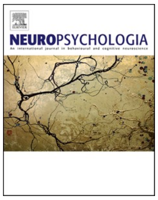
Neuropsychologia 159 (2021) 107924

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia



# The time course of processing handwritten words: An ERP investigation☆

Marta Vergara-Martínez [a,*], Eva Gutierrez-Sigut [b], Manuel Perea [a,c,d], Cristina Gil-López [e], Manuel Carreiras [d,f,g]

[a] ERI-Lectura, Universitat de València, Valencia, Spain
[b] Department of Psychology, University of Essex, Essex, UK
[c] Universidad Nebrija, Madrid, Spain
[d] Basque Center of Cognition, Brain, and Language, Donostia, Spain
[e] CNRS-Université Grenoble Alpes, Grenoble, France
[f] IKERBASQUE, Basque Foundation for Science, Bilbao, Spain
[g] University of the Basque Country (UPV/EHU), Bilbao, Spain

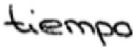
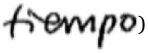
ARTICLE INFO

*Keywords:*
Visual word recognition
ERPs
Handwritten word processing

ABSTRACT

Behavioral studies have shown that the legibility of handwritten script hinders visual word recognition. Furthermore, when compared with printed words, lexical effects (e.g., word-frequency effect) are magnified for less intelligible (difficult) handwriting (Barnhart and Goldinger, 2010; Perea et al., 2016). This boost has been interpreted in terms of greater influence of top-down mechanisms during visual word recognition. In the present experiment, we registered the participants' ERPs to uncover top-down processing effects on early perceptual encoding. Participants' behavioral and EEG responses were recorded to high- and low-frequency words that varied in script's legibility (printed, easy handwritten, difficult handwritten) in a lexical decision experiment. Behavioral results replicated previous findings: word-frequency effects were larger in difficult handwriting than in easy handwritten or printed conditions. Critically, the ERP data showed an early effect of word-frequency in the N170 that was restricted to the difficult-to-read handwritten condition. These results are interpreted in terms of increased attentional deployment when the bottom-up signal is weak (difficult handwritten stimuli). This attentional boost would enhance top-down effects (e.g., lexical effects) in the early stages of visual word processing.

## 1. Introduction

While expert readers can quickly and accurately encode words when printed in a standard font, the scenario is very different when we encounter a shabbily handwritten word (e.g., compare surprise to ) (see Grainger, 2018; Grainger and Dufau, 2012, for reviews of the front-end of visual word recognition). As a matter of fact, in the pre-digital era, we often struggled to decipher what our doctor wrote in a medical prescription. Assuming that writing illegibility was not a deliberate decision to confuse the patients, a source of confusion comes from most of us being unfamiliar with medical terms: we lack any top-down feedback to help stimulus disambiguation. What is the empirical evidence in support of this claim? As first suggested by Manso de Zuniga et al. (1991), the natural physical ambiguity of handwritten words may require greater reliance on top-down processes. Indeed, in a series of behavioral experiments (lexical decision, naming), Barnhart and Goldinger (2010) found that variables that reflect top-down processing as word-frequency and semantic imageability exerted a greater impact on the processing of handwritten than on printed words. Similarly, Perea et al. (2016) reported larger effects of word-frequency in lexical decision tasks when handwritten words are difficult to read (e.g.,  [time]) compared to easier-to-read handwritten words (e.g. ) or printed words (tiempo). These findings were

---

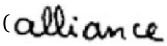
☆ Author's notes: The research reported in this article has been partially funded by: Spanish Ministry of Science, Innovation and Universities (Grant PSI2017-86210-P); Basque Government through the BERC 2018–2021 program; Agencia Estatal de Investigación through BCBL Severo Ochoa excellence award SEV-2015-0490; and through project RTI2018-093547-B-I00.

* Corresponding author. Dpto. de Psicología Evolutiva y de la Educación Universitat de València Av. Blasco Ibáñez, 21 46010-Valencia, Spain.
*E-mail address:* Marta.Vergara@uv.es (M. Vergara-Martínez).

https://doi.org/10.1016/j.neuropsychologia.2021.107924
Received 7 April 2021; Received in revised form 21 June 2021; Accepted 22 June 2021

interpreted in terms of the balance of bottom-up and top-down activity in fully interactive visual word recognition models (see Carreiras et al., 2014): stronger bottom-up signals (perceptually unambiguous stimuli) would reach their recognition threshold in a fast forward manner. In contrast, when the handwriting is smeary, the bottom-up signal is weak (perceptually ambiguous stimuli), and top-down processes would exert a greater influence. However, none of the above experiments examined the time-course of bottom-up and top-down processes during the recognition of handwritten words.

The main aim of the present experiment was to track down the time-course of the alleged cognitive mechanisms of top-down lexical feedback (as inferred from the word-frequency effect) when reading handwritten words. To characterize the timeline of the interaction between word-frequency and script (printed vs. handwritten) reported in behavioral measures, we registered both behavioral data (response times, accuracy) and event-related potentials (ERPs)—note that ERPs allow for an exquisite time-course tracking of lexical access (see Dufau et al., 2015; Grainger, 2018; Grainger and Holcomb, 2009; Vergara-Martínez et al., 2009; Vergara-Martínez et al., 2013). In the following lines, we first review some relevant background on the neural correlates of handwritten word processing, along with previous research on the interaction between the surface form of a word and word-frequency in the ERP literature in lexical decision. Next, we will introduce the experiment along with the predictions.

In an attempt to address the neuroanatomical signature of the processing of handwritten words, Qiao et al. (2010) conducted a semantic categorization fMRI experiment with easy handwritten (), difficult handwritten (), and printed (alliance) words. This manipulation allowed them to examine which brain areas showed a common response to all formats and which brain areas showed specific responses to handwritten or printed word processing. Qiao et al. (2010) found that, similar to printed stimuli, the recognition of handwritten words relied on the left ventral occipito-temporal cortex (i.e., visual word form area; henceforth VWFA). While the same ventral areas were activated irrespective of word format, difficult handwritten words activated the ventral stream to a larger degree than printed words and easy handwritten words. The difference in the strength of activation of the VWFA between difficult handwritten words and printed words was interpreted in terms of the larger perceptual processing demands of the most unfamiliar visually ambiguous stimuli. More importantly, for the difficult handwritten words, Qiao et al. (2010) found additional activation in a bilateral frontoparietal network. This finding was interpreted as reflecting the deployment of attentional resources to disambiguate difficult handwritten characters (i.e., an attentional amplification of reading pathways under the control of dorsal cortex). This explanation is consistent with the increase in the activation of parietal regions when reading words in a nonstandard format (e.g., rotated words; words displaced to visual periphery) reported by Cohen et al. (2008; see Mayall et al., 2001; Pammer et al., 2006, for similar findings). Taken together, these findings may be interpreted as a result of switching from an automatic word identification process to an attention-based reading strategy.

The key question in the present experiment is whether the larger effects of word-frequency observed for the difficult handwritten stimuli in lexical decision tasks (Barnhart and Goldinger, 2010; Manso De Zuniga et al., 1991; Perea et al., 2016) is related to the attentional amplification of the reading pathways during visual word recognition of handwritten stimuli (Qiao et al., 2010). In other words, we examined whether the lexical information that allegedly helps to resolve the ambiguity of the visual stimulus via top-down mechanisms (attentional boost) operates very early during low-level decoding in the VWFA. Whether the VWFA is sensitive to lexical factors is part of an intense debate between feedforward vs. fully interactive models of visual word recognition. Whereas the feedforward approach states that the VWFA activation mainly reflects orthographic processing (i.e., computation of abstract letter strings, Dehaene et al., 2001, 2002), there is evidence suggesting that orthographic processing in the VWFA can be modulated by higher-level factors such as word-frequency (Kronbichler et al., 2004; Price and Devlin, 2011; Whaley et al., 2016; see also Carreiras et al., 2014, for a review). The fine temporal resolution of electrophysiological measures such as ERPs can help elucidate whether there is a fast engagement of higher-level variables during visual word recognition of highly ambiguous stimuli (difficult handwritten words)—note that Qiao et al. (2010), Cohen et al. (2008) and Kronbichler et al. (2004) used fMRI. Hence, the present ERP experiment was designed to examine the electrophysiological signature of the increased word-frequency effects on handwritten words with a focus on the early stages of visual word processing.

To the best of our knowledge, this is the first study to investigate the EEG counterpart of top-down feedback on the processing of handwritten words. There have been, however, several ERP studies that, using printed (easily identifiable) letters, have examined the interaction between lower-level processing factors (e.g., letter case) and higher-level processing factors (e.g., word-frequency). In a lexical decision ERP experiment, Lien et al. (2012) analyzed the dynamics of letter-case mixing (nUcLeAr) and word-frequency. They found non-interactive effects of letter-case mixing and word-frequency in two ERPs typically associated to different stages in visual word recognition: the N170 and the P300. While the N170 was sensitive to case-mixing, word-frequency only modulated the later P300. First, the temporal-occipital N170 in the context of visual word recognition is an electrophysiological marker of visual expertise lateralized in the left hemisphere, which shows enhanced amplitudes for letter strings compared to non-linguistic control stimuli (Bentin et al., 1999; Maurer et al., 2005b; Rossion et al., 2003). Second, the P300 is considered a measure of stimulus classification in response selection (Luck, 1998) that reflects post-lexical categorization. The dissociation between letter case-mixing and word-frequency ERP effects observed by Lien et al. (2012) is in line with recent evidence (Vergara-Martínez et al., 2020b) on the interrelation between letter case and word-frequency in visual word recognition. Vergara-Martínez et al. (2020b) presented participants with lowercase and uppercase versions of words of different frequency (as well as nonwords) in a lexical decision ERP experiment, and found dissociable effects of letter-case and word-frequency both in the behavioral and ERP measures. While letter-case impacted early perceptual stages of visual word processing (N/P150) in the Vergara-Martínez et al. (2020b) experiment, word-frequency effects emerged around 250 ms post stimuli, and no interaction was observed between both factors in none of the ERP components under study. Taken together, the findings from Lien et al. (2012) and Vergara-Martinez et al. (2020b) suggest that these versions (MiXeD case or UPPERCASE versions) of printed stimuli require some additional attentional involvement in the early encoding stages, which would disrupt the normal time-course of visual word recognition (see Mayall et al., 2001). However, and more important for the aim of the present study, the absence of word-frequency effects in the earliest ERP components (N170, N/P150) would indicate that top-down lexical information was not crucial during the encoding stage (at least when using printed letters that were easily identified).

Notwithstanding, the nature of handwritten stimuli allows for predicting a greater involvement of top-down lexical factors to help mapping the handwritten stimuli onto stable, abstract, representations. Handwritten words differ from printed words in a number of parameters which tax their legibility (word-form geometric structure, certain lack of physical demarcation between letters, intra-variability in the shape of letters across words). Indeed, Vinckier et al. (2006) suggested that handwritten stimuli might exceed the capacity of the ventral stream for perceptual invariance, leading to the additional intervention of dorsal parietal regions (attentional-based reading). Accordingly, previous behavioral evidence of handwritten processing revealed larger effects of word-frequency for the difficult handwritten compared to the easy handwritten and printed versions of words (Perea et al., 2016). In contrast, Lien et al. (2012) and Vergara-Martínez et al. (2020b) obtained additive effects of letter case and word-frequency (both in the behavioral and in the ERP measures).

Thus, in the present experiment, we analyzed the electrophysiological signature of handwritten word processing to assess whether top-down lexical feedback (word-frequency effect) percolates into the early perceptual decoding stages. To do so, we presented words of high- and low-frequency and nonwords in an ERP lexical decision task. The stimuli could be presented in handwriting (either difficult-to-read or easy-to-read) or as printed stimuli. If lexical information helps to resolve the ambiguity of the visual stimulus via top-down attentional boost, we expect to observe differential effects of word-frequency in the ERP responses for the most ambiguous stimuli (difficult handwritten). More specifically, if the attentional amplification of the reading pathways already initiates during the encoding stages of the difficult handwritten stimuli, we predict to obtain differential effects of word-frequency early in the processing of difficult handwritten stimuli, possibly in an early ERP component as the N170. Note that the neuronal origin of the N170 has been related to the left occipital-temporal regions (Allison et al., 1994; Maurer et al., 2005b) or VWFA (Cohen and Dehaene, 2004), the brain area reported to over-respond to difficult handwritten words in the Qiao et al. (2010) study. Instead, if the attentional amplification of the reading pathways does not flow down into the earliest perceptual processing stages of handwritten word recognition, we would expect differential effects of word-frequency for difficult handwritten stimuli in later stages of word processing. This outcome would indicate that the attention-based reading strategies for handwritten stimuli that operate in very low-level decoding stages, are impervious to lexical access. In sum, in either scenario, the timeline of the differences in the latency and/or magnitude of the word-frequency effect across scripts will provide highly useful information on the earliest availability of top-down lexical feedback.

## 2. Method

Participants. Twenty-eight students (graduate or undergraduate) of 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 history of neurological or psychiatric disorder, and with normal (or corrected-to-normal) vision. Data from 8 participants were discarded due to tiredness and/or excessive artifacts in the EEG recording. The ages of the remaining 20 participants (15 women) ranged from 17 to 31 years (M = 22.9, SD = 3.9). 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 València and was in accordance with the declaration of Helsinki.

Materials. A sample of 312 Spanish words and 312 nonwords of five and six letters were selected from the stimuli used in the Perea et al. (2016) study (see Perea et al., 2016, Experiment 1, for detailed information on the stimuli). Half of the words were of high-frequency (M = 154.5 per million), and the other half were of low-frequency (M = 4.7 per million). The two sets of words were matched across a number of relevant psycholinguistic variables: Orthographic Neighborhood, Bigram Frequency, Concreteness, and Imageability (see Table 1). The list of words and nonwords is presented in Appendix A.

As detailed in Perea et al. (2016), three versions were created for each stimulus: one in the printed format (lowercase 24-pt Century non-monospaced: puñal [dagger]), one in an easy-to-read handwritten format (puñal; from now on: "easy handwritten") and one in the difficult-to-read handwritten format (puñal; from now on "difficult handwritten"). Note that the handwritten stimuli were scaled to match the dimensions of the printed stimuli as much as possible. Three counterbalanced lists were created in a Latin square manner so that each target stimulus was rotated across the different conditions. Different participants were randomly assigned to each list. Each list included 312 words (156 words of high-frequency and 156 words of low-frequency; 52 in each script format) and 312 nonwords (104 in each script format).

Procedure. Participants were seated comfortably in a dimly lit and sound-attenuated chamber. All stimuli were presented on a high-resolution monitor (1280 x 1024; 60 Hz) that was positioned at eye level at 70 cm from the participant. The stimuli were displayed in white against a dark-gray background and each character subtended about 0.4° of visual angle in height and 0.6° in width. Participants performed a lexical decision task: they were instructed to decide as accurately and rapidly as possible whether the stimulus was a Spanish word or not. They pressed one of two response buttons (SÍ [YES] and NO). The hand used for each type of response was counterbalanced across subjects. Reaction Times (RTs) were measured from stimulus onset until the participants' response. The sequence of events in each trial was as follows: a fixation cross ("+") appeared in the center of the screen for 800 ms followed by a 100 ms blank screen which was replaced by a stimulus word or nonword that remained on the computer screen for 500 ms. Participants could respond from the onset of the stimulus up to a maximum deadline of 2000 ms. Following participant response, a blank screen of random duration (either 500, 700 or 900 ms) was presented. Twelve practice trials preceded the experimental session, divided into 3 blocks (of approximately 200 trials each) separated by a 5-min break for resting and impedance checking. Along with the session, there were brief 10-sec breaks every 60 trials. To minimize subject-generated artifacts in the EEG signal during the presentation of the words/nonwords, participants were asked to refrain from blinking and eye movements from the onset of the fixation cross to the response. Each participant saw the words/nonwords in a different random order. The whole experimental session lasted approximately 35 min, excluding the EEG setup.

EEG recording and analyses. The electroencephalogram (EEG) was recorded from 29 Ag/AgCl electrodes mounted in an elastic cap (EASYCAP GmbH, Herrsching, Germany) according to the 10/20 system, which were referenced to the right mastoid and re-referenced off-line to the averaged signal from two electrodes placed on the left and right mastoids. Eye movements and blinks were monitored with electrodes placed on the right lower and upper orbital ridge and on the left and right external canthi. The EEG recording was amplified and band-pass filtered between 0.01 and 100 Hz with a sample rate of 250 Hz by a BrainAmp (Brain Products, GmbH, Gilching, Germany) amplifier. Impedances were kept below 5 KΩ. An off-line bandpass filter between

**Table 1**
Mean values of Psycholinguistic Characteristics of words across conditions (SDs in brackets) as provided in the B-Pal Spanish database (Davis and Perea, 2005).

| | # letters | LexEsp Freq[a]. | N[b] | imageability[c] | concreteness[c] | Mean log Bigram Freq | |
|---|---|---|---|---|---|---|---|
| | | | | | | Words | Nonwords |
| HF words | 5.5 | 154.4 (11.4) | 3.0 (2.8) | 5 (1.2) | 4.6 (1.05) | 2.7 (0.2) | 2.3 (.4) |
| LF words | 5.5 | 4.7 (1.2) | 3.2 (3.3) | 5.4 (0.9) | 5.5 (0.7) | 2.4 (0.3) | 2.3 (0.3) |

[a] Frequency per million.

[b] Orthographic Neighbors.

[c] Range: 1–7.

0.01 and 20 Hz was applied to the EEG signal. All single-trial waveforms (700 ms epochs with a 100 ms pre-stimulus baseline) were screened offline for amplifier blocking, drift, muscle artifact, eye movements, and blinks, through a semiautomatic data inspection procedure applied to the complete set of channels for each participant. Trials containing artifacts or/and incorrect responses were not included in the average ERPs. This led to an average rejection rate of 10.5% of all trials (4.2% due to artifact rejection; 6.3% due to incorrect responses). A minimum of 32 trials were included for each condition in the average ERP data from each participant (mean of the averaged number trials per condition across participants: M = 46, SD = 4.8). ERPs were averaged separately for each of the experimental conditions, each of the subjects, and each of the electrode sites.

As our main interest was on the earliest latency of the word-frequency effect (N170), we first identified the electrode sites with the maximum grand averaged N170 amplitude (125–225 ms) across all conditions. This led to the selection of two channel groups encompassing left occipital-temporal (T7, CP5, P3, P7 and O1) and the corresponding right occipital-temporal electrodes (T8, CP6, P4, P8 and O2). We performed onset latency analyses on the ERP data over these electrodes to assess the effects of word-frequency and its interaction with script on the N170 and further on. To correct for multiple comparisons, we used the Mass Univariate ERP toolbox (Groppe et al., 2011). To assess the interaction between word-frequency and script, running t-tests were applied at every sampling point (4 ms) for the 125–650 ms epoch on 2 x 2 level interactions that included Word-Frequency (High, Low) and either Script-easy (Printed, Easy handwritten) or Script-difficult (Printed, Difficult handwritten) by inputting the difference of the difference waves in the Mass Univariate ERP toolbox (see Gutierrez-Sigut et al., 2019 for a similar procedure). To address simple comparisons, we then performed the running t-tests between low- and high word-frequency conditions for each script.

## 3. Results

### 3.1. Behavioral results

In the latency analyses, we excluded the RTs shorter than 250 ms (0 observations in word trials; 1 observation in nonword trials) and the incorrect responses (6.3% of word trials and 7.5% of nonword trials). The mean RTs and accuracy rates per condition are displayed in Table 2. For the inferential analyses, we created generalized linear mixed effects in R with the lmer package (Bates et al., 2015). The fixed factors were Word-Frequency (encoded as $-0.5$ and 0.5 for the high- and low-frequency words, respectively) and Script (where the printed format was the reference for the easy handwritten and difficult handwritten script). We chose the most complex model that converged in terms of random effects intercepts and slopes. In the model based on latency data, we chose the Gamma distribution to avoid the interpretive issues of non-linear transformations in factorial designs. In the model based on the accuracy data, we chose the binomial distribution.

**Response time analyses.** Responses were faster for high-than for low-frequency words ($b = 55.514$, $SE = 5.421$, $t = 10.240$, $p < .001$). With respect to the printed vs. easy handwritten comparisons, responses were faster for printed than for easy handwritten words ($b = 26.172$, $SE = 4.407$, $t = 5.939$, $p < .001$). Importantly, the word-frequency effect was similar for the printed and the easy handwritten words (53 vs 55 ms; interaction: $b = -0.6298$, $SE = 4.103$, $t = -0.153$, $p = .878$). Regarding the printed vs. difficult handwritten comparison, responses were faster for printed than for difficult handwritten words ($b = 47.843$, $SE = 5.5518$, $t = 8.618$, $p < .001$). More importantly, the word-frequency effect was smaller for the printed than the difficult handwritten condition (53 vs 73 ms; interaction: $b = 23.286$, $SE = 8.5491$, $t = 2.724$, $p = .006$).

**Table 2**
Mean lexical decision times (in ms) and error rates (in percentage) for the word stimuli in the experiment.

| | Printed | Easy handwritten | Difficult Handwritten |
|---|---|---|---|
| High Frequency words | 579 (1.3) | 604 (2.4) | 624 (5.1) |
| Low Frequency words | 631 (6.7) | 658 (7.0) | 697 (15.5) |
| Word-frequency effect | 42 (5.4) | 54 (4.6) | 73 (10.4) |

Note: For the nonword stimuli, the mean RTs and error rates were: Printed: 699 ms (6.2%); Easy Handwritten: 747 ms (8.7%); Difficult Handwritten: 769 ms (6.3%).

**Accuracy analyses**. Responses were more accurate for high-than for low-frequency words ($b = -1.8254$, $SE = 0.3656$, $z = -4.994$, $p < .001$). With respect to the printed vs. easy handwritten comparisons, neither the printed vs. easy handwritten contrast nor its interaction with word-frequency approached significance (all $|zs| < 1.45$, all $ps > .14$). Regarding the printed vs. difficult handwritten comparisons, responses were more accurate for printed than for difficult handwritten words ($b = -1.5447$, $SE = 0.4352$, $z = -3.549$, $p < .001$). The interaction between script (printed vs. difficult handwritten comparison) and word-frequency went in the same direction as in the latency data, but it was not significant ($b = 0.4681$, $SE = 0.4080$, $z = 1.147$, $p = .251$).

Although informative, mean RTs in the lexical decision task represent the sum of different operations applied to sensory information, cognitive processing and motor execution. Unfortunately, they do not allow to address the specific stage(s) at which experimental effects might impact. Notably, the analyses of the RT distributions allow us to distinguish whether the locus of the effect taps onto encoding and/or evidence accumulation processes in lexical decision. To further examine the effect of word-frequency on word recognition times in each script, we conducted Vincentile analyses of the RT distributions (see Gomez and Perea, 2014, for a similar procedure). Specifically, we computed the .1, .3, 0.5, 0.7, and 0.9 quantiles for each participant and condition and then averaged the values for each quantile over the participants. In the framework of the diffusion model of lexical decision (Ratcliff et al., 2004), manipulations that tap the "quality of information" stage of the lexical decision (i.e., the word-frequency effect) task are expected to produce changes in the shape of the RT distributions: a greater word-frequency effect is expected to occur in the higher quantiles than at the leading edge of the RT distributions. Manipulations that tap on the early-encoding stage of stimuli, however, are expected to produce similar changes across quantiles (shift of the RT distributions). Firstly, Fig. 1A shows that there was a robust word-frequency advantage that increased in the higher quantiles for the printed (printed: 20, 38, 50, 71, and 97 ms at the 0.1, 0.3, 0.5, 0.7, and 0.9 quantiles, respectively), and for the easy handwritten condition (printed: 23, 34, 50, 66, and 84 ms at the 0.1, 0.3, 0.5, 0.7, and 0.9 quantiles, respectively), thus replicating earlier research (Perea et al., 2016). Critically, as shown in Fig. 1B for the difficult handwritten condition, the word-frequency effect not only changed across quantiles with a steeper slope, but it was also larger in the first quantiles (38, 57, 72, 92, and 111 at the 0.1, 0.3, 0.5, 0.7, and 0.9 quantiles, respectively). This finding suggests that word-frequency already taps onto an encoding stage of processing when the stimuli appear in the difficult handwritten script.

In sum, while these results suggest an additive pattern of script and word-frequency with regard to the easy handwritten manipulation, an interactive pattern between script and word-frequency was obtained in the difficult handwritten manipulation.

### 3.2. EEG results

Fig. 2 shows the ERP waves for the script and word-frequency comparisons in the occipital electrodes (O1, O2). The ERPs of all conditions showed an initial positive potential peaking around 100 ms, followed by a larger negativity ranging between 125 and 225 ms (N170). Next, a negativity peaking around 250 ms is followed by a larger negativity peaking around 400 ms (N400). Importantly, a word-

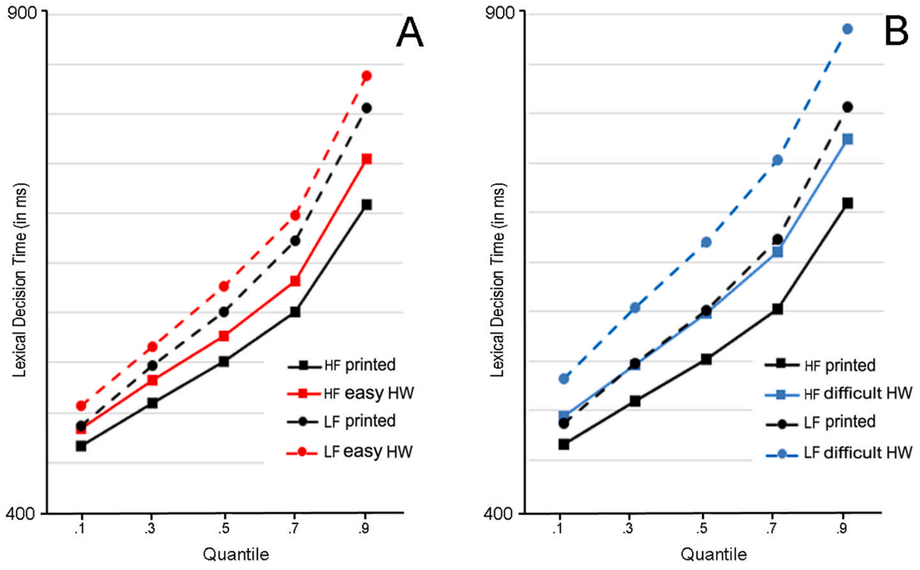


**Fig. 1.** Group RT distributions in the script and word-frequency manipulations in word stimuli. Script: printed, easy handwritten (easy HW), difficult handwritten (difficult HW); word-frequency: high frequency (HF), low frequency (LF). For clarity, the comparison of printed vs. easy handwritten script is shown in A, while the comparison of printed vs. difficult handwritten script is shown in B. Each point represents the average RT quantiles (.1, .3, 0.5, 0.7, and 0.9) in each condition. These values were obtained by computing the quantiles for each participant and subsequently averaging the obtained values for each quantile over the participants (see Vincent, 1912).

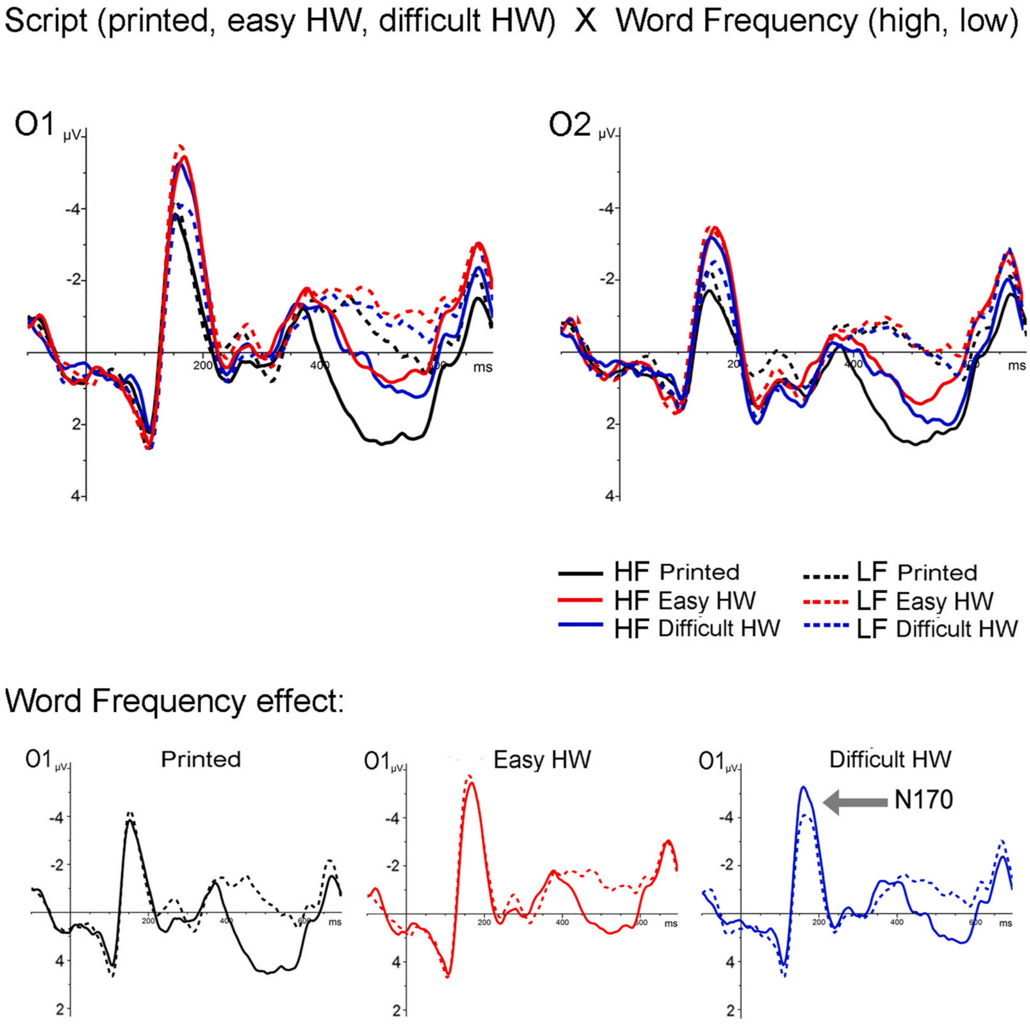


**Fig. 2.** Grand average event-related potentials to high-frequency (HF) and low-frequency (LF) words in the three script conditions: printed, easy handwritten (easy HW), difficult handwritten (difficult HW), in two occipital electrodes. For clarity, the lower panel depicts the word-frequency comparison (high-vs. low-frequency words) across each script.

frequency effect is present in the difficult handwritten condition, with larger N170 amplitudes for the high-compared to the low-frequency condition. Secondly, word-frequency effects are evident from approximately 350 ms in the printed script condition (larger negative amplitudes for the low compared to the high-frequency conditions). More specifically, the word-frequency effect was larger in the printed than in both easy and difficult handwritten conditions (see Figs. 2 and 3). This same pattern was also found in the LPC component (450–650 ms).

The *t*-test analyses (see Fig. 4) show robust differences regarding the time-course and size of the word-frequency effect across the three scripts. As shown in Fig. 4-panel A, the interaction between word-frequency and script (printed vs. easy handwritten) was only significant in the 400–470 ms time window. In contrast, Fig. 4-panel B shows that the interaction between word-frequency and script (printed vs. difficult handwritten) was significant in the N170 time window (145–160 ms), in the 224–270 ms interval, and in the 388–512 ms interval. Below, we describe the results of simple comparisons:

Word-Frequency and Script (printed vs. easy handwritten).

The interaction between Word-Frequency and Script (printed vs. easy handwritten) was only significant in the 400–470 ms time-window over electrodes P3 and P4. Although simple comparisons revealed that the printed and the easy handwritten conditions showed word-frequency effects in this interval (larger negative amplitudes were obtained for low-frequency words compared to the high-frequency words), word-frequency effects were significantly larger in the printed than in the easy handwritten condition, as shown in Fig. 3.

Word-Frequency and Script (printed vs. difficult handwritten).

Firstly, simple comparisons revealed word-frequency effects in the difficult handwritten condition (but not in the printed condition) over O1, O2, CP6 and P4 starting at around 150 ms post-stimuli (see the blue marks in Panel B: difficult handwritten script), with larger negative amplitudes for the high-frequency words condition compared to the low-frequency words condition.

Secondly, for the next significant interaction obtained in the

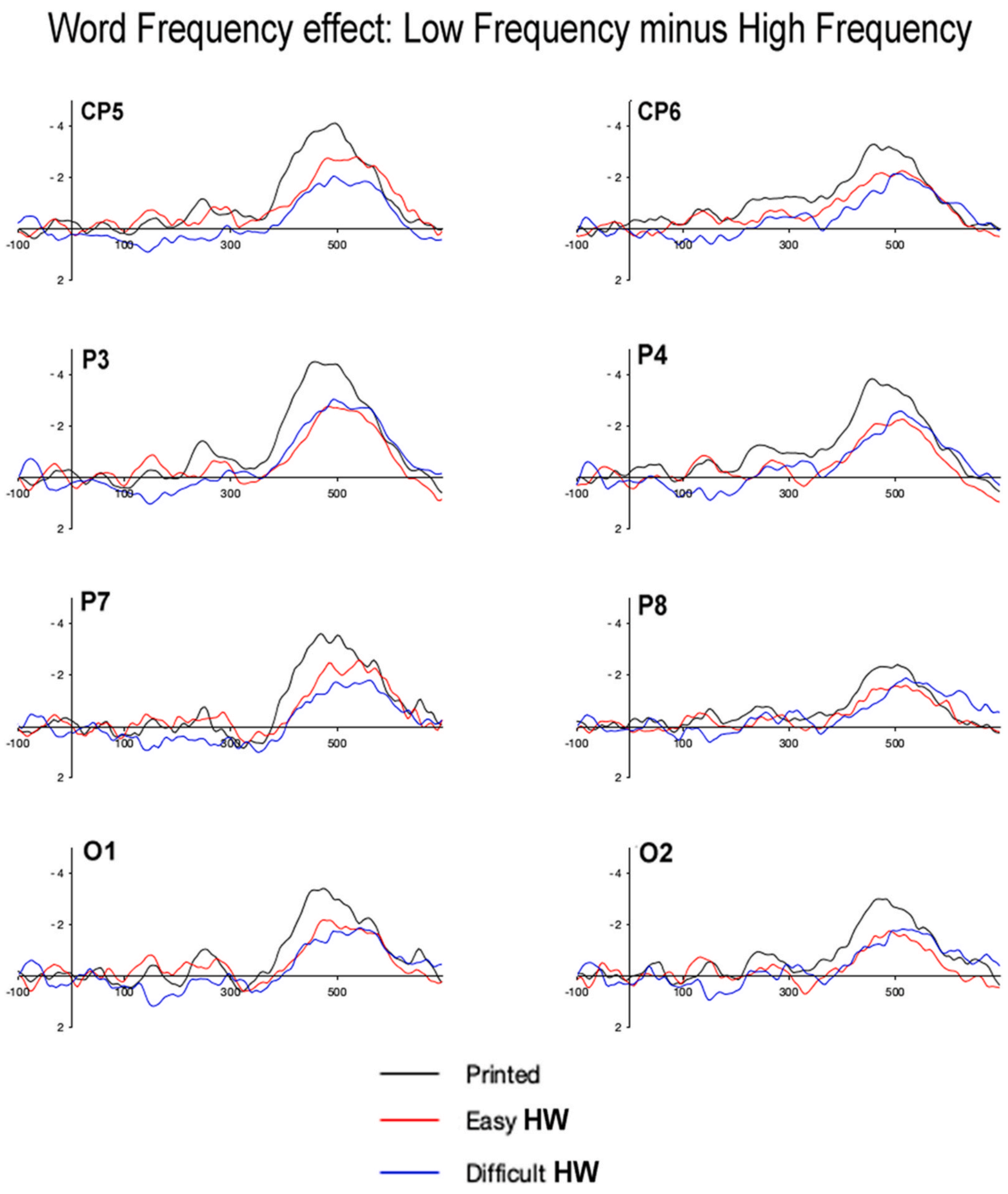


**Fig. 3.** Difference waveforms display the effect of Word-Frequency across each Script: Printed, Easy handwritten (Easy HW) and Difficult handwritten (Difficult HW) on 8 representative electrodes. The word-frequency effect is calculated as the difference in voltage amplitude between the ERP responses to low-versus high-frequency words.

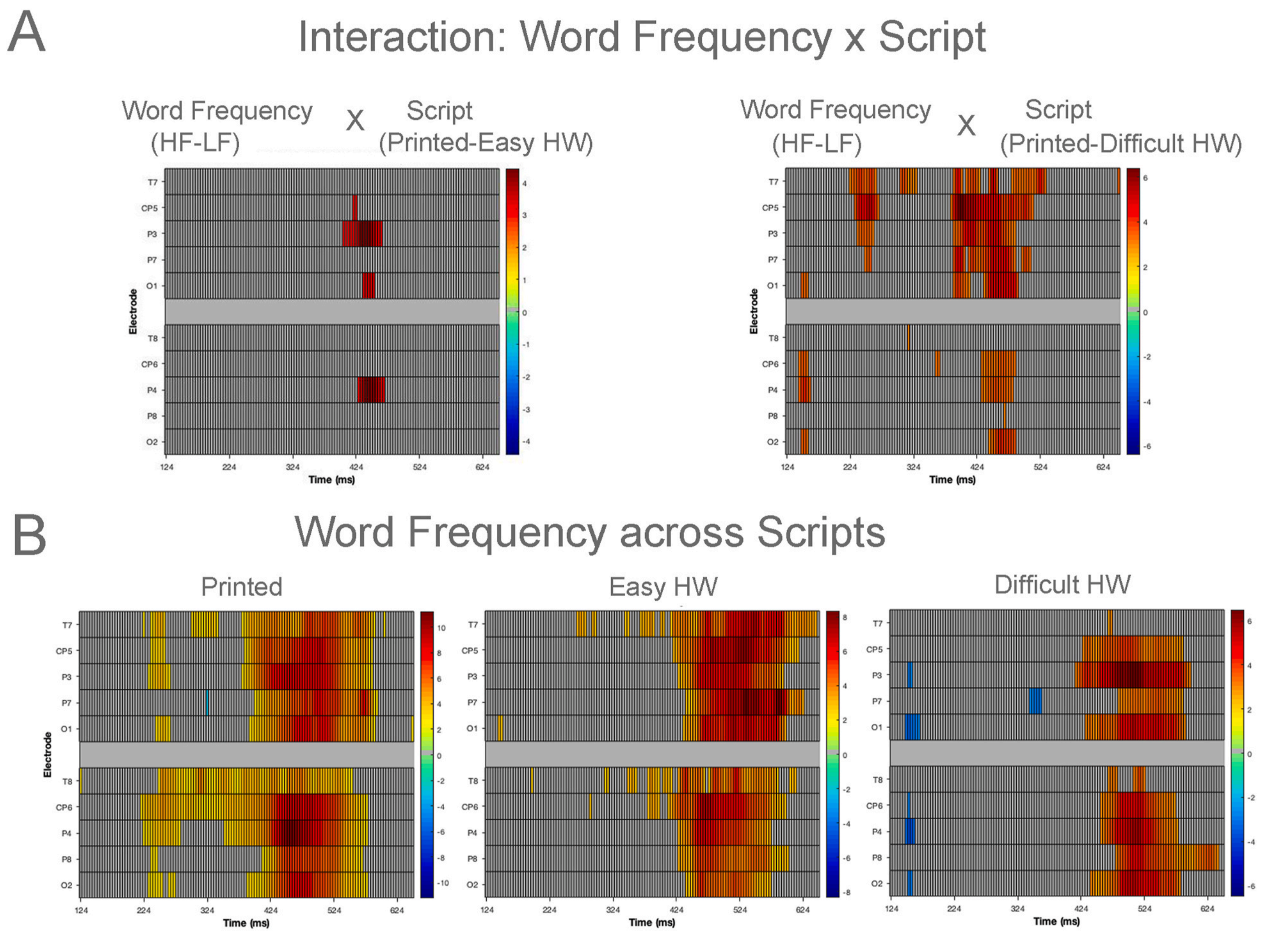


**Fig. 4.** Panel A displays the interaction between word-frequency and script by inputting the difference of the difference waves, either Script-easy: printed vs. easy handwritten (Easy HW), or Script-difficult: printed vs. difficult handwritten (Difficult HW), in the Mass Univariate ERP toolbox at the 10 electrodes analyzed between 125 and 650 ms post-stimuli. T values are color coded according to the legend shown at the right of each comparison. Panel B shows the results of the mass univariate statistical analysis of the time-course of the word-frequency effect for the printed, easy handwritten (Easy HW) and difficult handwritten (Difficult HW) script separately. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

224–270 interval, simple comparisons revealed that word-frequency effects in the printed script condition (but not in the difficult handwritten condition) were present over T7, CP5, P3 and P7, with low-frequency words eliciting larger negative amplitudes than high-frequency words (see Fig. 3).

Thirdly, for the significant interaction obtained in the 388–512 ms interval (N400), simple comparisons revealed that word-frequency effects were present in the printed script condition (but not in the difficult handwritten condition) over T7, CP5, P3 and O1 starting at 388 ms until 424 ms: larger negative amplitudes were obtained for low-frequency words compared to the high-frequency words. In the following interval (424–512 ms) the printed and the difficult handwritten conditions showed word-frequency effects. However, word-frequency effects were significantly larger in the printed than in the difficult handwritten condition, as shown in Fig. 3.

The differences regarding the time-course and size of word-frequency effects across scripts can be summarized as follows. First, the largest differences regarding word-frequency effects were observed in the printed vs difficult handwritten comparison, with the earliest effects of word-frequency in the difficult handwritten condition (N170). Second, while word-frequency effects in the printed condition were apparent in the 225–550 ms interval, the difficult handwritten condition showed delayed (starting around 424 ms) and reduced word-frequency effects. And third, the differences regarding word-frequency effects in the printed versus easy handwritten comparison revealed a reduced word-frequency effect for easy handwritten words in the 400–470 ms interval (footnote 1).

## 4. Discussion

Deciphering difficult handwritten words is an effortful process that might exceed the flexibility of automatic feature-to-letter and letter-to-word encoding. As a result, top-down processing may compensate for the handwritten words' natural physical ambiguity (see Barnhart and Goldinger, 2010; Manso De Zuniga et al., 1991; Perea et al., 2016, for behavioral evidence; see Qiao et al., 2012, for fMRI evidence). However, although informative, the results from the above-cited studies cannot ascertain whether top-down (lexical) information affects early or late processing stages due to the lack of the temporal resolution of their experimental methods. The present experiment directly addressed whether top-down information (as assessed by word-frequency) exerts a differential impact on the early encoding stages of visual word

---

[1] Following the suggestions of one Reviewer, in order to discard any bias on the results, we checked whether participants' own penmanship differed from the handwritten styles of the present stimuli. We went through the participants' filled-in forms and found a large variability among participants' handwriting with most of them showing a "cursive" (interconnected letters) handwriting style in lowercase. We acknowledge this observation opens the door for future research on whether letter disambiguation of handwritten stimuli could be modulated by perceptual or perceptual and motor experience.

recognition of handwritten word forms by analyzing the ERP signature of lexical-decision responses. As in prior experiments, we found a magnification of the word-frequency effect for difficult-to-read handwritten words on the word identification times (Barnhart & Goldinger, 2010, 2013, 2013; Manso De Zuniga et al., 1991; Perea et al., 2016). Instead, when the handwritten words were easy to read, the effects of surface form and word-frequency were additive, replicating the behavioral findings reported by Barnhart and Goldinger (2010) and Perea et al. (2016). More importantly, the ERP results showed an early word-frequency effect (N170 component) that was restricted to the difficult handwritten condition. Following this initial visual word processing stage, word-frequency effects were only sizeable for printed and easy handwritten words (225–550 ms). Instead, the word-frequency effects for the difficult handwritten condition were delayed (425–550 ms). Furthermore, after 400 ms post stimuli, the word-frequency effects in the easy and difficult handwritten formats were smaller than the word-frequency effects observed in the printed condition.

The finding of an early (N170) word-frequency effect restricted to the difficult handwritten stimuli favors interactive accounts of word recognition that assume that top-down lexical information percolates into early visual-perceptive stages of processing, at least when the stimuli are highly ambiguous (difficult handwritten). Additional evidence for this interpretation comes from the analyses of the RT distributions on the word-frequency effect. The RT distributions showed an already substantial word-frequency effect even in the lower quantiles of the difficult handwritten condition; this differs from the increasing word-frequency effect across quantiles in the printed condition and in the easy handwritten condition. The presence of very large word-frequency effects in the leading edge of the RT distributions (as was observed only in the difficult handwritten words) suggests an early locus of the word-frequency manipulation (e.g., an early encoding phase; see Gomez and Perea, 2020, for discussion). Altogether, the effects of word-frequency on the N170 amplitude for the difficult handwritten stimuli, along with the quantile analyses of the RT distributions, support the view that top-down lexical-semantic information plays a functional role during perceptual encoding of the most ambiguous stimuli.

In the context of visual word recognition, a number of different studies with different methodologies (e.g., see Lien et al., 2012; Vergara-Martínez et al., 2020, with words in isolation; see Chauncey et al., 2008, with masked priming) have reported early ERP effects of perceptual manipulations starting as early as 100 ms in terms of N/P150 or N170 components (footnote 2). These ERPs would reflect early perceptual/pre-lexical processes involved in the mapping of visual features onto location-specific letter representations. More specifically, the N170 component has been usually associated with perceptual expertise effects (Bentin et al., 1999; Maurer et al., 2005; Rossion et al., 2003), with larger negative amplitudes to word-like stimuli than to visual control stimuli such as symbol strings (Bentin et al., 1999; Brem et al., 2006; Maurer et al., 2005a, 2005b). The neuronal origin of the N170 has been related to left occipital-temporal regions (Allison et al., 1994) or "visual word form area" (VWFA) (Brem et al., 2006; Cohen and Dehaene, 2004; Dehaene et al., 2005), an area devoted to map perceptual features onto abstract information about visual words, allowing fast visual word recognition. Interestingly, the degree to which this early stage of processing is sensitive to top-down (lexical) influences has been a matter of debate (see Price and Devlin, 2011; see also Carreiras et al., 2014, for a review). Regarding the N170, some studies have found that words elicit a more negative N170 than pseudowords (e.g., Coch and Meade, 2016; Mahé et al., 2012; Maurer et al., 2005a). However, others (Bentin et al., 1999; Grossi and Coch, 2005; Maurer et al., 2005b) have not found a difference between words and pseudowords (nor between low and high-frequency words: Lien et al., 2012; Vergara-Martínez et al., 2020b) in the N170 amplitude. Importantly, the results of the present study did show more negative N170s for the high-frequency words than for the low-frequency words, but only when the stimuli corresponded to the difficult handwritten condition. Thus, our findings suggest that the visual word recognition system is permeable to top-down effects via word-frequency at very early stages of stimulus processing, at least when there is some degree of stimulus disruption (i.e., difficult handwritten stimuli). In other words, we claim that the difficult handwritten stimuli exceed the capacity of the ventral system to deal with perceptual invariance, thus requiring the additional intervention of top-down influences (via dorsal parietal regions: Qiao et al., 2010; Cohen et al., 2008)—this mechanism would facilitate the impact of lexical-semantic information down into perceptual processing stages. Note that this interpretation aligns well with previous findings showing that taxing the attentional system may lead to changes in the temporal dynamics of lexical access (see Vergara-Martínez et al., 2020a, for a discussion). For example, Hauk et al. (2009; see also Hauk et al., 2006) found early ERP components in the range of 100–200 ms to be sensitive to word-frequency with standard printed stimuli—critically, these studies used a very fast presentation rate (100 ms), which is a factor known to impact the nature of word processing. Indeed, Dambacher et al. (2012) found that the latency of word-frequency effect gradually decreases as the presentation rate of words increases.

The interpretation of the early word-frequency effects on the difficult handwritten condition in terms of larger attentional demands is consistent with previous findings of top-down effects on the N170 related to face processing under high cognitive or perceptual demands (see Aranda et al., 2010, for discussion). Note that, as a marker of perceptual expertise, and despite its relevance in the field of visual word recognition, most work on the characterization of the N170 derives from research on face processing (Eimer, 2011; Rossion and Jacques, 2011). The N170 is systematically larger in amplitude for pictures of faces than for other object categories (Bentin et al., 1996). A sound study in this field (Sreenivasan et al., 2009) revealed that perceptual demands –operationalized as the degree of discriminability of face stimuli-modulated the impact of attentional deployment on early visual processing stages, as shown by changes in the N170 amplitude. In their study, participants were presented with superimposed face-scene images for which face discriminability was manipulated parametrically. Participants' attention was directed to either face or scene information. Critically, attending to faces modulated the N170 amplitude only when faces were not highly discriminable (i.e., the magnitude of attention's influence on early perceptual processing was enhanced when the signal was of poor quality). Assuming an analogy between low-discriminable faces and difficult handwritten stimuli, the pattern of results obtained by Sreenivasan et al. (2009) is parallel to the present findings: When the signal was of poor quality (as is the case of difficult handwritten stimuli), word-frequency modulated the N170, which we interpret in terms of larger attentional deployment.

Besides the early effects, we also found an effect of word-frequency in later stages of processing: 225–550 ms in the printed and easy handwritten conditions and 425–550 ms in the difficult handwritten condition. The latency of word-frequency effects for the printed and easy handwritten conditions is consistent with previous studies which used the same paradigm, similar stimuli presentation rate, same language (Spanish), and similar word-frequency values (Vergara-Martínez et al., 2020b; see also Vergara-Martínez et al., 2020a, for a review on the latency of word-frequency effects). In line with previous interpretations (Barnhart & Goldinger, 2010, 2013, 2013; Becker and Killion, 1977; Manso De Zuniga et al., 1991; Perea et al., 2016) when the stimulus is

---

[2] As suggested by a Reviewer, we would like to note that the early difference between scripts at the N170 (see Fig. 2) is consistent with prior literature in the field (see Chauncey et al., 2008). The apparent difference between the printed and the handwritten conditions suggests an enhanced effort when mapping letter features onto abstract letter representations for the handwritten conditions. Notably, this pattern is different to the early ERP responses to printed words, where letter shape is preserved, thus providing a better matching with the prototypical letter representations.

(close to) pristine (printed words and easy handwritten), perceptual encoding operates in a feedforward fashion and the recruitment of top-down mechanisms of perception is delayed. The differences regarding the latency of the word-frequency effect in the difficult handwritten condition in the N400 window can be interpreted in terms of difficult handwritten script being less efficiently computed at a lexical-semantic level (see Grainger and Holcomb, 2009). This could be due to the fact that the quality of the lexical-semantic representations activated by difficult handwritten words is less stable than with printed (or easy handwritten) words. That is, the inherent ambiguity of handwritten stimuli would have induced a slower full-retrieval of lexical-semantic information, thus delaying the latency of word-frequency effects.

Finally, also of relevance here is the fact that in the latest stages of processing (450 ms), the largest effects of word-frequency were observed for the printed condition (as shown in Fig. 3). In the following lines, we consider two interpretations for this pattern of results. A plausible account for this large word-frequency effect reflected by a late positivity for the high-frequency compared to the low-frequency printed words could be found in the literature on recognition memory. Increased positive amplitudes have been obtained for words as a function of successive retrieval of memory representations (a differential trait of high-frequency words), which are also enhanced by orthographic knowledge (Bakker et al., 2015; Batternik and Neville, 2011; Bermudez-Margaretto et al., 2015; Liu and van Hell, 2020). Indeed, compared to the handwritten stimuli, the printed stimuli correspond to intact strings of letters which preserve normative features both at the intra-letter and the inter-letter levels within words. The consistent orthographic representations could have empowered the recognition of high-frequency words (in the printed format).

A second non-exclusive explanation of the enhanced positivity for the printed version of high-frequency words is related to the saliency of printed stimuli in the context of the present experiment. Due to the design of the experiment, the distribution of the standard vs non-standard scripts was asymmetrical: only one third corresponded to printed/standard stimuli. As suggested by Qiao et al. (2010), a larger exposure to non-standard stimuli may have induced top-down conscious adaptation strategies in subjects' expectancies (Kiefer, 2007; see also Strijkers et al., 2015 for discussion). Accordingly, participants' strategies of devoting more attention due to the global unfamiliarity of the experimental stimuli set might have led to enhanced post-lexical recognition responses to the stimuli which match by far (printed versions of high-frequency words) the representations stored in long term memory. Future studies may explicitly investigate the interrelations between the distribution of stimuli across experimental conditions (e.g., blocked vs. mixed stimuli list) and the dynamic adaptation of attentional strategies during visual word recognition.

In summary, the present study is the first to assess the electrophysiological brain signature of top-down recruitment during the processing of handwritten words. Previous research has already outlined the larger involvement of top-down information in order to disambiguate degraded stimuli as shown by larger effects of high-level variables (e.g., word-frequency; Barnhart and Goldinger, 2010; Perea et al., 2016) in behavioral measures. Here, we have tracked down the cognitive processes that underlie handwritten word reading to address the timeline of the alleged top-down lexical feedback. Our results revealed a word-frequency effect at an early perceptual processing stage (N170), but only for the difficult handwritten words. These findings extend previous findings on the implication of top-down attentional networks when the bottom-up signal is smeary (Qiao et al., 2010), as it does not only impact very low-level decoding stages but it also enhances the influence of lexical (word-frequency) information down into perceptual stages. Thus, our findings strongly suggest that recognizing difficult handwritten words induces an enhanced attentional deployment on visual word processing, allowing for an early effect of top-down information.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuropsychologia.2021.107924.

## Credit author statement

Marta Vergara-Martínez: Conceptualization, Formal analysis, Writing, Investigation. Eva Gutierrez-Sigut; Conceptualization, Formal analysis, Writing. Manuel Perea: Conceptualization, Formal analysis, Writing. Cristina Gil-López: Conceptualization, Formal analysis, Investigation. Manuel Carreiras: Conceptualization, Resources, Writing.

## References

Allison, T., McCarthy, G., Nobre, A., Puce, A., Belger, A., 1994. Human extrastriate visual cortex and the perception of faces, words, numbers, and colors. Cerebr. Cortex 4 (5), 544–554. https://doi.org/10.1093/cercor/4.5.544.

Aranda, C., Madrid, E., Tudela, P., Ruz, M., 2010. Category expectations: a differential modulation of the N170 potential for faces and words. Neuropsychologia 48 (14), 4038–4045. https://doi.org/10.1016/j.neuropsychologia.2010.10.002.

Bakker, I., Takashima, A., vanHell, J.G., Janzen, G., McQueen, J.M., 2015. Tracking lexical consolidation with ERPs: lexical and semantic-priming effects on N400 and LPC responses to newly-learned words. Neuropsychologia 79, 33–41. https://doi.org/10.1016/j.neuropsychologia.2015.10.020.

Barnhart, A.S., Goldinger, S.D., 2010. Interpreting chicken-scratch: lexical access for handwritten words. J. Exp. Psychol. Hum. Percept. Perform. 36, 906–923. https://doi.org/10.1037/a0019258.

Barnhart, A.S., Goldinger, S.D., 2013. Rotation reveals the importance of configural cues in handwritten word perception. Psychonomic Bull. Rev. 20, 1319–1326. https://doi.org/10.3758/s13423-013-0435-y.

Bates, D., Maechler, M., Bolker, B., Walker, S., 2015. Fitting linear mixed-effects models using lme4. J. Stat. Software 67, 1–48. https://doi.org/10.18637/jss.v067.i01.

Batterink, L., Neville, H., 2011. Implicit and explicit mechanisms of word learning in a narrative context: an event-related potential study. J. Cognit. Neurosci. 23 (11), 3181–3196. https://doi.org/10.1162/jocn_a_00013.

Becker, C.A., Killion, T., 1977. Interaction of visual and cognitive effects in word recognition. J. Exp. Psychol. Hum. Percept. Perform. 3, 389–401. https://doi.org/10.1037/0096-1523.3.3.389.

Bentin, S., McCarthy, G., Perez, E., Puce, A., Allison, T., 1996. Electrophysiological studies of face perception in humans. J. Cognit. Neurosci. 8, 551–565. https://doi.org/10.1162/jocn.1996.8.6.551.

Bentin, S., Mouchetant-Rostaing, Y., Giard, M.H., Echallier, J.F., Pernier, J., 1999. ERP manifestations of processing printed words at different psycholinguistic levels: time course and scalp distribution. J. Cognit. Neurosci. 11, 35–60. https://doi.org/10.1162/089892999563373.

Bermudez-Margaretto, B., Beltrán, D., Domínguez, A., Cuetos, F., 2015. Repeated exposure to "meaningless" pseudowords modulates LPC, but not N (FN) 400. Brain Topogr. 28 (6), 838–851. https://doi.org/10.1007/s10548-014-0403-5.

Brem, S., Bucher, K., Halder, P., Summers, P., Dietrich, T., Martin, E., Brandeis, D., 2006. Evidence for developmental changes in the visual word processing network beyond adolescence. Neuroimage 29 (3), 822–837. https://doi.org/10.1016/j.neuroimage.2005.09.023.

Carreiras, M., Armstrong, B.C., Perea, M., Frost, R., 2014. The what, when, where, and how of visual word recognition. Trends Cognit. Sci. 18, 90–98. https://doi.org/10.1016/j.tics.2013.11.005.

Chauncey, K., Holcomb, P.J., Grainger, J., 2008. Effects of stimulus font and size on masked repetition priming: an event-related potentials (ERP) investigation. Lang. Cognit. Process. 23 (1), 183–200. https://doi.org/10.1080/01690960701579839.

Coch, D., Meade, G., 2016. N1 and P2 to words and wordlike stimuli in late elementary school children and adults. Psychophysiology 53 (2), 115–128. https://doi.org/10.1111/psyp.12567.

Cohen, L., Dehaene, S., 2004. Specialization within the ventral stream: the case for the visual word form area. Neuroimage 22, 466–476. https://doi.org/10.1016/j.neuroimage.2003.12.049.

Cohen, L., Dehaene, S., Vinckier, F., Jobert, A., Montavont, A., 2008. Reading normal and degraded words: contribution of the dorsal and ventral visual pathways. Neuroimage 40 (1), 353–366. https://doi.org/10.1016/j.neuroimage.2007.11.036.

Davis, C.J., Perea, M., 2005. BuscaPalabras: a program for deriving orthographic and phonological neighborhood statistics and other psycholinguistic indices in Spanish. Behav. Res. Methods 37 (4), 665–671. https://doi.org/10.3758/BF03192738.

Dambacher, M., Dimigen, O., Braun, M., Wille, K., Jacobs, A.M., Kliegl, R., 2012. Stimulus onset asynchrony and the timeline of word recognition: event-related potentials during sentence reading. Neuropsychologia 50 (8), 1852–1870. https://doi.org/10.1016/j.neuropsychologia.2012.04.011.

Dehaene, S., Cohen, L., Sigman, M., Vinckier, F., 2005. The neural code for written words: a proposal. Trends Cognit. Sci. 9, 335–341. https://doi.org/10.1016/j.tics.2005.05.004.

Dehaene, S., Le Clec'H, G., Poline, J.B., Le Bihan, D., Cohen, L., 2002. The visual word form area: a prelexical representation of visual words in the fusiform gyrus. Neuroreport 13 (3), 321–325. https://doi.org/10.1097/00001756-200203040-00015.

Dehaene, S., Naccache, L., Cohen, L., Le Bihan, D., Mangin, J.-F., Poline, J.-B., Rivière, D., 2001. Cerebral mechanisms of word masking and unconscious repetition priming. Nat. Neurosci. 4, 752–758. https://doi.org/10.1038/89551.

Dufau, S., Grainger, J., Midgley, K.J., Holcomb, P.J., 2015. A thousand words are worth a picture: snapshots of printed-word processing in an event-related potential megastudy. Psychol. Sci. 26 (12), 1887–1897. https://doi.org/10.1177/0956797615603934.

Eimer, M., 2011. The face-sensitive N170 component of the event-related brain potential. In: Calder, A.J., Rhodes, G., Johnson, M., Haxby, J. (Eds.), Oxford Handbook of Face Perception. Oxford University Press, pp. 287–306.

Gomez, P., Perea, M., 2014. Decomposing encoding and decisional components in visual-word recognition: a diffusion model analysis. Q. J. Exp. Psychol. 67, 2455–2466. https://doi.org/10.1080/17470218.2014.937447.

Grainger, J., 2018. Orthographic processing: a 'mid-level' vision of reading. Q. J. Exp. Psychol. 71 (2), 335–359. https://doi.org/10.1080/17470218.2017.1314515.

Grainger, J., Dufau, S., 2012. The front-end of visual word recognition. In: Adelman, J.S. (Ed.), Visual Word Recognition Vol. 1: Models and Methods, Orthography and Phonology. Psychology Press, pp. 159–184.

Grainger, J., Holcomb, P.J., 2009. Watching the word go by: on the time-course of component processes in visual word recognition. Language and Linguistic Compass 3, 128–156. https://doi.org/10.1111/j.1749-818X.2008.00121.x.

Groppe, D.M., Urbach, T.P., Kutas, M., 2011. Mass univariate analysis of event related brain potentials/fields I: a critical tutorial review. Psychophysiology 48 (12), 1711–1725. https://doi.org/10.1111/j.1469-8986.2011.01273.x.

Grossi, G., Coch, D., 2005. Automatic word form processing in masked priming: an ERP study. Psychophysiology 42, 343–355. https://doi.org/10.1111/j.1469-8986.2005.00286.x.

Gutierrez-Sigut, E., Vergara-Martínez, M., Perea, M., 2019. Deaf readers benefit from lexical feedback during orthographic processing. Sci. Rep. 9 (1), 1–13. https://doi.org/10.1038/s41598-019-48702-3.

Hauk, O., Patterson, K., Woollams, A., Watling, L., Pulvermüller, F., Rogers, T.T., 2006. [Q:] When would you prefer a SOSSAGE to a SAUSAGE? [A:] At about 100 msec. ERP correlates of orthographic typicality and lexicality in written word recognition. J. Cognit. Neurosci. 18 (5), 818–832. https://doi.org/10.1162/jocn.2006.18.5.818.

Hauk, O., Pulvermüller, F., Ford, M., Marslen-Wilson, W.D., Davis, M.H., 2009. Can I have a quick word? Early electrophysiological manifestations of psycholinguistic processes revealed by event-related regression analysis of the EEG. Biol. Psychol. 80 (1), 64–74. https://doi.org/10.1016/j.biopsycho.2008.04.015.

Kiefer, M., 2007. Top-down modulation of unconscious 'automatic' processes: a gating framework. Adv. Cognit. Psychol. 3 (1–2), 289–306. https://doi.org/10.2478/v10053-008-0032-2.

Kronbichler, M., Hutzler, F., Wimmer, H., Mair, A., Staffen, W., Ladurner, G., 2004. The visual word form area and the frequency with which words are encountered: evidence from a parametric fMRI study. Neuroimage 21 (3), 946–953. https://doi.org/10.2478/v10053-008-0032-2.

Lien, M.C., Allen, P.A., Crawford, C., 2012. Electrophysiological evidence of different loci for case-mixing and word frequency effects in visual word recognition. Psychonomic Bull. Rev. 19 (4), 677–684. https://doi.org/10.3758/s13423-012-0251-9.

Liu, Y., van Hell, J.G., 2020. Learning novel word meanings: an ERP study on lexical consolidation in monolingual, inexperienced foreign language learners. Lang. Learn. 70 (S2), 45–74. https://doi.org/10.1111/lang.12403.

Luck, S.J., 1998. Sources of dual-task interference: evidence from human electrophysiology. Psychol. Sci. 9, 223–227. https://doi.org/10.1111/1467-9280.00043.

Mahé, G., Bonnefond, A., Gavens, N., Dufour, A., Doignon-Camus, N., 2012. Impaired visual expertise for print in French adults with dyslexia as shown by N170 tuning. Neuropsychologia 50, 3200–3206. https://doi.org/10.1016/j.neuropsychologia.2012.10.013.

Manso De Zuniga, C., Humphreys, G.W., Evett, L.J., 1991. Additive and interactive effects of repetition, degradation, and word frequency in the reading of handwriting. In: Besner, D., Humphreys, G.W. (Eds.), Basic Processes in Reading: Visual Word Recognition. Erlbaum, pp. 10–33.

Maurer, U., Brandeis, D., McCandliss, B.D., 2005a. Fast, visual specialization for reading in English revealed by the topography of the N170 ERP response. Behav. Brain Funct. 1, 1–13. https://doi.org/10.1186/1744-9081-1-13.

Maurer, U., Brem, S., Bucher, K., Brandeis, D., 2005b. Emerging neurophysiological specialization for letter strings. J. Cognit. Neurosci. 17, 1532–1552. https://doi.org/10.1162/089892905774597218.

Mayall, K., Humphreys, G.W., Mechelli, A., Olson, A., Price, C.J., 2001. The effects of case mixing on word recognition: evidence from a PET study. J. Cognit. Neurosci. 13, 844–853. https://doi.org/10.1162/08989290152541494.

Oldfield, R.C., 1971. The assessment and analysis of handedness: the Edinburgh inventory. Neuropsychologia 9 (1), 97–113. https://doi.org/10.1016/0028-3932(71)90067-4.

Pammer, K., Hansen, P., Holliday, I., Cornelissen, P., 2006. Attentional shifting and the role of the dorsal pathway in visual word recognition. Neuropsychologia 44 (14), 2926–2936. https://doi.org/10.1016/j.neuropsychologia.2006.06.028.

Perea, M., Gil-López, C., Beléndez, V., Carreiras, M., 2016. Do handwritten words magnify lexical effects in visual word recognition? Q. J. Exp. Psychol. 69 (8), 1631–1647. https://doi.org/10.1080/17470218.2015.1091016.

Price, C.J., Devlin, J.T., 2011. The interactive account of ventral occipitotemporal contributions to reading. Trends Cognit. Sci. 15 (6), 246–253. https://doi.org/10.1016/j.tics.2011.04.001.

Qiao, E., Vinckier, F., Szwed, M., Naccache, L., Valabrègue, R., Dehaene, S., Cohen, L., 2010. Unconsciously deciphering handwriting: subliminal invariance for handwritten words in the visual word form area. Neuroimage 49 (2), 1786–1799. https://doi.org/10.1016/j.neuroimage.2009.09.034.

Ratcliff, R., Gomez, P., McKoon, G., 2004. A diffusion model account of the lexical decision task. Psychol. Rev. 111, 159–182. https://doi.org/10.1037/0033-295X.111.1.159.

Rossion, B., Jacques, C., 2011. The N170: understanding the time course of face perception in the human brain. In: Luck, S.J., Kappenman, E.S. (Eds.), The Oxford Handbook of Event-Related Potential Components. Oxford University Press, pp. 115–141.

Rossion, B., Joyce, C.A., Cottrell, G.W., Tarr, M.J., 2003. Early lateralization and orientation tuning for face, word, and object processing in the visual cortex. Neuroimage 20, 1609–1624. https://doi.org/10.1016/j.neuroimage.2003.07.010.

Sreenivasan, K.K., Goldstein, J.M., Lustig, A.G., Rivas, L.R., Jha, A.P., 2009. Attention to faces modulates early face processing during low but not high face discriminability. Atten. Percept. Psychophys. 71 (4), 837–846. https://doi.org/10.3758/APP.71.4.837.

Strijkers, K., Bertrand, D., Grainger, J., 2015. Seeing the same words differently: the time course of automaticity and top–down intention in reading. J. Cognit. Neurosci. 27, 1542–1551. https://doi.org/10.1162/jocn_a_00797.

Vergara-Martínez, M., Duñabeitia, J.A., Laka, I., Carreiras, M., 2009. ERP correlates of inhibitory and facilitative effects of constituent frequency in compound word reading. Brain Res. 1257, 53–64. https://doi.org/10.1016/j.brainres.2008.12.040.

Vergara-Martínez, M., Perea, M., Gómez, P., Swaab, T.Y., 2013. ERP correlates of letter identity and letter position are modulated by lexical frequency. Brain Lang. 125 (1), 11–27. https://doi.org/10.1016/j.bandl.2012.12.009.

Vergara-Martínez, M., Gomez, P., Perea, M., 2020a. Should I stay or should I go? An ERP analysis of two-choice versus go/no-go response procedures in lexical decision. J. Exp. Psychol. Learn. Mem. Cognit. 46, 2034–2048. https://doi.org/10.1037/xlm0000942.

Vergara-Martínez, M., Perea, M., Leone-Fernandez, B., 2020b. The time course of the lowercase advantage in visual word recognition: an ERP investigation. Neuropsychologia 146, 107556. https://doi.org/10.1016/j.neuropsychologia.2020.107556.

Vincent, S.B., 1912. The function of vibrissae in the behavior of the white rat. Behavioral Monographs 1. Whole No. 5.

Vinckier, F., Naccache, L., Papeix, C., Forget, J., Hahn-Barma, V., Dehaene, S., Cohen, L., 2006. What" and "where" in word reading: ventral coding of written words revealed by parietal atrophy. J. Cognit. Neurosci. 18 (12), 1998–2012. https://doi.org/10.1162/jocn.2006.18.12.1998.

Whaley, M.L., Kadipasaoglu, C.M., Cox, S.J., Tandon, N., 2016. Modulation of orthographic decoding by frontal cortex. J. Neurosci. 36 (4), 1173–1184. https://doi.org/10.1523/jneurosci.2985-15.2016.