can modulate the temporal dynamics of lexical access (see Vergara-Martínez et al., 2020a, for discussion).

Based on this evidence, we expect sizeable word-frequency effects to appear in the N400 time window, with larger negativities for the low-frequency words compared to high-frequency ones. However, given that word illegibility can shift the timing of word-frequency effects, incomplete words, such as top-only stimuli, may elicit earlier top-down lexical engagement. Still, since the constituent letters in top-only words retain clear and unambiguous features necessary for identification, we do not anticipate word-frequency effects emerging as early as the P100 or N170. Overall, the exploratory analysis of the timing of word-frequency effects on early visual components will provide valuable insight into the interplay between bottom-up perceptual input and top-down lexical processes.

2. Methodology

2.1. Participants

Twenty-nine students at the University of Valencia participated in the experiment in exchange for a small gift or course credit. All of them were native Spanish speakers with no neurological or psychiatric disorder history and normal (or corrected) vision. Data from 5 participants were discarded due to tiredness or excessive artefacts in the EEG recording. The ages of the remaining 24 participants (12 women) ranged from 18 to 40 years old (M = 25.25, SD = 5.97). All participants were right-handed, as assessed with an abridged Spanish version of the Edinburgh Handedness Inventory (Oldfield, 1971). All participants gave informed consent before the experiment. The research was approved by the Research Ethics Committee of the University of Valencia and was in accordance with the Declaration of Helsinki.

Since we have no comparable ERP data to run a power analysis, we used Boudewyn et al. (2017) and Jensen and MacDonald's (2023) guidelines to ensure the number of participants and trials for sufficient statistical power in our experiment. Specifically, Jensen and MacDonald (2023) performed Montecarlo simulations on actual ERP data (ERN, LRP, N170, MMN, P3, N2pc, and N400) to estimate the relationship between experiment design parameters (number of participants, trials and effect magnitude) and statistical power. We looked at their results for the N170 and the N400, as these two ERPs are critical for our predictions and were obtained under relatively similar paradigms to ours. Importantly, to assess the statistical quality of our comparisons, we looked at the effect magnitude of the N170 and the N400 in a previous study of our lab. Vergara-Martínez et al. (2021) obtained an N170 effect magnitude of 2.3 µV approx. (printed vs difficult handwritten script) and an N400 effect magnitude of 2.5 µv approx. (low vs high frequency words). Using the effect magnitudes in Vergara-Martínez et al. (2021) along with the number of participants and stimuli of our present study, Jensen and MacDonald's (2023) results revealed that for the N170, a 2.3 µV effect, 24 participants and 28 trials (note that for the N170 the simulations were obtained with either 28 or 56 trials), the probability of achieving a $p < .05$ (statistical power) reached .95. For the N400, a 2.5 µV effect, 24 participants and 42 trials, the probability of achieving a $p < .05$ reached .9. Hence, the sample size in the present experiment (24 participants with 50 trials per condition) provides a reasonable level of statistical power for detecting effects of similar magnitude.

2.2. Materials

Two-hundred Spanish words of four to eight letters (M = 5.38) were selected from the EsPal database (Duchon et al., 2013). The letters of these words were non-ambiguous in their upper part. Half of those words were of high frequency[1] (Mean Zipf = 4.9, SD = 0.29), and the other half were of low frequency (Mean Zipf = 3.96, SD = 0.2) in the subtitle-based counts of EsPal – the specific details of the stimuli in other psycholinguistic measures are presented in Table 1. Both high and low-frequency words were matched for length (in the number of letters), orthographic neighbourhood, imageability, concreteness, and bigram frequency. In addition, a list of 200 pseudowords was created using Wuggy (Keuleers & Brysbaert, 2010) for the lexical decision task. These pseudowords were proportionally equated in length (M = 5.39, SD = 1.15) and bigram frequency with the word set. Two versions were created for each stimulus: one with the top-only stimulus and the other with its complete form (Figure 1). The top-only manipulation of words was set above the horizontal line of the lowercase letter "e" in Courier New font (based on Perea et al., 2012b). Stimulus-format was counterbalanced across two lists. Therefore, all stimuli were presented across participants in each stimulus-format manipulation. Different participants were randomly assigned to one of the two counterbalanced lists. Each list included 200 words (100 of high frequency [50 complete

Table 1. Mean Values of Psycholinguistic Characteristics of Words Across Conditions (SDs in Parentheses) as Provided in the EsPal Database (Duchon et al., 2013) and B-Pal Spanish Database (Davis & Perea, 2005).

							Mean positional bigram frequency (token)	
	No. of letters	Zipf freq. subtitle	N	Lev-N	Imageability	Concreteness	Words	Pseudowords
Range	4–8	3.42-6.13	0–41	1–2.75	2.01–6.78	2.32–6.72	156.1–5046.4	27.1–2003
HF words	5.36 (1.13)	4.61 (0.55)	12.25 (9.72)	1.32 (0.34)	4.47 (1.26)	4.32 (1.08)	979 (646.2)	615.7 (399.5)
Range	4–8	2–5.02	0–33	1–2.3	1.88-6.6	2.73-6.22	63.1–3429.1	61.5–3453.3
LF words	5.41 (1.12)	3.81 (0.49)	11.6 (9.02)	1.34 (0.32)	4.66 (1.18)	4.6 (0.84)	922.3 (649.1)	755.1 (585.5)
p values (HF vs LF)	0.75	< 0.01	0.62	0.71	0.33	0.07	0.53	.07

HF = high frequency, LF = low frequency, Zipf freq. = subtitle-frequency, log10(frq) + 3, *N* = number of substitution orthographic neighbours, Lev-N = Levenshtein's distance.

Figure 1. Example of the word stimulus-format manipulation in a given experimental stimulus (madre [mother]).

words and 50 top-only words] and 100 of low frequency [50 complete words and 50 top-only words]) and 200 pseudowords (100 complete pseudowords and 100 top-only pseudowords). The order of the stimuli was randomised for each participant.

2.3. Procedure

Participants were seated comfortably in a dimly lit and sound-attenuated chamber. All stimuli were presented on a high-resolution monitor positioned at eye level at 80 cm from the participant. The stimuli were displayed in white (RGB: 220, 220, 220) lowercase Courier New 28-pt font (i.e. a highly common typeface) against a dark-gray background (RGB: 41, 41, 41). Each word subtended about 0.6° of visual angle in height. Visual angle in width varied as a function of word length. For 4-letter words, the visual angle corresponded to 2.3°; for 5-letter words, 2.8°; for 6-letter words, 3.4°; for 7-letter words, 4°; and for 8-letter words, 4.5°. Participants performed a 2-choice forced lexical decision task: they were instructed to decide as accurately and rapidly as possible whether the stimulus was a Spanish word, pressing the button "SÍ" (YES), or not, pressing the button "NO", in a response box. The hand used for each type of response was counterbalanced across subjects. The sequence of events in each trial was as follows: A fixation cross ("+") appeared in the centre of the screen for 1000 ms, followed by a 200 ms blank screen, replaced by a stimulus word that remained on the screen for 500 ms. Participants could respond from the onset of the stimulus up to a maximum deadline of 2000 ms. After the participants' response, a blank screen of random duration (between 500 and 900 ms) was presented. To minimise subject-generated artefacts in the EEG signal during the presentation of the experimental stimuli, participants were asked to refrain from blinking and eye movements from the onset of the fixation cross until the offset of the target stimulus. Sixteen warm-up trials, which were not further analysed, were presented at the beginning of the session. Along with the session, there were four brief 15-second breaks every 65 trials. Each participant saw the stimuli in a different random order. The whole experimental session lasted approximately 20 min, excluding the EEG setup.

2.4. EEG recording and analyses

The EEG was recorded from 32 Ag/AgCl electrodes mounted in an elastic cap (EASYCAP GmbH, Herrsching, Germany) according to the 10/20 system and online referenced to the right mastoid electrode site. The EEG was amplified, and bandpass filtered between 0.01–100 Hz with a sample rate of 250 Hz by a BrainAmp (Brain Products, Gilching, Germany) amplifier. Eye movements and blinks were monitored with electrodes placed on the right lower and upper orbital ridge and the left and right external canthi. Impedances were kept below 5 KΩ during the recording session. The EEG signal was band-pass filtered between 0.1-20 Hz. As we expected early perceptual effects in the occipital-temporal electrode sites, data was re-referenced to the average of all electrodes for the early perceptual ERP analyses (Rossion et al., 2003; Winsler et al., 2022) and to the mastoids average for the following ERP analyses (Luck, 2014). All single-trial waveforms were screened offline for amplifier blocking, drift, muscle artefacts, eye movements, and blinks through a semiautomatic data inspection procedure applied to each participant's complete set of channels. This was done for an 800 ms epoch with a 100 ms pre-stimulus baseline. Baseline correction was performed using the average voltage in the 100 ms preceding the stimuli onset. Trials containing artefacts and/or incorrect responses were not included in the average ERPs or the statistical analyses. Due to artefacts and/or incorrect responses, approximately 12.22% of the trials were excluded: 7.04% due to EEG artefacts and 5.18% due to incorrect responses. There was no statistical difference across conditions in the number of rejections due to artefacts ($p > .1$). Nevertheless, an ANOVA on the number of included trials per condition based on correct responses revealed that there were significant effects of word-frequency ($F(1, 23) = 36.782$; $p < .001$), reflecting that on average, more correct responses were observed for high – than for low-frequency words; and of stimulus-format ($F(1, 23) = 4.781$; $p = .039$), reflecting that more correct responses were observed for complete words compared to incomplete ones. Notably, a minimum of 30 trials were included for each condition in the average ERP data from each participant (mean of the average number of word trials per condition across participants: M = 43.8, SD = 4.81). ERPs were averaged separately for each of the experimental conditions, each of the subjects, and each of the electrode sites.

As we expected early perceptual effects in the occipital-temporal electrode sites, data was re-referenced to the average of all electrodes for the early perceptual ERP analyses (Rossion et al., 2003; Winsler et al., 2022) and to the mastoids average for the following ERP analyses (Luck, 2014).

As described in the hypothesis section, the experiment included both confirmatory and exploratory analyses. Accordingly, two different analyses strategies were employed. Firstly, for the confirmatory analyses, we focused on early components (P100, N170) using single-site measures, as our interest was in peak amplitude and peak latency (i.e. non-linear measures; see Luck, 2014; Zhang & Kappenman, 2024). To this end, we identified the *peak locus* within the standard time epoch of each component (P100: 90–150 ms, N170: 150–200 ms; Bayer et al., 2012; Civera et al., 2024; Winsler et al., 2022). For both components, the largest *peak* amplitudes encompassed occipital-temporal sites (P100: P3/4, P7/8, O1/2; N170: P7/8, O1/2), in line with previous findings regarding their topographic distribution (Luck, 2014; Maurer & McCandliss, 2008).

Secondly, for the exploratory analyses of presentation format and word-frequency effects beyond P100 and N170, we used the Mass Univariate ERP toolbox (Groppe et al., 2011) applying *false discovery rate* (FDR; Benjamini & Hochberg, 1995) correction for multiple comparisons. Specifically, we analysed differences between 90 and 700 ms at each sampling point over 15 individual electrodes (P7/8, O1/2, Fz, Cz, Pz, FC1/2, C3/4, CP1/2, P3/4), using off-line referencing to the linked mastoids. The results of the Mass Univariate analyses guided the selection of the time windows and cluster-based electrode sites for the subsequent repeated-measures ANOVAs on the ERP components subject to exploratory analysis. Figure 3 displays the corresponding *t*-tests: Panel A compares top-only and complete words within each word-frequency condition, while Panel B compares high – and low-frequency words within each presentation format.

3. Results

3.1. Behavioural results

In the latency analyses, we excluded the RTs shorter than 250 ms (0 observations) and the incorrect responses (7.1% of trials for words and 7.2% for nonwords). Table 2 displays the mean RTs and accuracy rates in each condition. For the inferential analyses on the response times and accuracy, we employed generalised linear mixed-effects models in R (R Core Team, 2023) with the *lme4* package (Bates et al., 2015). Simple effects tests, in the case of a significant interaction, were conducted using the *emmeans* package (Lenth, 2021). For the word data, the fixed factors were Stimulus Format (encoded as −.5 [top-only] and .5 [complete]) and Word Frequency (encoded as −.5 [high-frequency] and .5 [low-frequency]). For the modelling of latency data, we employed the Gamma distribution (see Lo & Andrews, 2015, for the advantages of this option for RT data); for the accuracy data, we chose the binomial distribution. We chose the most complex random-effects structure that converged successfully, which included random intercepts and random slopes for Stimulus Format by both subject and by item, along with the correlation between each intercept and its corresponding slope. In R notation, this corresponds to (1 + Format | Subject) + (1 + Format | Item). Note that Item refers to the lexical identity of the word, regardless of visual format (e.g. the word *madre* [mother], whether presented in complete or top-only form, corresponds to the same item).

Table 2. Mean correct response times (RTs, in ms), error rates (in percentages), and standard errors (in parentheses) for word stimuli.

Format	Frequency	Mean RT (ms)	Error Rate (%)
Top-only	High	677 (4.7)	6.5 (0.65)
	Low	711 (4.8)	9.5 (0.96)
Complete	High	640 (5.0)	2.7 (0.78)
	Low	675 (4.3)	9.8 (0.77)

Note: For the nonwords, mean correct response times (RTs) were 815 ms (SE = 5.9) for the top-only format and 753 ms (SE = 5.9) for the intact format. Error rates were 9.1% (SE = 0.58) for top-only and 5.6% (SE = 0.58) for intact format. SEs were within-subject standard errors corrected for bias using the procedure proposed by Cousineau and O'Brien (2014).

Response time analyses

Responses were faster for high – compared to low-frequency words ($b = 32.007$, $SE = 5.056$, $t = 6.331$, $p < .001$), and for complete compared to top-only words ($b = -43.819$, $SE = 4.712$, $t = -9.299$, $p < .001$). Both effects were additive, with no evidence of an interaction ($b = 1.053$, $SE = 6.239$, $t = 0.169$, $p = .866$).

Accuracy analyses

Responses were more accurate for high – compared to low-frequency words ($b = -1.091$, $SE = 0.230$, $z = -4.750$, $p < .001$), and for complete compared to top-only words ($b = 0.612$, $SE = 0.239$, $z = 2.555$, $p = .011$). In addition, there was a significant interaction between word-frequency and stimulus-format ($b = -1.150$, $SE = 0.301$, $z = -3.814$, $p < .001$): simple effects tests showed higher accuracy for the complete words over the top-only words for high-frequency words ($b = -1.186$, $SE = 0.328$, $z = -3.612$, $p < .001$), but not for low-frequency words ($b = -0.037$, $SE = 0.228$, $z = -0.161$, $p = 0.872$).

3.2. ERP results

Figure 2 shows the ERP waves for the Stimulus-Format and Word-Frequency comparisons in the frontal (Fc1,

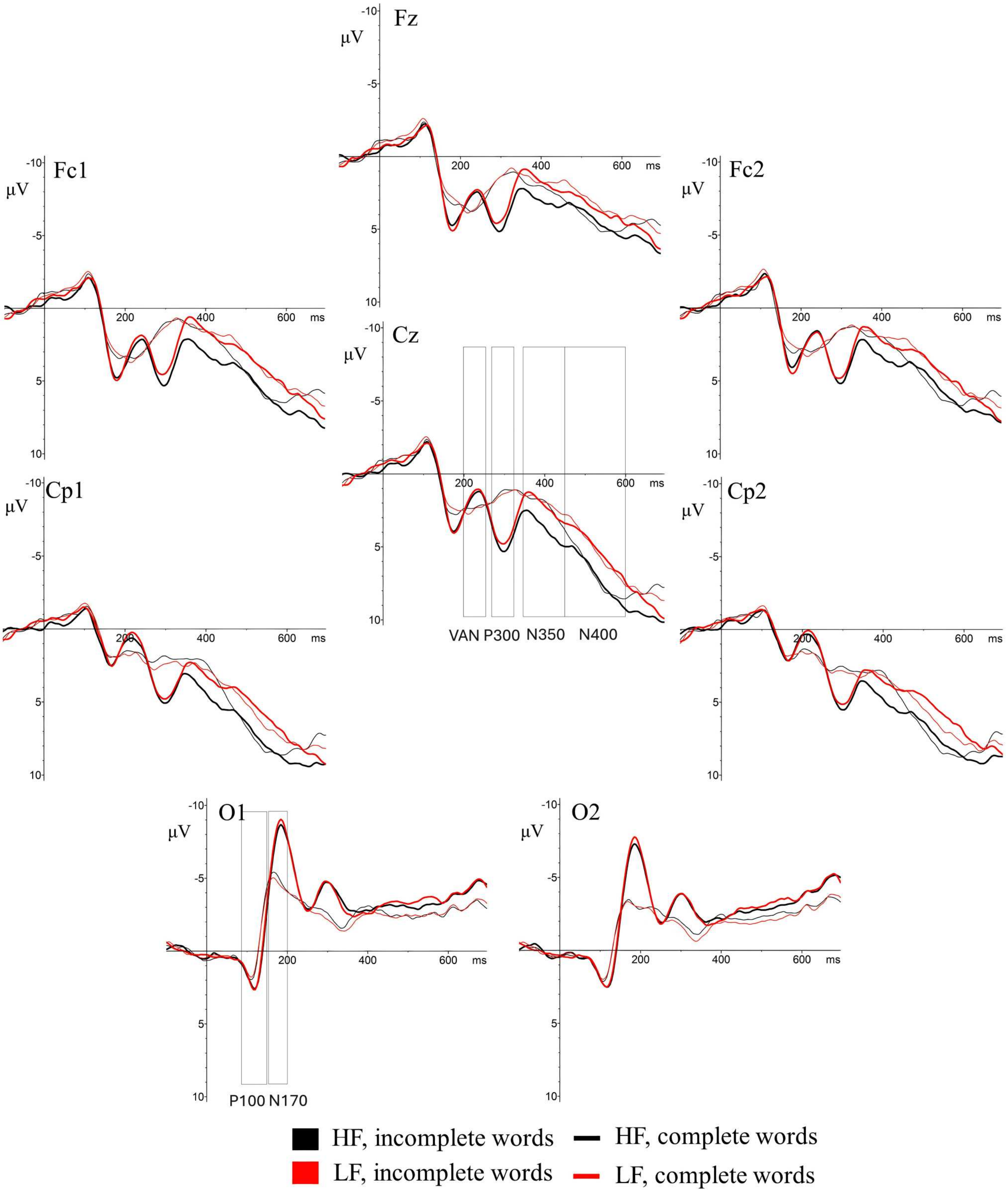


Figure 2. Grand-average event-related potentials to high-frequency (HF) and low-frequency (LF) words in the two Stimulus-Format conditions: complete and top-only words, in frontal, central and occipital electrodes. Data was re-referenced to the mastoids average for all electrodes except for the occipital electrodes (O1, O2), which were re-referenced to the average of all electrodes. Bold lines represent top-only (incomplete) words; thin lines represent complete words. Black lines indicate HF words; red lines indicate LF words.

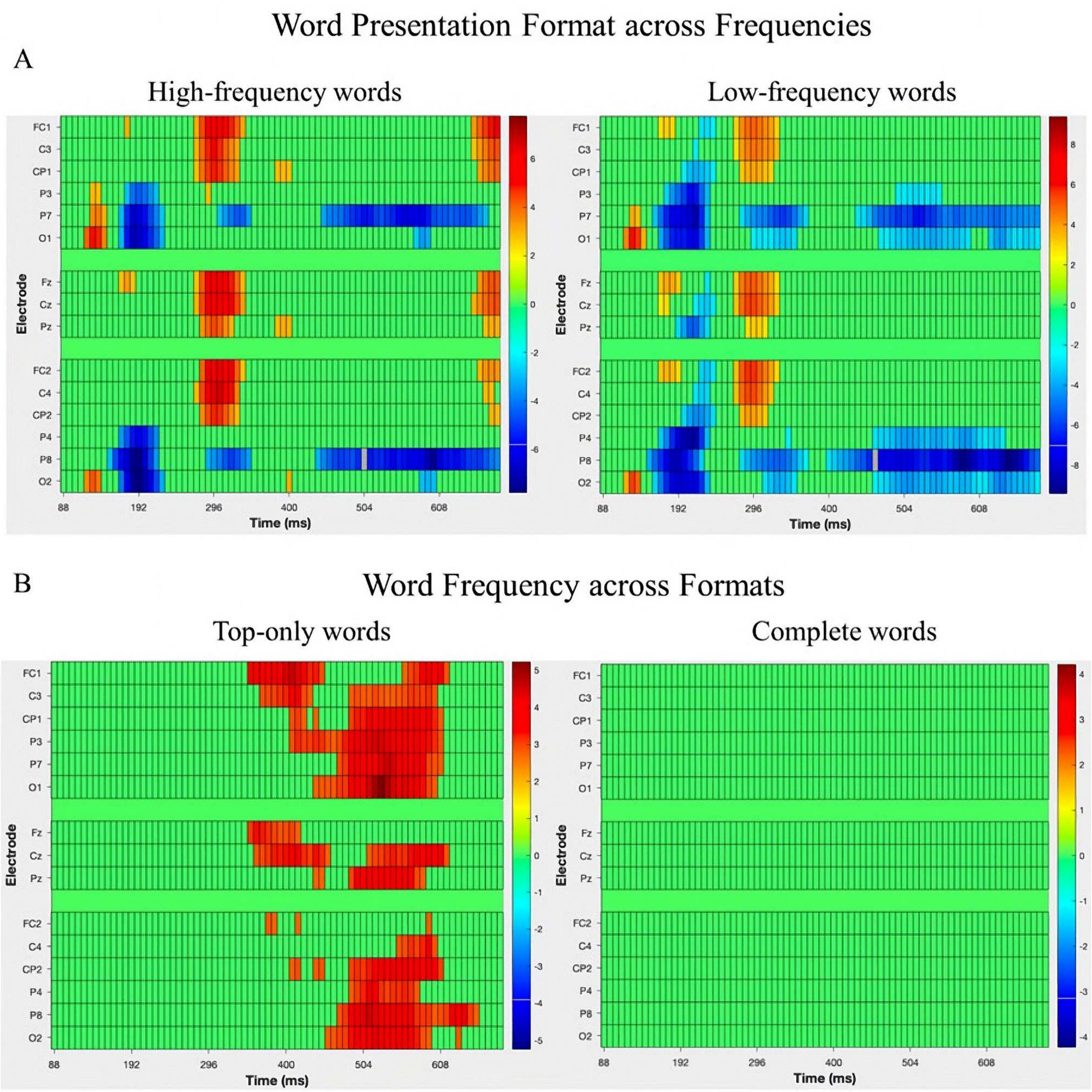


Figure 3. Results of the *Mass Univariate statistical analysis* of the time-course of the A) the presentation format effect at each frequency level, and B) the word-frequency effect for each presentation format. Positive *t*-values indicate more positive amplitudes for incomplete words compared to complete ones (Panel A) and for high-frequency words compared to low-frequency ones (Panel B). Data were re-referenced to the mastoids average.

Fz, Fc2), central (Cp1, Cz, Cp2) and occipital electrodes (O1, O2). During all the epoch, the frontal-central electrodes reflect the inverted ERP pattern in the occipital electrodes due to the differences in the offline reference (Luck, 2014; Rossion et al., 2003). At the earliest stages, the occipital electrodes show an initial positive peak around 100 ms (P100), followed by a larger negative peak between 150 and 200 ms (N170). In both cases, the peak amplitudes and latencies are larger for incomplete words than for complete words. From that point onward, three distinctive peaks are observed over frontal-central electrodes in response to incomplete stimuli: a negative peak around 200 ms, positive peak around 300 ms, and another negative peak at around 350 ms. This pattern resembles the ERP response reported by Wilenius-Emet et al. (2004) for scrambled line-drawing objects. These peaks likely correspond to the VAN (approximately 200 ms), the P300 (300 ms) and the N350 (350 ms). Notably, the N350 shows word-frequency effects only for the top-only words, with low-frequency words eliciting larger negativities than high-frequency words. By approximately 450 ms post-stimuli, word-frequency effects are observed for both stimulus types.

The Mass Univariate analysis revealed differences in the time-course and scalp distribution of the presentation format the word-frequency effects. As shown in Panel A (Figure 3), effects of presentation format were observed for both high – and low-frequency words. Following the P100 and N170 time windows, perceptual effects also emerged during the Closure stage (VAN: 200–240 ms), primarily over occipital, parietal and occipital-temporal electrodes sites. These effects later extended to a more frontal-central distribution (P300: 270–336 ms) and remained over occipital-temporal sites between 450–700 ms.

In contrast, panel B (Figure 3) shows word-frequency effects restricted to top-only words in late time windows (350–600 ms). Although broadly distributed across the scalp, the word-frequency effect appears temporally segmented into two subcomponents. Between 350 and 450 ms (N350), the word-frequency effect is mainly located over left and central frontal electrodes. From 450 to 600 ms (N400), the word-frequency effect becomes more widely distributed. No earlier word-frequency effects were observed.

These exploratory analyses informed the selection of the following time windows and cluster electrodes: VAN (200–240 ms: O1/2, P3/4, P7/8, Fc1/2, C3/4, Cp1/2, Fz, Cz, Pz), P300 (270–336 ms: Fc1/2, C3/4, Cp1/2, Fz, Cz, Pz), N350 (350–450 ms: Fc1, C3, Cp1, P3, Fz, Cz), N400 (450–600 ms: O1/2, P3/4, P7/8, C3/4, Cp1/2, Cz, Pz).

Separate repeated-measures analyses of variance (ANOVAs) were computed on each time window. All ANOVAs included Word-Frequency (high, low-frequency) and Stimulus-Format (complete, top-only words) as factors. However, for the P100 and N170 ANOVAs, topographic factors were also included, as we were interested in their peak amplitude and peak latency: Electrode (occipital: O1/2, parietal: P7/8, and, only for the P100, occipital-temporal: P3/4) and Hemisphere (left, right) (Luck, 2014; Zhang & Kappenman, 2024). Effects for the hemisphere and electrode factor are reported when they interact with the experimental manipulations. Furthermore, two different statistical analyses were performed for these early components; one for the peak amplitudes and another for the peak latencies (as previous ERP studies have revealed peak latency effects in these components; Goffaux et al., 2003; Tanaka, 2020). For the components included in the exploratory analyses, we conducted cluster-based measures analyses using mean amplitude as a linear measure, following the recommendations from previous studies (Luck, 2014; Zhang & Kappenman, 2024), As a result, topographic information was not considered in these analyses. In all analyses, list (List 1, List 2) was also included as a between-subjects factor to account for variance attributable to the counterbalanced lists (Pollatsek & Well, 1995). To control sphericity, Greenhouse-Geisser sphericity correction was applied in those analyses where a factor (Electrode) contained more than two levels (P100 analyses). Interactions between factors were followed up with simple Post Hoc test effects. We detail the ANOVAs results below.

Presentation Format influenced both the peak amplitude and peak latency of the early perceptual components (P100, N170). In both cases, top-only words elicited larger amplitudes and longer latencies compared to complete words (see Table 3 for the statistical results; see Figure 4 for the topographic distribution of effects). For the P100, the effect was specific to occipital and parietal electrodes.

Perceptual effects were also present at later stages associated with Closure phenomena (VAN and P300), where top-only words elicited larger amplitudes. The effect of Presentation Format persisted into the N400 epoch (450-600 ms), where complete words elicited larger negativities than top-only words. In contrast, Word-Frequency effects emerged in later time windows (350-450, 450-600 ms), with low-frequency words eliciting larger negativities than high-frequency words. Latency differences in the Word frequency

Table 3. Summary of the F, *p*, and η^2p values for the peak latency and peak amplitude comparisons of word presentation format and word frequency over the critical regions at the two time-epochs: 90–150 ms, 150–200 ms.

		Format		Format x Electrode			Format x Frequency		Frequency	
		F	η^2p		F	η^2p	F	η^2p	F	η^2p
P100	Peak latency	34.11***	.608	…	…	…	…	…	…	
	Peak amplitude	…	…		15.56***	.414	…	…	…	…
				O	9.01**	.291	…	…	…	…
				P	4.85*	.181	…	…	…	…
				OT	…	…	…	…	…	…
N170	Peak latency	10.14**	.316	…		…	…	…	…	…
	Peak amplitude	79.01***	.782	…		…	…	…	…	…

df of comparisons = 1,22. *$p < .05$. **$p < .01$. ***$p < .001$. O: occipital, P: parietal, OT: occipital-temporal electrodes.

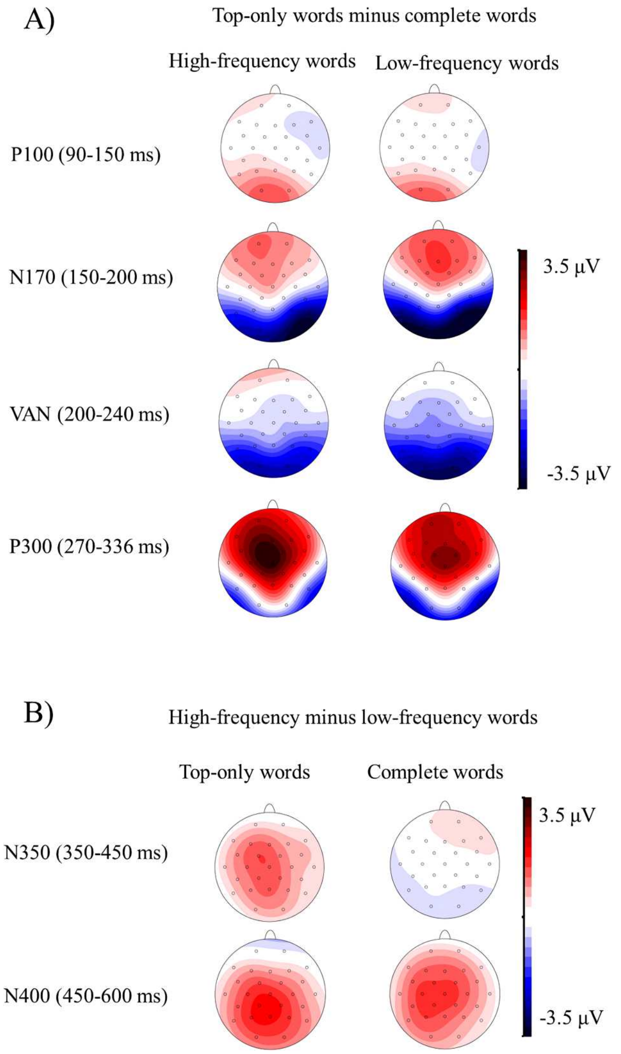
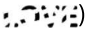


Figure 4. Topographic distribution of the A) Stimulus-Format effects and B) Word-Frequency effects in each time window. Data were re-referenced to the average of all electrodes for the P100 and N170 components, and to the mastoids average for the VAN, P300, N350 and N400 components.

effect were observed between top-only and complete words. The interaction between Presentation Format and Word-Frequency in the 350-450 ms epoch (N350) revealed a significant word-frequency effect in top-only words and a significant effect of presentation format for high-frequency words. In the 450-600 ms epoch (N400), a significant main effect of Word-Frequency was found (see Table 4 for statistical results; see Figure 4 for topographic distribution of effects).

In summary, the behavioural results revealed main effects of word frequency and stimulus format: high-frequency words were identified with higher accuracy and faster reaction times compared to the low-frequency ones, the same as complete words compared to top-only words. In the accuracy data, the interaction between word-frequency and stimulus-format revealed higher accuracy for the complete words over the top-only words for high-frequency words, but not for low-frequency words. Importantly, the ERP analyses showed that the early (P100 and N170) and Perceptual Closure related ERPs (VAN and P300) were sensitive to the Stimulus-Format manipulation, but not to the Frequency manipulation. In contrast, the Closure N350 ERP (350-450 ms) for top-only words was sensitive to Word Frequency. Finally, from 450-600 ms, the N400 was sensitive to Word Frequency, both for top-only and complete words (see Figure 5 for the latency of the Frequency effect across Stimulus-Format).

4. Discussion

The Perceptual Closure principle reflects the process of filling in missing portions of an incomplete stimulus (e.g.: ) to produce an identifiable object (e.g. see Bartlett, 1916; Snodgrass & Kinjo, 1998). While behavioural priming experiments have examined the processing of top-only and bottom-only words in comparison to complete words (Perea et al., 2012a, 2012b), these behavioural studies do not provide insights into the time course of Perceptual Closure during visual word recognition.

Previous research has characterised the ERP signature (i.e. VAN, NcL, N350) of Perceptual Closure by comparing the visual processing of fragmented vs. intact visual

Table 4. Summary of the F, *p*, and η^2p values for the comparisons of presentation format and word frequency over the clusters at four time-epochs: 200–240 ms, 270–336 ms, 350–450 ms, 450–600 ms.

	Format				Format x Frequency		Frequency	
	F	η^2p			F	η^2p	F	η^2p
VAN	26.38***	0.545			…	…	…	…
P300	30.03***	0.577			…	…	…	…
N350	…	…			5.84*	0.21	5.37*	0.196
			Format:	HF	4.20*	0.16		
				LF	…	…		
			Frequency:	Top	17.26***	0.44		
				Full	…	…		
N400	7.23*	0.248			…	…	25.93***	0.541

df of comparisons = 1,22. *$p < .05$. **$p < .01$. ***$p < .001$.

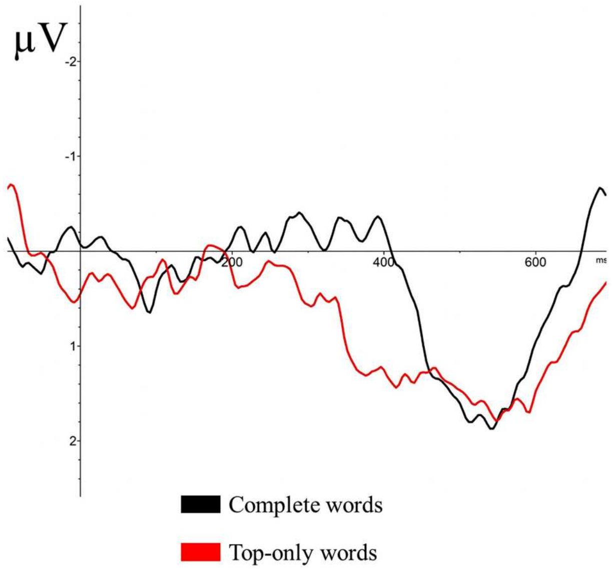
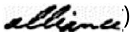


Figure 5. Difference waveforms of the Word-Frequency manipulation across both Presentation Formats: complete and top-only words on the N350 cluster. The Word-Frequency effect is defined as the voltage difference between the ERP responses to high-minus low-frequency words. Data were re-referenced to the mastoids average. The black line represents complete stimuli; the red line represents top-only stimuli.

images of different objects. However, it remains unknown whether these components also index closure processes in partial word displays (e.g. top-only words).

The present experiment was designed to fill this gap by comparing complete and top-only words while recording electrophysiological responses. Notably, prior ERP and behavioural studies have examined visual word recognition under perceptually challenging conditions – such as difficult handwritten words (e.g. ) – revealing an interaction between low-level processing (format: printed vs. handwritten) and high-level lexical processing (word frequency: low – vs. high-frequency words) in early ERP components (e.g. N170; see Vergara-Martínez et al., 2021). To test whether top-down lexical influences contribute to the recognition of incomplete words, we manipulated word frequency in the experiment.

Behavioural word identification times revealed additive effects of stimulus-format (a low-level factor, with faster responses for complete than for top-only words) and word frequency (a higher-level factor, with faster responses for high – than for low-frequency words). This pattern differs from Perea (2012), who found a larger frequency effect for top-only words compared to complete words. However, our study differs from Perea's (2012) sentence reading study in two key ways: ours is a lexical decision task, and in Perea's (2012) experiment, the target stimuli could contain potentially ambiguous letters, which may have increased reliance on top-down effects.

Critically, ERP analyses provided richer insights into the continuous neural processes that underlie the behavioural results: both low – and high-level processing factors exerted their influence across distinct time windows. Stimulus-Format impacted early components (P100, N170) and Perceptual Closure components (VAN, P300), whereas the Word Frequency affected a later Closure related ERP (N350) and lexical-semantic stages (N400). Notably, both low – and high-level factors interacted during the N350. Below, we examine these effects and their implications.

First, incomplete stimuli differed from complete ones in the P100: higher amplitudes and longer latencies were elicited by incomplete compared to complete stimuli. The P100 is a positive-going deflection recorded over scalp temporo-occipital regions, commonly peaking between 100 and 130 ms after a visual stimulus onset (e.g. for vertical bars: Johannes et al., 1995; for occluded buildings and faces: Liu et al., 2020). This component reflects the processing of basic visual information (linked to the extrastriate visual cortex, Khateb et al., 2002; Luck, 2014), determining the overall visibility of a stimulus (Boutet et al., 2021). Thus, both P100 amplitude and latency are sensitive to changes in low-level visual properties such as image contrast, luminance, colour, and face inversion (Marcar & Wolf, 2024). For instance, inverted faces elicit higher P100 amplitudes and longer latencies than upright faces (Marzi & Viggiano, 2007); flanked stimuli elicit higher P100 amplitudes than isolated ones (Winsler et al., 2022); and blurred faces elicit delayed P100 latencies than clear faces (Goffaux et al., 2003). These findings suggest that the more visually degraded a stimulus is, the greater its impact on P100 amplitude and latency.

Although larger stimuli usually elicit greater P100 amplitudes (Bayer et al., 2012; Busch et al., 2004; Pfabigan et al., 2015), our results show the opposite: top-only words, despite being smaller, produced the largest amplitudes. This suggests that incompleteness may impact P100 more strongly than size, particularly in tasks requiring fine-grained letter recognition. Notably, previous studies used much larger size differences than those used here, indicating that even subtle distortions – rather than size alone – can modulate both P100 amplitude and latency in written stimuli.

Next, the N170 component was also sensitive to the stimulus-format manipulation. This is not surprising, as the N170 is known to reflect orthographic perceptual feature processing (Bentin et al., 1999; Maurer et al., 2005; Maurer & McCandliss, 2008; Winsler et al., 2022).

Like the P100, top-only words elicited larger N170 amplitudes and longer latencies than complete ones, consistent with prior findings that N170 increases when letter processing is more difficult (Civera et al., 2024; Vergara-Martínez et al., 2021; Winsler et al., 2022). Similarly, the N170 latency is delayed when the perceptual features of a stimulus are disrupted, such as in mirror-reversed alphabet characters or inverted faces (Tanaka, 2020). Thus, incomplete words entail higher complexity in establishing an orthographic code (i.e. the encoding of letter identity and letter position within the stimulus; see Grainger, 2018).

As expected, we obtained a main effect of stimulus-format in a negativity peaking around 200–240 ms post-stimulus, where top-only words elicited larger amplitudes compared to complete words. We interpret this negativity as the VAN, as larger amplitudes are elicited by scrambled versions of the target stimuli (Förster et al., 2020; Liu et al., 2020; Wilenius-Emet et al., 2004). Besides, the VAN is elicited by consciously perceived disrupted stimuli (also known as *aware conditions*) (Pitts et al., 2014), as was also ensured in our experiment (i.e. stimuli presentation lasted 500 ms).

The VAN has been interpreted in terms of subjective awareness of stimulus incompletion and the underlying mechanisms of its conscious recovery. Importantly, since it is found with perceptually incomplete stimuli regardless of the stimulus type (objects, line drawings, faces, and orthographic stimuli), it may reflect a common process toward completion peaking around 200-300 ms (Liu et al., 2020). Moreover, the absence of frequency effects in the VAN reveals that top-down influences do not reach this stage of processing. Hence, the VAN might not represent the point of Closure but rather the computations leading up to its output (i.e. subjective awareness) (Sehatpour et al., 2006).

This negative deflection, which we interpret as VAN, likely reflects the disruption of the spatial and configural structure of top-only words, which in turn impairs the integration of sub-lexical information into whole-word units. Hence, in the present experiment, the VAN may capture processes partially similar to those indexed by the N250. This ERP peaks around 250 ms in the context of masked priming paradigm and is interpreted to index the interface between sublexical and whole-word lexical representations (Grainger & Holcomb, 2009; Holcomb & Grainger, 2006). Notably, larger N250 amplitudes are obtained when orthographic word form is impaired. However, in the absence of masked priming, the N250 often peaks later (around 250–300 ms: Dickson & Federmeier, 2014; Vergara-Martínez et al., 2020b), whereas in our data this negative deflection peaked before 250 ms. Moreover, while previous studies have reported lexical top-down on the N250 (see Grainger et al., 2012; Massol et al., 2011), no such effects (either of word-frequency of lexicality) were observed in this time window (see supplementary analysis). Thus, the differences between the VAN and the N250 may reflect the specific manipulation used in the present study.

In line with previous ERP studies on visual awareness (Förster et al., 2020), we found an effect of stimulus-format in the P300 component: larger positive amplitudes were elicited by the top-only words compared to the complete ones. Previous work suggests that, although the P300 does not correlate with the activation of the mechanisms that generate awareness, it does correlate with the further conscious processing of the task-relevant stimuli in working memory (Koivisto & Grassini, 2016). In line with this, we hypothesise this greater P300 amplitude for the top-only words reflects a greater effort in the search for the abstract representation of the word stored in memory (Förster et al., 2020; Koivisto & Grassini, 2016; Schröder et al., 2021).

Of particular interest, there was an interaction between presentation format and word-frequency in the N350 (350-450 ms). High-frequency top-only words elicited reduced negativities compared to both low-frequency top-only words and high-frequency complete words. The N350 has been interpreted as a Closure-related ERP component, as it is sensitive to the identification of stimuli when object parts and overall structural configuration are readily recoverable (Schendan & Kutas, 2002). Importantly, unlike the VAN, the N350 is not modulated by the degree of object fragmentation preceding recognition, but rather reflects the process of stimulus identification itself (Sehatpour et al., 2006). The reduced N350 amplitudes for high-frequency top-only words suggest that top-down information (e.g. word-frequency) facilitates the Closure point of incomplete words, consistent with findings associating smaller amplitudes with identified stimuli (Sehatpour et al., 2006).

Interestingly, word-frequency effects for complete words were not observed until the late N400 (450-600 ms), an ERP associated with the processing of abstract lexical representations. The N400 is a negative-going wave peaking around 400 ms post-stimulus with a central and parietal scalp distribution (Luck, 2014). It is widely recognised as an index of semantic access and has been extensively used in visual word recognition research to examine factors that influence meaning retrieval from written language (for a comprehensive review, see Kutas & Federmeier, 2011). Among other factors, word-frequency modulates N400 amplitude (McWeeny & Norton, 2020; Vergara-Martínez et al., 2017; see Vergara-Martínez et al., 2020a, for review). In the present experiment, low-frequency words elicited larger negativities than high-frequency ones, consistent with prior findings that greater difficulty in accessing lexical representations increases N400 amplitudes (Kutas et al., 2006; Meade et al., 2019; Vergara-Martínez et al., 2020a).

Regarding the misalignment in the time course of the frequency effect between top-only (N350) and complete words (N400), we propose that top-down information exerts a stronger and earlier influence when visual input is partially disrupted. Supporting this view, fMRI research has shown increased parietal activation during the processing of non-standard word formats (e.g. rotated words), thus reflecting a greater allocation of attentional resources (Qiao et al., 2010; Cohen et al., 2008; see Mayall et al., 2001; Pammer et al., 2006). In turn, factors that increase attentional demands during stimulus processing can shift the temporal dynamics of lexical access (see Hauk et al., 2006, 2009; Dambacher et al., 2012; Fernández-López et al., 2025). Therefore, the accelerated impact of word frequency for top-only words may be explained by top-down enhancement due to an attentional amplification. These increased attentional demands would facilitate Closure for incomplete words (as shown in the N350).

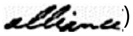
Interactive activation models can account for the interplay between bottom-up and top-down information during visual word recognition (McClelland & Rumelhart, 1981; see Carreiras et al., 2014, for review). In these models, information is assumed to cascade continuously across the orthographic – phonological – lexical – semantic levels. This architecture enables higher lexical-level representations (e.g. lexical or semantic information) to feed back and constraint processing at lower levels, including orthographic representations. More recent proposals, such as predictive coding, integrate principles of neuronal processing (i.e. Friston, 2005; Rao & Ballard, 1999) to provide a more biologically grounded account of how top-down influences can shape both early perceptual activity and later interaction, such as those observed in the N400 range.

The predictive coding framework proposes that neural networks, integrated by feedforward and feedback pathways, learn the statistical regularities of sensory input and use this information to generate predictions about incoming stimuli (Rao & Ballard, 1999). These predictions are conveyed by feedback pathways, where top-down information (expectations) influences lower levels of processing. In contrast, feedforward pathways transmit the discrepancy between the predicted and actual input: the prediction error. This prediction error serves to update internal representations and refine subsequent predictions, allowing the system to continually adapt and optimise perception.

According to the Prediction Error Model of Reading (PEMoR; Gagl et al., 2020), word identification is based on an optimised neuronal code that relies on informative non-redundant features, the *orthographic prediction error* (oPE). The oPE reflects the deviation of a given letter-string from an internally generated knowledge-based orthographic expectation. An increase in oPE may modulate the degree to which top-down information influences word recognition. When the input is visually clear and unambiguous (e.g. standard printed complete words: metro), oPE is low, and processing system is guided by statistical regularities acquired through reading experience. As a result, top-down connections (e.g. lexical-semantic knowledge) may exert minimal influence on lower-level processing. In contrast, when the input is visually degraded (e.g. top-only words: metro), oPE increases.[2] This elevated prediction error may boost attentional networks (Qiao et al., 2010; see also Smout et al., 2019, for the relation between prediction error and attention) which might in turn increase the impact of lexical-semantic top-down feedback.

Specifically, wordlike letter strings are more likely to activate high-frequency word units than low-frequency word units, due to differences in their resting level of activation. Compared to complete letters, the greater oPE associated with top-only letters would amplify feedback signals from word level stage, either by carrying more information or by reaching lower identification stages earlier. This would account for the earlier emergence of word-frequency effects for top-only words (350-450 ms) compared to complete words (450-600 ms).

Although top-down effects in response to disrupted stimuli are not new (see Schendan & Ganis, 2015; Vergara-Martínez et al., 2021), their time-course differs across studies. For instance, Vergara-Martínez et al. (2021) reported word-frequency effects for difficult handwritten words, but not for easier handwritten or printed words, emerging in the N170 component. Similarly, in an fMRI study, Heilbron et al. (2020) found top-down modulations in the early sensory cortical areas for letters embedded in heavy visual noise (e.g. 80% opacity, e.g. HOUSE). In contrast, in the present experiment, the word-frequency effect for incomplete words (but not for their complete counterparts) emerged in the N350 window. This temporal divergence likely reflects differences in the type and degree of perceptual disruption, which could determine when and how top-down mechanisms are engaged.

Indeed, although top-only words in the present experiment are visually degraded, the upper parts of letters remained perceptually unambiguous, preserving distinctive orthographic features (e.g. vertical strokes, ascenders) that are critical for letter and word identification (Bouma, 1973; Pelli et al., 2006). Within the predictive coding framework, orthographic predictions may still match effectively to the partial input. As a result, the orthographic prediction error (oPE) remains informative enough to trigger lexical-level processing at mid-latency stages, consistent with the emergence of word-frequency effects around 350 ms (N350). In contrast, a manipulation like difficult handwriting (e.g. ) reduces the precision of orthographic predictions, impairing the match between incoming input and stored representations. This increase in the oPE may engage compensatory top-down mechanisms earlier, as in the N170 (Vergara-Martínez et al., 2021). Thus, the dynamic tuning between perceptual input and prior orthographic knowledge provides a plausible explanation for the temporal variability of word-frequency effects across different types of degraded or non-standard word stimuli (Gagl et al., 2020; Heilbron et al., 2020).

This interpretation may also explain previous ERP studies on impoverished object images using rapid categorisation (Schendan & Ganis, 2015) where the most disrupted stimuli recruited stored knowledge around 250 ms, whereas the least impoverished stimuli did so around 450 ms (N400). Overall, the greater the perceptual disruption, the earlier top-down factors intervene.

In sum, our results revealed that: (1) top-only words elicit a series of ERPs associated to Perceptual Closure (VAN, P300 and N350); (2) top-down information impacted perceptual closure at a relatively later processing stage: N350. As the N350 showed interaction between stimulus format and frequency, we propose that this epoch marks the actual Closure point for incomplete stimuli: that is, the stage at which the global word form and its meaning coalesce. We conclude that high-level information does not percolate into earlier components (as it does with difficult handwritten words on the N170; Vergara-Martínez et al., 2021) because top-only words still provide unambiguous letter features, ensuring that, although hindered, orthographic pre-lexical processing can proceed primarily in a bottom-up manner until approximately 350-450 ms post-stimulus.

Health and safety

All mandatory laboratory health and safety procedures have been complied with in the course of conducting the experimental work.

Open practices statement

The data, scripts, outputs, and materials for the experiment are available at OSF link https://osf.io/gtsjc/?view_only=9199608052124c398263884ddf583a88 and the experiment was not preregistered.

Notes

1. As in many previous experiments that treat lexical frequency as a binary factor, our design used clearly separated sets of high – and low-frequency words. This approach allows for interpretable comparisons between distinct lexical regimes but does not capture the full gradient of frequency effects. Future studies could address this by sampling words across a continuous and evenly distributed frequency range and by adopting analysis strategies that model both participant – and item-level variability.
2. Although orthographic predictions are driven by knowledge-based orthography, the present experimental context also helps prediction refinement (Limanowski et al., 2020). As suggested by a Reviewer, the random intermixing of top-only and complete word presentations might have encouraged a "standard" reading mode, leading to a prediction-based visual completion of the top-only words. This observation opens the door for future research addressing how the impact of different presentation formats (e.g. blocked vs. mixed) affect the updating of predictions over time (e.g. comparing early versus late trials in the experiment).

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Disclosure statement

No potential conflict of interest was reported by the authors.

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Declaration of interest statement

The authors report there are no competing interests to declare.

Ethics approval

The research was approved by the Research Ethics Committee of the University of Valencia and was in accordance with the Declaration of Helsinki.

Consent to participate and for publication

Informed consent was obtained from all individual participants included in the study.

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