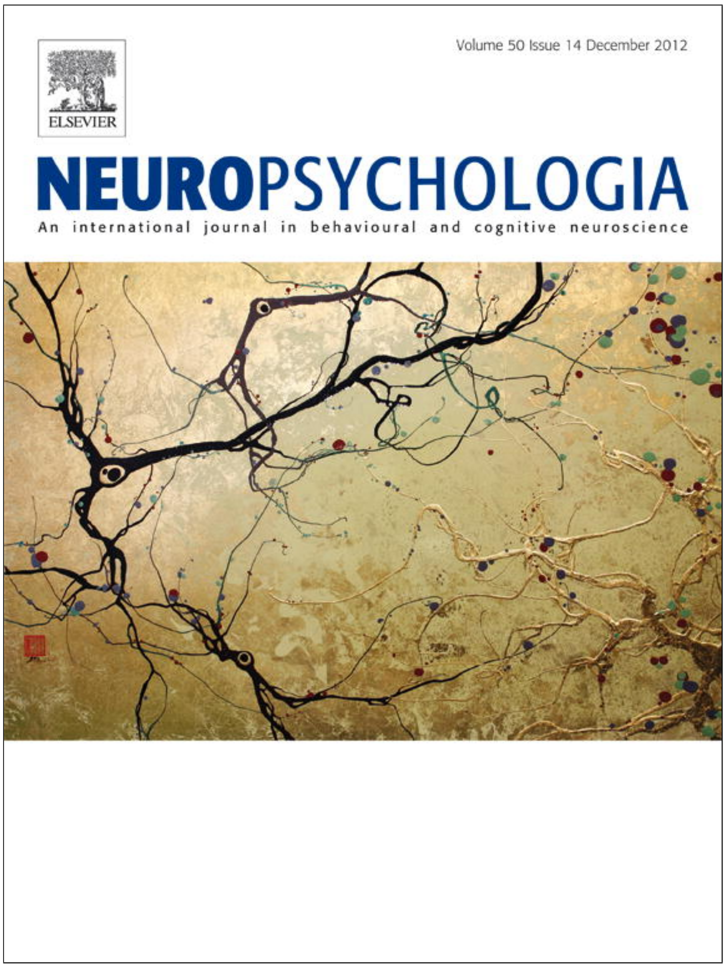
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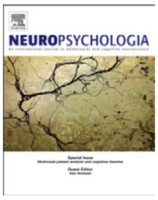

Electrophysiological markers of syllable frequency during written word recognition in French

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ABSTRACT

Several empirical lines of investigation support the idea that syllable-sized units may be involved in visual word recognition processes. In this perspective, the present study aimed at investigating further the nature of the process that causes syllabic effects in reading. To do so, the syllable frequency effect was investigated in French using event related potentials while participants performed a lexical decision task (Experiment 1). Consistent with previous studies, manipulating the frequency of the first syllable in words and pseudowords yielded two temporally distinct effects. Compared to items with a first syllable of low frequency, items with a syllable of high frequency elicited a weaker P200 component, reflecting early sub-lexical facilitation, and a larger N400 component, supposed to ensue from competition between syllabic neighbours. To examine which factors determine the strength of interference during lexical access, regression analyses were conducted on the late temporal window potentials. The inhibitory syllable frequency effect was best predicted by leader strength, that is, the frequency ratio between the most frequent syllabic neighbour and the others. When this variable was directly manipulated while controlling for syllable frequency and number of higher frequency syllabic neighbours (Experiment 2), electrophysiological data confirmed the impact of leader strength. The results are discussed in the context of interactive activation-based models augmented with syllabic representations.

1. Introduction

Since the earliest attempts to analyze reading behaviour, at the dawn of experimental psychology, it has been largely accepted that visual word recognition processes must involve functional units larger in size than the single letter, and smaller than the word. Yet, despite extensive investigation, the exact nature of sublexical reading units and the mechanisms through which their perception influences reading still escapes full understanding. Several empirical lines of investigation support the idea that syllable-sized letter strings might be important, and one major source of evidence comes from the finding that printed words that begin with a frequent syllable tend to be harder to identify than those with a less frequent first syllable, a phenomenon known as the syllable frequency effect. The present study aimed at investigating further the nature of the process that causes the syllable frequency effect, by examining the time-course of processing through event related potentials (ERPs) collected during the lexical decision task.

In a seminal study, Carreiras, Alvarez, and de Vega (1993) compared recognition latencies for words with initial syllables of high frequency to those for words with syllables of low frequency. An inhibitory effect was found, high syllable-frequency (HSF) words being processed more slowly than low syllable-frequency (LSF) words. Since that first report, the effect has been replicated in several languages: Spanish (Alvarez, Carreiras, & Taft, 2001; Conrad, Carreiras, & Jacobs, 2008; Conrad, Carreiras, Tamm, & Jacobs, 2009), French (Chetail & Mathey, 2009; Conrad, Grainger, & Jacobs, 2007; see also Mathey & Zagar, 2002) and German (Conrad & Jacobs, 2004; Hutzler, Conrad, & Jacobs, 2005; Stenneken, Conrad, & Jacobs, 2007). At a theoretical level, the effect has been accounted for in terms of competition among candidate words sharing the initial syllable (Carreiras et al., 1993). The more frequent a syllable, the more words share it. This pool of words sharing a given syllable at the same position is referred to as the syllabic neighbourhood, a notion forged by analogy with orthographic neighbourhood (Coltheart, Davelaar, Jonasson, & Besner, 1977). During lexical access, neighbours are

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activated and compete with the target, thus delaying its processing. Carreiras et al. (1993) argued that competition would be stronger when there are numerous syllabic neighbours, that is, when the target contains a high-frequency syllable rather than a low-frequency one.

At a computational level, one account of the syllable frequency effect, based on the interactive activation model (McClelland & Rumelhart, 1981), consists in including a syllabic representation level between the letter level and the word level (see Conrad et al., 2009; Mathey, Zagar, Doignon, & Seigneuric, 2006). In such a framework, syllabic effects ensue from two complementary processes, bottom-up facilitation from syllable to word units, and lexical inhibition. First, when a letter string is presented, letter units activate syllable units, and excitation reaches the word level via direct facilitatory connections between the syllable and the word level. If the resting level of the syllable units varies as a function of syllable frequency, the activation of units corresponding to high frequency syllables will rise faster and hence, facilitate lexical activation. Alternatively, if top-down connections from word to syllable units are implemented, the activation of units corresponding to high-frequency syllables will be enhanced by the lexical reverberation. Second, syllable activation spreads to all syllabic neighbours at the lexical level. Because each lexical unit has inhibitory connections to all other lexical units, the competition across lexical candidates increases as a function of the number of syllabic neighbours. In a recent paper, Conrad, Tamm, Carreiras, and Jacobs (2010) devised such a model and successfully reproduced the inhibitory effects obtained in the Spanish language, and further showed early facilitation on the activation of syllable units when varying resting levels were used.

One limit of behavioural studies on the syllable frequency effect is that they do not enable to separate the two putative components of syllable frequency effects – early sub-lexical facilitation and late lexical competition –, given that reaction times capture only the total duration of the perceptual process. Furthermore, with reaction times, the facilitatory and inhibitory effects might cancel each other, leading to an underestimation of the influence of syllable frequency. One way to bypass such limits is to use tasks that enable to assess syllable frequency effects before lexical competition arises (Stenneken et al., 2007). Another solution is to grasp the precise time course of the two effects by means of neurophysiological techniques such as ERPs. Accordingly, a temporal dissociation of the two components of the syllable frequency effect was found both in Spanish (Barber, Vergara, & Carreiras, 2004) and in German (Hutzler, Bergmann, Conrad, Kronbichler, Stenneken, & Jacobs, 2004). In an early temporal window corresponding to the P200 component, LSF words elicited a larger positivity than HSF words, reflecting early facilitation. This pre-lexical effect was followed by a later effect in the N400 temporal window where HSF words elicited a larger negativity than LSF words, presumably corresponding to the competition phenomenon. Interestingly, several other lexical variables affect the N400 component. High-frequency words elicit a smaller N400 compared to low-frequency words and similarly words elicit a smaller N400 compared to pseudowords (see Bentin, McCarthy, & Wood, 1985). Accordingly, the syllable-frequency effect went in the opposite direction to the effect of both lexical frequency (Barber et al., 2004) and lexicality (Hutzler et al., 2004), consistent with behavioural findings.

In French however, the only ERP study manipulating syllable frequency produced non-conclusive results. Goslin, Grainger, and Holcomb (2006) ran two experiments using a go/no-go semantic categorization task. In the first experiment in which they manipulated consonant-vowel syllable frequency, they obtained no significant effect in the 150–300 ms window. Syllable frequency effects were observed in the 300–600 ms temporal range, but HSF words produced more positive potentials than LSF words, a pattern which would normally be interpreted as facilitatory rather than inhibitory in the context of the N400 component. The first aim of the present study was therefore to assess whether ERP patterns during processing of French words confirm the dissociation of early facilitation and later interference with HSF words, using the same task (lexical decision) and design as in the Spanish and German studies.

The second aim was to examine in more detail which factor determines the interference effect. The hypothesis of lexical competition between syllabic neighbours is crucial to account for inhibitory syllable frequency effects. Similarly to what has been proposed for orthographic neighbourhood (e.g., Grainger, O'Regan, Jacobs, & Segui, 1989). Perea and Carreiras (1998) speculated that the competition between syllabic neighbours would be driven by a subset of neighbours, namely those of higher lexical frequency than the target word. Lexical units of higher frequency are assumed to enjoy an activation advantage, implemented in interactive activation-based models as a higher resting level. Combined with word-to-word inhibitory connections, this activation advantage would slow or even block the gradual activation of lower-frequency competitors, a phenomenon known as hysteresis (see e.g., McClelland & Rumelhart, 1988). Hence, inhibitory effects of syllabic neighbourhood would presumably depend on the presence and number of higher frequency syllabic neighbours (HFSNs). Indeed, several authors reported that in the lexical decision task, words with many HFSNs were recognised more slowly than words with fewer HFSNs (e.g., Mathey & Zagar, 2002; Perea & Carreiras, 1998). In addition, Perea and Carreiras (1998) showed in post-hoc regression analyses that the number of HFSNs was a better predictor of the inhibitory effect than the total number of syllabic neighbours. Yet, the evidence is not totally consistent. Conrad et al. (2008) reported an inhibitory effect of syllable frequency while both the number of syllabic neighbours and the number of HFSNs were controlled for, thus calling into question the hypothesis that the number of HFSNs is the crucial variable triggering the interference effect. Therefore, whereas the existence of inhibitory syllable frequency effects is clearly demonstrated, the exact nature of the factor which drives them still needs clarification.

The first experiment investigated the syllable frequency effect in French using ERPs. The effect was examined both in words and in pseudowords to ensure that the syllable frequency effect in the N400 temporal window was opposite to the lexicality effect. In addition, to disentangle the respective weight of the different syllabic variables during lexical access (e.g., syllable frequency, number of HFSNs), we conducted regression analyses between syllabic variables and electrophysiological activity.

2. Experiment 1

2.1. Method

2.1.1. Participants

Nineteen healthy native French speakers took part in the experiment. All were right-handed, had normal or corrected to normal vision, and were paid for their participation.

2.1.2. Materials

To manipulate syllable frequency, 80 pairs of bisyllabic words with a consonant-vowel first syllable were selected in the French lexical database Lexique (New, Pallier, Brysbaert, & Ferrand, 2004) according to the frequency of their first phonological syllable. Syllable frequencies were drawn from the InfoSyll database (Chetail & Mathey, 2010). In each pair, one of the words had a first syllable of high frequency (HSF word) while the other had a first syllable of low frequency (LSF word). The HSF and LSF words were matched for lexical frequency, number of letters, orthographic neighbourhood, frequency of the second syllable, as well as initial and summed bigram frequency (see Table 1). For the purpose of the lexical decision task, 80 pairs of orthographically legal and pronounceable pseudowords were added. They were created by randomly combining the first syllables of the words with fresh second syllables attested in the French orthography. One half of the pseudowords had therefore a first syllable of high frequency, while the other half had a first syllable of low frequency. Paired pseudowords were matched on the same variables as the words.

2.1.3. Procedure

Participants were seated in a comfortable armchair with a headrest in a sound-attenuated room. They were presented with stimuli printed in white against a black background on a computer screen at a distance of one meter. They had to decide as quickly and as accurately as possible whether the stimulus was a French word or not by pressing one of two buttons on a joystick with their dominant hand. Each trial began by a fixation cross (+) for 1000 ms, followed by a 200 ms black screen. Then, the stimulus was displayed during 1500 ms or until the participant responded. If the participant gave an incorrect response, a visual feedback signal was provided. The stimulus was followed by a 500-ms black screen, and then a symbol (***) was displayed during 1000 ms to invite the participants to blink their eyes. This was followed by a black screen for 500 ms. The 320 items (160 words and 160 pseudowords) were divided into five blocks approximately five min-long. The experiment was preceded by a brief practice session to familiarize participants with the setting.

Table 1
Word characteristics in Experiment 1.

	Syllable frequency	
	High (HSF words)	Low (LSF words)
N	80	80
Manipulated variables		
First syllable frequency	2341	427
Number of HFSNs	38	13
Controlled variables		
Lexical frequency	11.14	11.71
Number of letters	6.34	6.10
Number of orthographic neighbours	0.89	0.84
Second syllable frequency	281	352
First bigram frequency	3950	3779
Mean summed bigram frequency	1846	1856

Notes: HSF: high syllable frequency. LSF: low syllable frequency. Frequencies are given in number of occurrences per million.

2.1.4. Data acquisition

Continuous EEG was recorded at a sampling rate of 512 Hz (analog filtering: 0.1–100 Hz; amplification × 20) with an ASA EEG/ERP system (ANT software, the Netherlands), using 32 Ag/AgCl electrodes embedded in a wave-guard cap (ANT) according to the 10–20 international system. The left mastoid was used as reference, and the recording was re-referenced off-line to a linked mastoids reference. All impedances were kept below 5 kΩ. Horizontal and vertical eye movements were monitored using two bipolar recordings: one between each outer canthus and one between a supra-orbital electrode and an electrode just below the lower lid on the left side.

2.2. Results and discussion

2.2.1. Factorial design analyses

Pre-processing was performed with EEgLab software (Delorme & Makeig, 2004). A digital 15 Hz low-pass filter was applied before analyses. Epochs were extracted from 100 ms before stimulus onset to 700 ms post-stimulus. Baseline correction was performed using the average activity in the 100 ms preceding word onset. After rejection of invalid trials (i.e., epochs eliciting electrical activity greater than ± 100 μV), epochs were averaged for each experimental condition. Statistical analyses were performed on mean amplitudes measured in three post-target time windows (200–260 ms, 325–400 ms, 425–500 ms). Repeated measures ANOVAs were carried out using the columnar approach

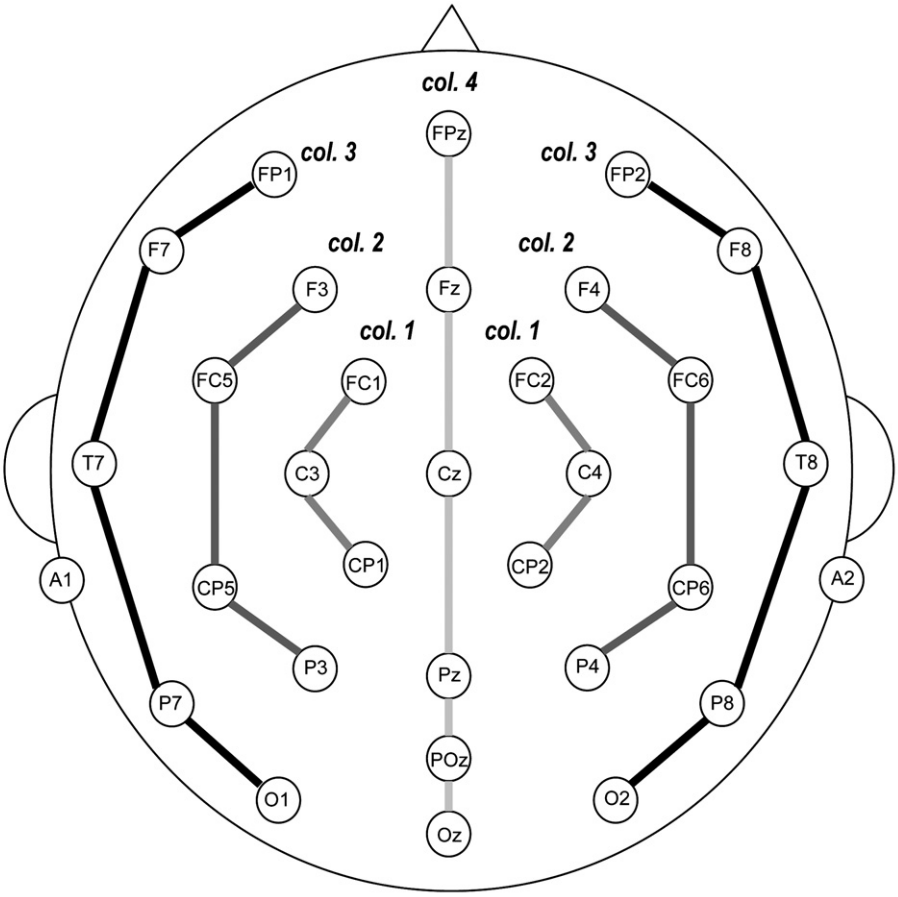

Fig. 1. The four analysis columns used for ANOVAs (col.: column).

(e.g., Holcomb & Grainger, 2006). This method consists in dividing the head into seven separate parasagittal columns along the antero-posterior axis of the head (Fig. 1). The electrodes in each of three pairs of lateral columns and one midline column were analysed in four ANOVAs. Analyses for columns 1 (col. 1), 2 (col. 2), and 3 (col. 3) involved an hemisphere factor (left vs. right), as well as a sagittal factor with three, four, or five levels (respectively, col. 1: FC1/FC2, C3/C4, CP1/CP2; col. 2: F3/F4, FC5/FC6, CP5/CP6, P3/P4; col. 3: FP1/FP2, F7/F8, T3/T4, T5/T6, O1/O2). Analysis for column 4 (col. 4) included a single sagittal factor with six levels (FPz, Fz, Cz, Pz, POz, Oz). As argued by Holcomb and Grainger (2006), an advantage of the columnar approach is that it provides

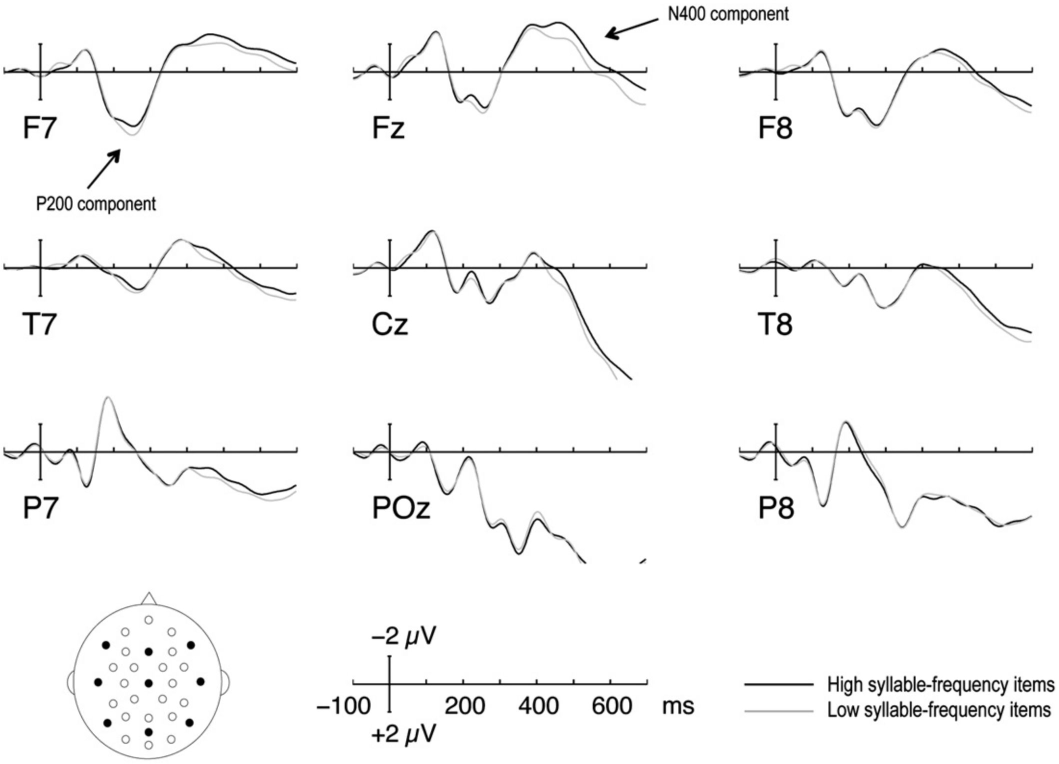

Fig. 2. Grand average waveforms for HSF and LSF items (words and pseudowords collapsed) at nine representative electrodes (Experiment 1).

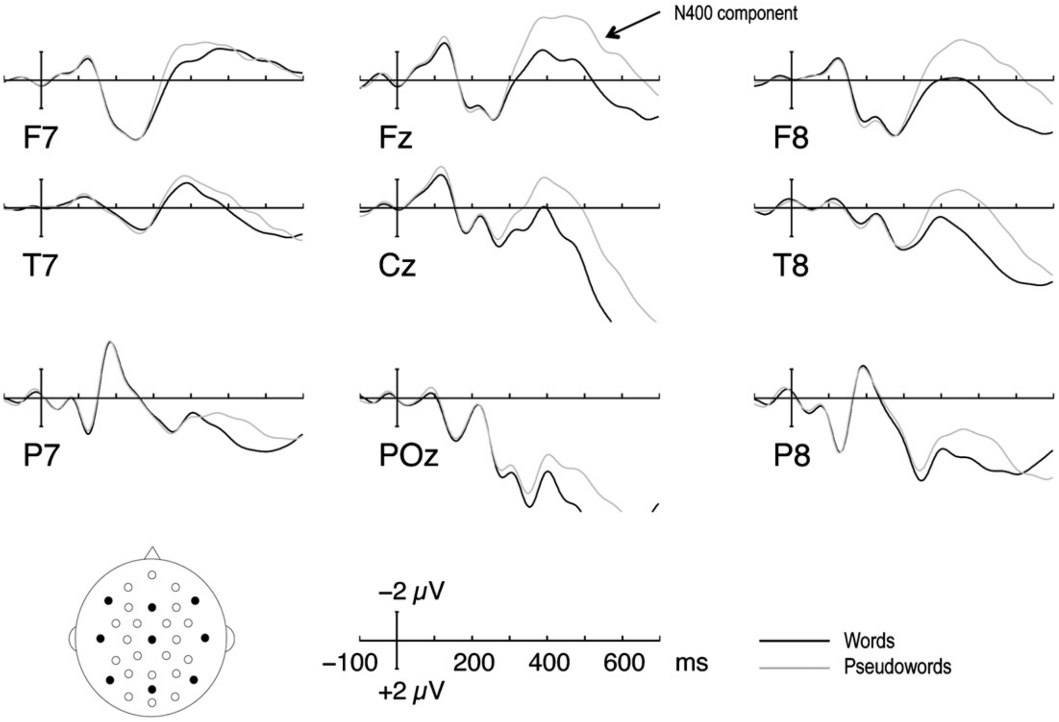

Fig. 3. Grand average waveforms for words and pseudowords (HSF and LSF items collapsed) at nine representative electrodes (Experiment 1).

an analysis of the entire head into different regions (left and right, anterior and posterior). This approach therefore allows small clusters of sites to influence the analysis because all sites are considered rather than, for example, averaging over sites to reduce the number of levels of the electrode factor. The Greenhouse–Geisser correction was applied when appropriate.

Based on previous studies and on visual inspection, three temporal windows were defined (200–260 ms, 325–400 ms, and 425–500 ms). In the earliest one, there was an effect of syllable frequency, with LSF words eliciting more positive amplitudes than HSF words (P200 component). In the two following windows, there was a negative deflection (N400 component), with HSF words eliciting more negative waves than LSF words (Fig. 2). Concerning lexicality, the typical effect was found in the N400 component, with pseudowords eliciting a larger negativity than words (Fig. 3).

2.2.1.1. Syllable frequency effect for words. In the 200–260 ms temporal window, the syllable frequency effect was significant in col. 1, $F(1,18)=4.41$, $p=.050$, and marginally significant in col. 4, $F(1,18)=3.92$, $p=.063$. In the 325–400 ms temporal window, an interaction between syllable frequency and hemisphere was found in col. 1: $F(1,18)=6.57$, $p=.019$, in col. 2: $F(1,18)=4.24$, $p=.054$, and col. 3: $F(1,18)=4.96$, $p=.039$, indicating that the syllable frequency effect was stronger in the right hemisphere than in the left hemisphere. In the 425–500 ms temporal window, there was a significant interaction between syllable frequency, hemisphere, and electrode in col. 3, $F(4,72)=4.63$, $p=.009$, indicating a stronger interaction between syllable frequency and hemisphere in the most anterior electrodes.

2.2.1.2. Syllable frequency effect for pseudowords. In the 200–260 ms temporal window, an interaction between syllable frequency and hemisphere was found in col. 1: $F(1,18)=4.65$, $p=.045$, in col. 2: $F(1,18)=6.07$, $p=.024$, and col. 3: $F(1,18)=6.09$, $p=.024$, indicating that the syllable frequency effect was stronger in the left hemisphere than in the right hemisphere. In the 325–400 ms temporal window, there was no significant effect involving syllable frequency. In the 425–500 ms window, the effect of syllable frequency was significant in col. 1: $F(1,18)=9.16$, $p=.007$, in col. 2: $F(1,18)=6.14$, $p=.023$, in col. 4: $F(1,18)=5.35$, $p=.033$, and marginally significant in col. 3: $F(1,18)=3.40$, $p=.082$. An interaction between syllable frequency and electrode site was found in col. 1: $F(2,36)=5.64$, $p=.018$, col. 2: $F(3,54)=4.22,=.044$, and col. 4: $F(5,90)=5.01$, $p=0.13$, indicating that the syllable frequency effect was the strongest in the anterior electrodes. A marginal interaction was also found between syllable frequency and hemisphere in col. 2: $F(1,18)=3.29$, $p=.086$, and in col. 3: $F(1,18)=4.27$, $p=.054$, indicating that the syllable frequency effect was stronger in the left hemisphere than in the right hemisphere.

2.2.1.3. Lexicality effect. In the 200–260 ms temporal window, no significant lexicality effect was found. In the 325–400 ms temporal window, the lexicality effect was significant in the four columns, col. 1: $F(1,18)=12.55$, $p=.002$, col. 2: $F(1,18)=13.16$, $p=.002$, col. 3: $F(1,18)=14.41$, $p=.001$, and col. 4: $F(1,18)=12.53$, $p=.002$. The effect was stronger in the right hemisphere than in the left hemisphere (col. 1: $F(1,18)=10.15$, $p=.005$, col. 2: $F(1,18)=6.29$, $p=.022$). The effect was also stronger at anterior electrodes, col. 1: $F(2,36)=4.14$, $p=.035$, col. 2: $F(3,54)=7.64$, $p=.004$, col. 3: $F(4,72)=9.29$, $p=.002$, and col. 4: $F(5,90)=7.50$, $p=.002$, especially in the left hemisphere as indicated by the interaction between lexicality, hemisphere, and electrode in col. 1: $F(2,36)=3.69$, $p=.062$, col. 2: $F(3,54)=3.25$, $p=.037$, and col. 3: $F(4,72)=4.34$, $p=.012$. The same pattern of results was found in the 425–500 ms temporal window. The lexicality effect was significant in the four columns, col. 1: $F(1,18)=26.78$, $p<.001$, col. 2: $F(1,18)=28.15$, $p<.001$, col. 3: $F(1,18)=29.38$, $p<.001$, and col. 4: $F(1,18)=25.81$, $p<.001$. The effect was stronger in the right hemisphere, col. 1: $F(1,18)=59.43$, $p<.001$, col. 2: $F(1,18)=46.00$, $p<.001$, and col. 3: $F(1,18)=23.35$, $p<.001$, and at the most anterior electrode in col. 4, $F(5,90)=4.50$, $p=.021$.

To summarize, contrasting syllable frequency in both words and pseudowords yielded distinct ERP effects at different time windows. HSF items elicited a smaller positivity than LSF items around 200 ms after stimulus onset, whereas they gave rise to a larger negativity later on. Additionally, as can be seen in Fig. 4, the late effect was delayed for pseudowords (425–500 ms) compared to words (325–400 ms).

As previously underlined, the exact nature of the factors driving interference effects still needs clarification. To distinguish between number of HFSNs and syllable frequency as source of interference effects in the N400 temporal window, we conducted regression analyses on the whole stimulus set. Importantly, some previous studies pointed out that the lexical frequency of higher frequency neighbours should also be taken into account – in addition to the number of neighbours – to explain neighbourhood effects (e.g., Pollatsek, Perea, & Binder, 1999). Especially, Bard (1990) argued that within a cohort of lexical candidates, a single outlier of very high frequency relative to the others constitutes a predominant competitor and would therefore strongly determine the amount of lexical interference during word processing. This analysis fits particularly well in the context of syllabic neighbourhood because syllabic cohorts are very broad (compared to orthographic neighbourhood cohorts for example), and it is unlikely that all HFSNs significantly contribute to the competition process. Rather, the most frequent HFSN (henceforth referred to as the leader of the cohort) may play a decisive role in the competition. We therefore included this variable in the regression analyses.

2.2.2. Regression analyses

The same pre-processing procedure was applied as for the ANOVAs, except that mean amplitudes were averaged for the 19 participants for each word, rather than averaged per condition for

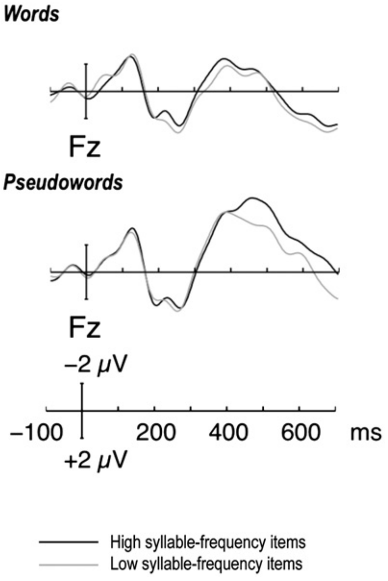

Fig. 4. Grand average waveforms for HSF and LSF items at Fz.

each participant. Hierarchical regression analyses were conducted on voltage for each electrode in the 325–400 ms temporal window, given that the general analysis showed that the strongest inhibitory syllable frequency effect was found in this temporal window. To test our predictions concerning the factors determining the importance of the inhibitory syllable frequency effect, four predictors were considered (see Perea & Carreiras, 1998; Conrad et al., 2008 for a similar method): lexical frequency, first syllable frequency, number of HFSNs, and leader strength. Leader strength is a measure of neighbour distribution according to their lexical frequency. To compute this variable, we selected for each word all its HFSNs sharing the same first syllable, and calculated for each word the ratio of the frequency of the highest frequency HFSN candidate to the summed frequency of all HFSNs. The measure ranges from 0 to 1, with values close to one reflecting a strong leader, that is a leader much more frequent than other HFSNs. As shown in Table 2, several of the four predictors were inter-correlated.

Table 2
Inter-correlations for the four predictors entered in the regression analysis.

	1	2	3	4
1. Lexical frequency	–	03	−53***	21*
2. Syllable frequency		–	33***	−07
3. Number of HFSNs			–	−40***
4. Leader strength				–

Notes: HFSN: higher frequency syllabic neighbours. Leader strength was computed on orthographic syllables.

* $p < .05$.

*** $p < .001$.

Lexical frequency (log-transformed) was entered first, given that this variable – usually correlated to syllabic variables – explains most of the variance of word recognition latencies (e.g., Yap & Balota, 2009). Syllable frequency (log-transformed) was then entered, followed by number of HFSNs, and leader strength was added as the last predictor. Regression analyses were conducted twice, the first time with leader strength computed on phonological syllables, the second one with leader strength computed on orthographic syllables. Pearson

Table 3
Pearson product-moment (*r*) and partial (*pr*) correlations between voltage and four predictors as a function of electrode.

Predictors										
Leader strength										
	Lexical frequency		Syllable frequency		Number of HFSNs		Computed on SP		Computed on SO	
	r	*pr*	*r*	*pr*	*r*	*pr*	*r*	*pr*	*r*	*pr*
Column 1										
FC2	.16*	.17*	−.07	−.10	−.03	.03	−.07	−.06	−.17*	−.19*
C4	.19*	.21*	−.04	−.09	−.05	.04	−.04	−.04	−.12	−.15^{+}
CP2	.14^{+}	.19*	.01	−.07	.03	.09	−.06	−.02	−.14^{+}	−.13
FC1	.10	.17*	−.02	−.08	.07	.10	−.13^{+}	−.08	−.23**	−.21*
C3	.08	.18*	.03	−.06	.11	.11	−.18*	−.12	−.24**	−.21**
CP1	.12	.21*	.06	−.04	.10	.14^{+}	−.10	−.04	−.16*	−.13
Column 2										
F4	.19*	.14^{+}	−.10	−.09	−.11	−.03	−.03	−.06	−.13	−.18*
FC6	.24**	.16^{+}	−.08	−.05	−.16*	−.07	.02	−.03	−.09	−.16^{+}
CP6	.16*	.17*	−.01	−.06	−.02	.04	−.03	−.02	−.12	−.14^{+}
P4	.16*	.22**	.06	−.04	.05	.12	−.07	−.02	−.11	−.09
F3	.09	.15^{+}	−.04	−.10	.05	.07	−.15^{+}	−.12	−.23**	−.22**
FC5	.15^{+}	.20*	.00	−.07	.04	.09	−.13^{+}	−.10	−.20*	−.20*
CP5	.05	.15*	.08	−.01	.16*	.15^{+}	−.15^{+}	−.07	−.20*	−.15^{+}
P3	.10	.19*	.10	−.01	.14^{+}	.17*	−.10	−.02	−.14^{+}	−.09
Column 3										
FP2	.08	.18*	.03	−.06	.11	.11	−.18*	−.12	−.24**	−.21*v
F8	.23**	.12	−.13	−.07	−.22**	−.13	.03	−.05	−.07	−.16*
T8	.26**	.19*	−.08	−.07	−.16*	−.07	−.02	−.07	−.12	−.20*
P8	.07	.09	.07	.04	.04	.05	−.01	.01	−.04	−.03
O2	.09	.13	.06	.01	.06	.11	.02	.07	−.01	.02
FP1	.16*	.09	.01	.03	−.09	−.07	−.05	−.09	−.11	−.16^{+}
F7	.17*	.25**	−.24**	−.31**	−.06	.10	−.13	−.12	−.17*	−.19*
T7	.11	.17*	−.11	−.16^{+}	.02	.08	−.17*	−.15^{+}	−.18*	−.18*
P7	.03	.12	.10	.02	.15^{+}	.15^{+}	−.08	−.01	−.10	−.04
O1	.08	.12	.09	.03	.06	.10	−.00	.04	−.01	.02
Column 4										
FPz	.17*	.09	−.15*	−.10	−.15^{+}	−.08	−.03	−.07	−.09	−.15^{+}
Fz	.13	.15^{+}	−.23**	−.23**	−.06	.05	−.14^{+}	−.14^{+}	−.16*	−.18*
Cz	.12	.18*	−.10	−.14^{+}	.04	.11	−.12	−.07	−.19*	−.18*
Pz	.14^{+}	.18*	.02	−.05	.04	.11	−.04	−.00	−.08	−.07
POz	.14^{+}	.1*	.07	−.01	.05	.13	−.02	.03	−.03	−.01
Oz	.08	.13	.10	.03	.08	.14^{+}	.03	.08	.04	.08

Notes: HFSN: higher frequency syllabic neighbours. Grey squares highlight significant or marginally significant partial correlations.

** $< .01$,

* $< .05^{+} < .10$,

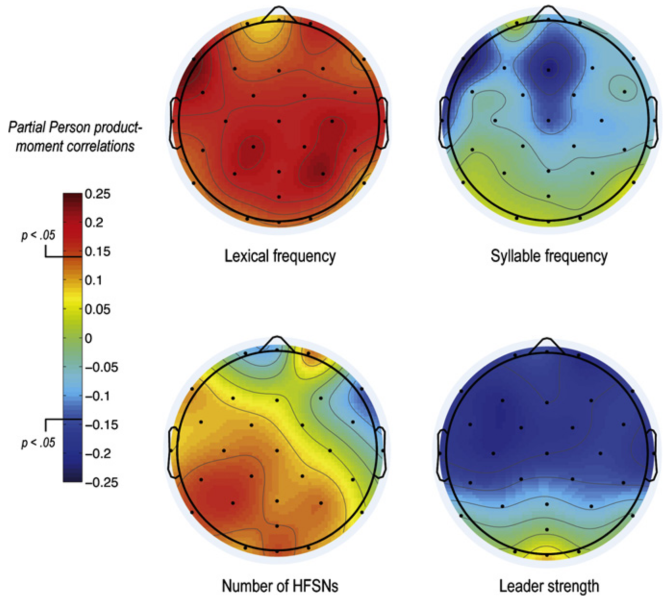

Fig. 5. Topographic representation of partial correlations for the four predictors entered in the regression analysis (325–400 ms temporal window).

product-moment (r) and partial correlations between predictors and voltage are presented in Table 3, and partial correlations are topographically represented in Fig. 5. Two predictors were widely correlated to voltage when the effects of the other predictors were partialled out, namely lexical frequency and leader strength. Positive correlations were found all over the scalp for lexical frequency (22 out of 30 electrodes were significantly or marginally significantly correlated), indicating that the more frequent the word, the smaller the N400 component. Leader strength was also predicting voltage, but only when it was computed on orthographic syllables[1]. In that case, partial correlations were negative (19 out of 30 electrodes), showing that words with high leader strength elicited larger N400 waveforms. Electrodes for which correlations were not significant were systematically located in the anterior region. Accordingly, entering leader strength in the regression model after the three other predictors significantly increased R^2 for 19 electrodes. On the contrary, syllable frequency and number of HFSNs displayed significant partial correlations for only few electrodes. For syllable frequency, negative correlations were found at four electrodes in the anterior-central region, and for number of HFSNs, five electrodes in the posterior region showed positive correlations.

To sum up, the regression analyses provided clear-cut outcomes. First, the fact that few posterior electrodes were correlated with the number of HFSNs and that these correlations were positive confirm the results found in the factorial design analyses involving the difference in the number of HFSNs. Strength of competition, neurophysiologically reflected by an increased negativity in the N400 temporal window, is not directly related to the number of HFSNs. Second, leader strength was widely correlated with voltage. This supports the assumption that the weight of the leader within a syllabic cohort plays a crucial role in the competition, as proposed by Bard (1990) for phonological neighbourhood effects. When leader strength is high, the most frequent HFSN can exert a strong inhibitory influence on other neighbours, including the target. On the contrary, when leader strength is low, the leader of the cohort is not really distinct from other HFSNs, and its inhibitory effect may be weakened because competitors cancel each other, causing only weak inhibition towards the target word.

Interestingly, leader strength predicted electro-physiological variations only when it was computed on words sharing orthographic syllables (e.g., *moment*,/mo.mɑ̃/ and *moral*,/mo.ʀal/, but not *moment*,/mo.mɑ̃/ and *mauvais*/mo.ve/). This supports an orthographic locus of syllabic effects. The relevant syllable-like units processed within written polysyllabic words predominantly correspond to letter clusters rather than to phonological syllables (see Chetail & Mathey, 2009; Conrad et al., 2010; but see Conrad et al., 2007). Consistently, Stenneken, Conrad, Goldenberg, and Jacobs (2003) reported the case of a dyslexic adult with severe phonological impairments who exhibited a reliable syllable frequency effect. This means that syllable frequency influenced visual word processing independently from accessing the phonological word form (see also Caramazza & Miceli, 1990).

To directly test the impact of the relative frequency of HFSNs during visual word recognition, leader strength was factorially manipulated in Experiment 2 while controlling for both syllable frequency and number of HFSNs. In that case, we expected a greater negativity in late temporal windows for words with a high leader strength than for words with a low one.

3. Experiment 2

3.1. Method

3.1.1. Participants

Seventeen healthy native French speakers took part in the experiment. All were right-handed, had normal or corrected to normal vision, and were paid for their participation. None of them participated in the previous experiment.

3.1.2. Materials

Fifty-four pairs of bisyllabic words with a consonant-vowel first syllable were selected in Lexique (New et al., 2004) according to leader strength, computed as the ratio of the frequency of the highest frequency neighbour to the summed frequency of the HFSNs. In each pair, one of the words had a high leader strength (high LS word), meaning that its highest frequency syllabic neighbour was much more frequent than other HFSNs, while the other had a low leader strength (low LS word), that is no leader highly distinguishable from other HFSNs. The high and low LS words were matched for syllable frequency, number of HFSNs, lexical frequency, number of letters, orthographic neighbourhood, frequency of the second syllable, as well as initial and summed bigram frequency (see Table 4). Given the results of the previous regression analyses, syllabic variables taken into account were computed on orthographic rather than phonological syllables. For the purpose of the lexical decision task, 54 pairs of orthographically legal and pronounceable pseudowords were added. They were created by randomly

Table 4
Word characteristics in Experiment 2.

	High LS words	Low LS words
N	54	54
Example	Lisière	Barrière
Manipulated variables		
Leader strength	0.56	0.24
Controlled variables		
First syllable frequency	361	354
Number of HFSNs	14	14
Lexical frequency	6.42	6.68
Number of letters	6.00	6.15
Number of orthographic neighbours	1.54	1.54
Second syllable frequency	271	166
First bigram frequency	1131	1363
Mean summed bigram frequency	1796	1735

Notes: LS: leader strength. HFSN: higher frequency syllabic neighbour. Frequencies are given in number of occurrences per million. Syllabic measures are computed on orthographic syllables.

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[1] The pattern of results for the syllable frequency and number of HFSNs predictors did not change whether these variables were computed on phonological or orthographic syllables (no effect in either case).

combining the first syllables of the words with fresh second syllables attested in the French orthography. Paired pseudowords were matched on the same variables as the words.

3.1.3. *Procedure*

The procedure was identical to that of Experiment 1.

3.1.4. *Data acquisition*

Data acquisition was the same as in Experiment 1, except that continuous EEG was recorded at a sampling rate of 2024 Hz with a Biosemi EEG/ERP system.

3.2. *Results*

The same pre-processing as in Experiment 1 was applied on the continuous EEG. Repeated measures ANOVAs were performed on mean amplitudes measured in the three post-target time windows (200–260 ms, 325–400 ms, 425–500 ms). Visual inspection led us to add a fourth temporal window (600–650 ms). As shown in Fig. 6, high LS words elicited more negative amplitudes than low LS words in late temporal windows (325–400 and 600–650). Concerning the lexicality effect, pseudowords elicited a larger negativity than words from 325 to 600 ms (Fig. 7).

3.2.1. *Leader strength effect for words*

In the first three temporal windows (200–260 ms, 325–400 ms, and 425–500 ms), there was no significant effect, except a three-way interaction in col. 1 between leader strength, hemisphere, and electrode, $F(2,32)=3.73$, $p=.049$, $F(2,32)=3.56$, $p=.051$, and $F(2,32)=4.08$, $p=.031$, respectively. However, further examination showed that none of the local effects of leader strength reached significance. In the 600–650 ms temporal window, the effect of leader strength was significant in col. 2, $F(1,16)=5.69$, $p=.030$, in col. 4, $F(1,16)=4.36$, $p=.053$, and marginally significant in col. 3, $F(1,16)=3.68$, $p=.075$. In col. 1, there was a marginally significant three-way interaction between leader strength, hemisphere, and electrode, $F(2,32)=3.41$, $p=.062$, showing after decomposition

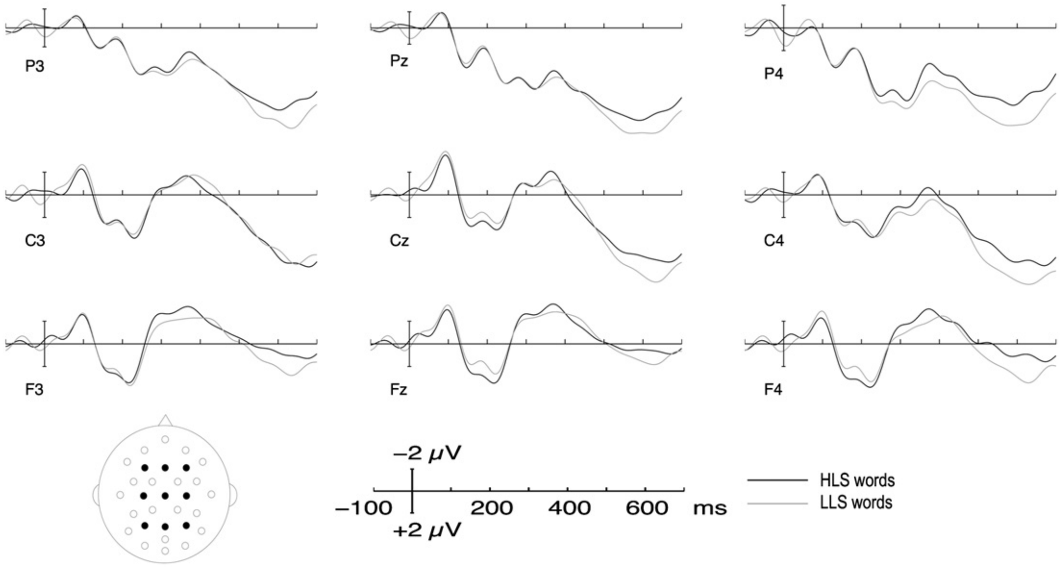

Fig. 6. Grand average waveforms for high and low LS words at nine representative electrodes (Experiment 2).

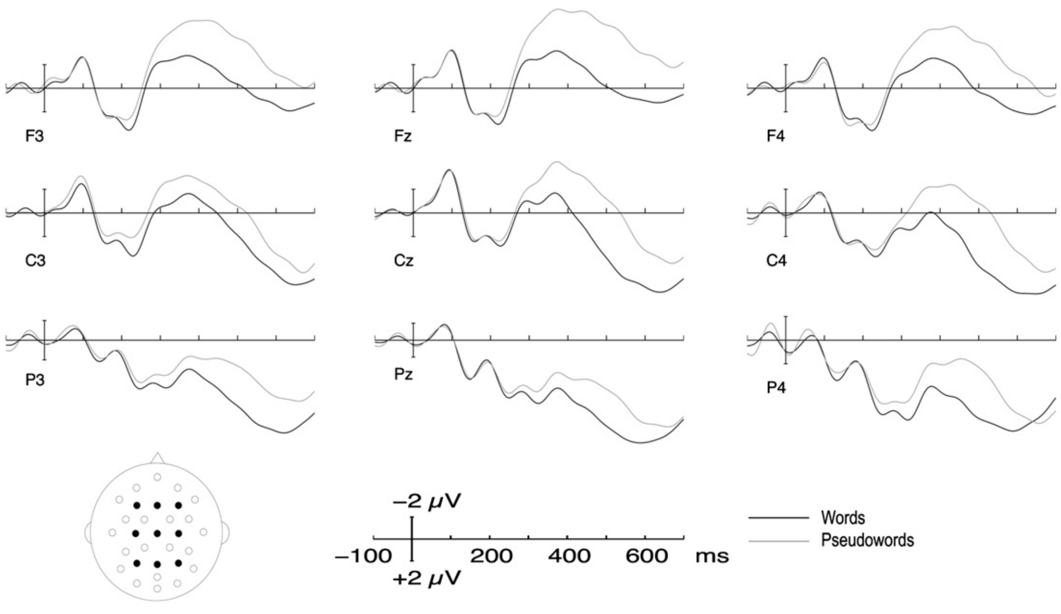

Fig. 7. Grand average waveforms for words and pseudowords (high and low LS items collapsed) at nine representative electrodes (Experiment 2).

that the effect of leader strength in the left hemisphere was present only for the most anterior electrodes, $F(1,16)=4.67$, $p=.046$.

3.2.2. *Lexicality effect*

In the 200–260 ms temporal window, the lexicality effect was significant only in col. 1, $F(1,16)=4.72$, $p=.045$, the effect being stronger in the left hemisphere, $F(1,16)=7.55$, $p=.014$. In the 325–400 ms temporal window, the effect was significant in the four columns, col. 1: $F(1,16)=21.37$, $p<.001$, col. 2: $F(1,16)=19.94$, $p<.001$, col. 3: $F(1,16)=13.26$, $p=.002$, and col. 4: $F(1,16)=28.44$, $p<.001$. The effect was stronger in the right hemisphere in col. 3: $F(1,16)=6.29$, $p=.023$, and at anterior electrodes, col. 1: $F(2,32)=3.62$, $p=.040$, col. 2: $F(3,48)=3.69$, $p=.040$, col. 3: $F(4,64)=6.83$, $p<.001$, and col. 4: $F(5,80)=4.46$, $p=.007$. In the 425–500 ms temporal window, the lexicality effect was also significant in the four columns, col. 1: $F(1,16)=25.20$, $p<.001$, col. 2: $F(1,16)=25.54$, $p<.001$, col. 3: $F(1,16)=18.53$, $p<.001$, and col. 4: $F(1,16)=32.11$, $p<.001$, the effect being weaker in the central electrodes in col. 1: $F(2,32)=4.00$, $p=.029$, especially in the left hemisphere, $F(2,32)=3.88$, $p=.048$. Finally, in the 600–650 ms temporal window, the lexicality effect was significant in three columns, col. 1: $F(1,16)=17.91$, $p<.001$, col. 2: $F(1,16)=15.85$, $p<.001$, and col. 4: $F(1,16)=14.57$, $p=.002$. The effect was stronger at anterior electrodes, col. 4: $F(5,80)=5.00$, $p<.001$, as well as in the left hemisphere, col. 2: $F(1,16)=4.77$, $p=.044$, col. 3: $F(1,16)=5.29$, $p=.035$, this difference being more important at posterior electrodes, col. 2: $F(1,16)=10.57$, $p<.001$, col3: $F(4,64)=10.65$, $p<.001$.

3.3. *Discussion*

Contrasting words according to leader strength yielded the expected effect, namely words belonging to a syllabic neighbour cohort with a strong leader (high LS words) elicited greater negativity than words with a weaker leader (low LS words). This effect was found while both syllable frequency and number of HFSNs were controlled for, thus supporting the claim that the relative frequency of HFSNs during visual word recognition impacts visual word processing.

Though the effect seemed to emerge around 400 ms after word display, it reached significance only in the 600–650 ms temporal window. The positive peak observed around 600 ms may reflect the combination of the N400 component and a late P300 component (see Holcomb, Grainger, & O'Rourke, 2002) ensuing from a binary decision between two equiprobable events (Kutas & van Petten, 1988). Interestingly, this effect is similar to orthographic neighborhood effects on monosyllabic words. Items with a large number of orthographic neighbours produced a greater negativity (compared to items with a small number) in late temporal windows such as 550–800 ms (Holcomb et al., 2002). These differences were interpreted by the authors as an increase of global lexical activation during stimulus processing ensuing from the presence of a high number of orthographic neighbours. In the same line, it is worth noting that in previous ERP studies on syllable frequency, analyses were usually not performed after 500–600 ms, but visual inspection of waveforms suggests that the effect extended well over these time points (Hutzler et al., 2004; see also Goslin et al. for significant effects between 550 and 600 ms).

In Experiment 1, evidence for competition between syllabic neighbours was found in the N400 window, whereas varying leader strength – the variable supposed to be the source of syllabic neighbourhood effects – yielded a later effect in the second experiment. This temporal discrepancy can be accounted for by differences in the stimuli used. First, due to construction constraints, words were less frequent in Experiment 2 (6.55) than in Experiment 1 (11.42), $t(266)=3.25$, $p<.001$. Second, words in Experiment 2 had a lower mean first bigram frequency (1338) than those in Experiment 1 (3865), $t(266)=8.51$, $p<.001$, and Mathey et al. (2006) argued that a temporal delay in the activation of syllable-like units occurs when words begin with a low-frequency first bigram, this delay having repercussions on the competition process itself at the lexical level. Thus, variations among stimuli most likely explain why the latency of the leader strength effect was later than what could have been expected based on Experiment 1.

4. General discussion

The first aim of the present study was to test whether syllabic effects in French written word recognition ensue from a dual process of facilitation and inhibition, as proposed in Spanish and German. Accordingly, we found in Experiment 1 that syllable frequency influenced neurophysiological activity in both early and late stages of word and pseudoword processing. Second, to constrain the interpretation of the inhibitory component, we examined the source of the competition effect by means of regressions analyses. Data showed that the number of HFSNs was not the most relevant predictor to explain inhibitory syllable frequency effects. Rather, the extent to which the most frequent neighbour, the "leader" of the cohort differs from other HFSNs in terms of lexical frequency consistently explained neurophysiological activity around 400 ms post-target. In experiment 2, the direct manipulation of leader strength yielded a convergent effect around 600 ms post-target. In sum, although the number of HFSNs does not seem to be the relevant experimental parameter, our findings bring further support to the claim that HFSNs cause the competition. However, their frequency relations, rather than their number, need to be taken into account to determine whether or not competing candidates will quickly emerge and inhibit the target word unit.

4.1. *The dual nature of syllabic frequency effects in visual word processing*

Syllabic effects have almost always been accommodated in interactive activation-based frameworks (see Carreiras et al., 1993; Conrad et al., 2009, 2010; Mathey et al., 2006), especially because the interactive activation framework (e.g., McClelland & Rumelhart, 1981) is most appropriate to account for competition effects such as those assumed in syllabic inhibition effects. In such a framework, the inhibitory syllable frequency effect has been explained as resulting from two complementary processes, a facilitatory between-level process enhanced by the frequency of syllables, and an inhibitory within-level process between syllabic neighbours (e.g., Conrad et al., 2009, 2010; Mathey et al., 2006). The results of the present ERP study are fully consistent with this view. The weaker positivity of the P200 component for HSF words (compared to LSF words) may reflect the early sub-lexical facilitation, while the larger negativity of the N400 component for HSF words may be produced by the later competition between syllabic neighbours. Thus the present results obtained in French closely mirror those of previous ERP studies in Spanish and German (Barber et al., 2004; Hutzler et al., 2004, respectively). Taken together, the three studies thus suggest that the processes underlying syllabic effects are not different across languages, despite large variations in syllabic complexity and orthographic transparency. It should be mentioned that with a different task and design, Goslin et al. (2006) failed to observe a P200/N400 dissociation in

French. However, their use of a more complicated design which combined syllable frequency and syllable congruency may have led to select less typical French words, for example with less clear syllabic boundaries, thus restricting the emergence of syllabic effects (cf. their discussion of Experiment 1).

Interestingly, both effects were present for the pseudowords, but only the late inhibitory effect was delayed (425–500 ms temporal window) compared to words (325–400 ms temporal window). This lends further support to the hypothesis that the early effect is due to sublexical unit activation, whereas the late component is related to lexical activity.

4.2. Leader strength and competition

A central and specific aspect of syllable frequency effects is their inhibitory nature, which has been explained since the very first report of the effect in terms of competition between syllabic neighbours (Carreiras et al., 1993). It has often been assumed that the number of HFSNs drives the competition process, but this hypothesis has suffered from a lack of specification concerning the precise relationships and role of the different neighbours during the competition process.

Up to now, interpretations of syllable frequency effects in visual word recognition have focused on syllabic neighbourhood density – computed in token frequency (i.e., syllable frequency) or in type frequency (i.e., number of syllabic neighbours) – and syllabic neighbourhood frequency, computed in type frequency (i.e., number of HFSNs). On the contrary, token computation of syllabic neighbourhood frequency (i.e., the frequency of HFSNs) has not been considered, despite evidence showing the importance of the frequency of the higher frequency neighbours in other domains of word recognition (e.g., Bard, 1990; Davis, 2003; Pollatsek et al., 1999). Here, we demonstrated empirically that the relative frequency of HFSNs plays a predominant role in the intensity of competition, and therefore in the amount of inhibition other, whatever their number. On the contrary, if there is one leader, that is, one competitor much more frequent than the remaining ones, it has the potential to strongly inhibit the other competitors, and its activation would accrue faster because it receives little inhibition. So, the target word receives a strong inhibition from the leader which cannot be compensated by sub-lexical facilitation.

Further, the fact that an effect of leader strength was found only when orthographic syllabic neighbours were taken into account (regression analyses, Experiment 1) suggests that the inhibitory effects we reported are driven by *orthographic* representations, and that orthographic syllabic units may be represented at the sub-lexical level. Such representations may develop during learning to read via exposure to frequently co-occurring letter combinations, as frequent orthographic syllables naturally tend to correspond to frequent orthographic clusters (Adams, 1981; Seidenberg, 1987; see Conrad et al., 2010) and orthographic chunking of letter strings into orthographic syllable-like units may be driven by the distinction between consonant and vowel letters (Chetail & Content, 2012; see also Kandel, Hérault, Grosjacques, Lambert, & Fayol, 2009).

4.3. Localization of the effects

The results showed different localizations for syllable frequency, lexical frequency and lexicality effects. Syllabic effects were mostly located in frontal and central regions, which is compatible with previous ERP studies on syllable frequency (Barber et al., 2004; Hutzler et al., 2004), while both lexical frequency and lexicality effects were more distributed. More generally, studies on syllabic effects – not only on syllable frequency effects – consistently showed that syllabic manipulations produce neurophysiological changes in the anterior and central areas of the scalp rather than in posterior areas (Ashby, 2010; Carreiras, Vergara, & Barber, 2005; Doignon-Camus, Bonnefond, Touzalin-Chretien, & Dufour, 2009; Dominguez, Alija, Cuetos, & de Vega, 2006; but see Dominguez, Alija, & Cuetos, 2010).

At a neuroanatomical level, the fMRI study of Carreiras, Mechelli, and Price (2006) showed that the dissociation of syllable frequency effects and lexical frequency/lexicality effects observed in behavioural and neurophysiological lexical decision experiments is also reflected in the mapping of functional brain areas. Especially, they reported that low-frequency words increased activation relative to high-frequency words in the left dorsal opercularis, the pre-supplemental motor area (SMA), and the sulcus between the anterior cingulate and SMA, whereas HSF words increased activation relative to LSF words in the left anterior temporal region (low-frequency words only). First, this neuroanatomical dissociation supports the claim that although lexical frequency/lexicality effects and late effects of syllable frequency occur in the same temporal window (roughly around 400 ms post-target), they correspond to different cognitive processes. Second, as the authors suggested, the fact that the brain localization of the syllable frequency effect (left anterior temporal region) is situated just posteriorly to another area associated to semantic processing during lexical decision tasks provides converging evidence in favour of the hypothesis that the syllable frequency effect is tightly related to lexical access processes.

In conclusion, the present study successfully replicated in French the temporal dissociation of facilitatory and inhibitory syllabic effects. Furthermore, the findings showed that the inhibition process is particularly sensitive to the distribution of higher frequency syllabic neighbours according to their lexical frequency. While this factor has rarely been considered until now in empirical studies of syllable frequency, it supports the lexical competition account and contributes to understand the specific conditions controlling the emergence of inhibitory syllable frequency effects.

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