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Syllable frequency effects in French visual word recognition: An ERP study

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Abstract

This study examined event-related potentials (ERPs) associated with differences in the frequency of the initial syllable of target words whose syllabic structure provided either a match or mismatch with the /CV/ and /CVC/ syllables under analysis. Results showed ERP effects that were consistent with syllabic activation between 300 and 600 ms, with high frequency syllables producing more positive potentials than those of low frequency. The syllabic locus of these effects was verified by their presence only in the matched syllabic condition, showing that frequency effects respected known syllable boundaries. Syllable frequency effects were also noted in an earlier time window, between 150 and 300 ms. However, these effects were only seen when manipulating /CVC/ frequency, not /CV/, and were common to both the matched and unmatched conditions. These results suggest that phoneme representations are directly activated following presentation of a printed word, and syllable representations are only activated following phoneme activation.

Keywords

Lexical access; Syllable; Frequency; French; ERP

1. Introduction

An area of increasing interest in visual word recognition concerns the possible use of intermediate, sublexical units, between orthographic and lexical units. One of the units of particular interest for this intermediary role is the syllable. A number of behavioral studies in Spanish (Alvarez et al., 2001; Carreiras et al., 1993; Perea and Carreiras, 1998), German (Conrad and Jacobs, 2004), and French (Mathay and Zagar, 2002) have shown that high frequency syllables can have an inhibitory effect on word recognition, increasing response latencies in lexical decision tasks. The assumption being that, in an interactive activation model (McClelland and Rumelhart, 1981), syllabic neighbors are activated during the course of visual word recognition, therefore greater syllabic frequency (and number of possible neighbors) results in increased inhibitory connections between lexical competitors.

It is only recently that this behavioral evidence has been supported with event-related potentials (ERPs), allowing a more detailed examination of the time course of visual word recognition and the potential role of the syllable. In the original ERP study of syllable frequency (Barber et al., 2004), the frequency of Spanish lexical items and their initial /CV/ syllables was manipulated in disyllabic words. The authors reported a negative relationship between syllable frequency and an ERP potential starting at 150 ms and continuing across the N400-words

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beginning with a high frequency syllable generated more negative-going waveforms than words beginning with a low frequency syllable. ERP effects due to lexical frequency were also found between 350 and 500 ms, with high frequency words leading to a reduction of the N400 when compared to low frequency words.

It is widely accepted that the N400 is sensitive to semantic aspects of word processing (e.g., Holcomb, 1993). However, it has recently been proposed (Holcomb et al., 2002) that orthographic neighbors are activated at the same time as target words, therefore words with large neighborhoods would lead to greater semantic activation, and so greater negativity. Similarly, Barber et al. (2004) have suggested that the increased N400 due to high frequency syllables is indicative of the similar activation of a cohort of syllabic, rather than orthographic, neighbors. The early presence of syllabic effects, occurring prior to those arising from differences in lexical frequency, has also been taken as evidence of a pre-lexical role for syllables in Spanish, with syllabic units used during lexical access in the visual domain.

These findings have recently been replicated in a study of Hutzler et al. (2004) examining the effect of /CV/ frequency in German. They found significant syllabic ERP effects between 190 and 280 ms and 450 and 550 ms, with high frequency initial /CV/ syllables resulting in more negative potentials than those with low frequency. As in the study of Barber et al. (2004), lexical frequency effects were only found in later epochs, between 350 and 550 ms, also supporting the case for pre-lexical syllabic activation. Additional evidence comes from a study of Carreiras et al. (2005a) who presented words and pseudowords that were colored such that there was a match or mismatch between syllable and color boundaries. The authors suggest that the presence of color-syllabic congruency effects between 180 and 260 ms in low, but not high frequency words provided evidence for interference in syllable recognition. As in the previous studies, the temporal dissociation of these effects from those associated with lexicality was provided as evidence to support the dual route hypothesis of visual word recognition in Spanish, with syllables playing a functional pre-lexical role.

In French, the syllable has enjoyed favored status as the primary perceptual unit in spoken word recognition for a number of years, ever since the seminal study of Mehler et al. (1981). In this study, a sequence monitoring task was used to measure the detection latencies of target speech fragments found at the start of subsequent carrier words. Carrier words were arranged in pairs such that they shared their first three phonemes but had different initial syllables, with the target phoneme sequences corresponding to the initial two or three phonemes. For example, for the carrier pair 'pa.lace' and 'pal.mier', participants were asked to detect the sequences /pa/ and /pal/. The results of this study showed that the detection latencies of the targets which corresponded to the first syllable of the carrier word were significantly faster than when they did not, independent of the length of the target. Therefore, in our example, the sequence /pa/ would have been detected faster in 'pa.lace' than 'pal.mier', with the reverse for the sequence /pal/. This cross-over interaction, known as the *syllable effect*, provided convincing evidence for the role of the syllable in pre-lexical segmentation and classification. The role of the syllable in French visual word recognition has also been explored, using both the syllable frequency paradigm (Mathay and Zagar, 2002) and masked syllable priming (Carreiras et al., 2005b; Ferrand et al., 1996). In the study by Ferrand et al. (1996), masked primes were presented that corresponded to the initial syllable of words, non-words, and pictures, in both lexical decision and naming tasks. They found that detection latencies were faster if the initial syllable of the prime corresponded with that of the target in the naming task, but not the lexical decision task. It was suggested that this task disparity pointed to the activation of syllabic units in output phonology as the syllabic effects were only found when the subjects were required to articulate their response. If syllabic units were used during lexical access, then the effects should have been seen in both tasks. However, in the later study, Carreiras et al. (2005b) did find significant facilitation with syllabic priming in a lexical decision task, even when there was only a partial

orthographic overlap between prime and target. Syllable priming has also been found to have an affect upon lexical decisions in Spanish, producing either facilitatory or inhibitory effects dependent upon the frequency of the syllable prime (Carreiras and Perea, 2002). While syllabic priming effects were found to be limited to cases of syllabic congruency, as they were in the naming task of Ferrand et al. (1996), differences in the SOA between the two studies could explain disparity in the significance of the priming effect in the lexical decision tasks. In the study of Ferrand et al. (1996), prime durations were very short, at only 29 ms, compared with between 64 and 160 ms in the study of Carreiras and Perea (2002).

One of the main aims of the current study is to verify whether the ERP effects associated with differences in syllable frequency found in Spanish and German can also be seen in French, with the hope that these findings might shed light over the locus of behavioral syllabic effects. However, in this study, we extend the previous ERP studies by examining the syllabic context of these effects, and whether they are also present for more complex initial syllables.

According to the hypothesis put forward by Carreiras et al. (1993), not only is the representation of the target word activated during visual word recognition, but also those that share the same initial syllable as the target. They suggest that the frequency of the initial syllable is directly related to the size of the cohort of the syllabically related candidates and that the lateral inhibition mechanisms operating between syllabic competitors interfere with the recognition of the target word. Therefore, as the frequency of the initial syllable of a target word increases, so does the cohort of syllabically related competitors, leading to increased recognition delays and greater semantic activation. In the study of Barber et al. (2004) using ERPs, this led to an increased negativity at around 400 ms. However, it is also possible that the effects seen in this study could be due to the activation of a cohort of competitors that were phonemically, rather than syllabically, related to the target word. That is, rather than the effect being based upon the cohort of candidates sharing the same initial /CV/ syllable of the target, the observed ERP effects could be due to the activation of candidates sharing the initial two phonemes of the target. Our own analyses show a significant correlation between the total frequency of the phonemic and syllabically related cohort of candidates for the 225 /CV/ and /CVC/ French sequences used in our study ($r=0.52$, $t(223)=8.9$, $p<0.0001$). That is, while the frequency of the initial syllable of a word might provide an accurate indication of frequency of the syllabically activated cohort, it is also related to the frequency of a phonemically activated cohort. Therefore, while /CV/ syllable frequency was manipulated as part of the initial syllable of /CV.CV(C)/ carrier words, we do not know whether syllable frequency effects are indeed syllabic in nature or whether they reflect processing at the phonemic level. In our experiments, we borrow from the experimental design of Mehler et al. (1981) described earlier to verify whether /CV/ or /CVC/ syllable frequency effects are found in target words with /CV.CV(C)/ and /CVC.CV(C)/ structures. If the locus of the frequency effects is indeed syllabic, rather than phonemic, then they should only be found when syllabic conditions are matched. This study also departs from previous ERP studies of syllable frequency in the choice of task used to evoke visual word recognition from participants. In previous studies, a lexical decision task was used to compare the latency of lexical and syllabic effects. With lexical effects established at around 350 ms in the previous studies, the focus of this study lies in the comparison of syllabic effects in matched and mismatched syllabic conditions. Therefore, to maximize the number of observations across experimental conditions and minimize the potential effects of both the task and participant response strategies upon potential pre-lexical syllabic effects, a post-lexical, semantic decision task was chosen for this study. In a go/no-go task, participants were asked to make a go response only for a number of animal probe words whose ERP data were later discarded, leaving the test conditions free from overt participant response.

2. Experiment 1: /CV/ syllable frequency

The main aim of this experiment was to examine the time course of possible syllabic activation in French visual word recognition. Participants were presented with bisyllabic French words whose initial /CV/ sequence corresponded to syllables of either low or high frequency. These target words were also split between a syllabically matched condition, having an initial /CV/ syllable, and mismatched condition, where the initial syllable was /CVC/. The activation of a syllabic cohort of lexical candidates should be indicated by a significant difference in ERP waveforms between high and low frequency syllables in the matched condition only. If an effect of syllable frequency was also found in the syllabically mismatched condition, this would indicate that the locus of activation was phonemic, rather than syllabic. This combined effect would result from the activation of a cohort of possible candidates sharing the initial two phonemes of the target word. Based upon the previous conclusions of Barber et al. (2004) and Hutzler et al. (2004), pre-lexical activation should be indicated by frequency effects seen in time windows ending less than 350 ms after target presentation. This premise follows from the timing of lexical frequency effects found in both studies, which were only seen 350 ms after target presentation.

2.1. Methods and materials

2.1.1. Participants—Twenty-one university students, all right-handed native speakers of French, took part in the experiment (16 women) aged between 18 and 28 (mean 21.15 years). All were paid for their time.

2.1.2. Stimuli—A list of 240 disyllabic words, all between 5 and 10 letters, was selected from the Lexique (New et al., 2001) French corpus. The first half of these words was of the form /CV.CV(C)/, i.e., with a /CV/ initial syllable (e.g., /fa.min/, “famin”). The remaining words were of the form /CVC.CV(C)/, with the intervocalic consonant cluster chosen to elicit a /CVC/ initial syllable (e.g., /jas.min/, “jasmine”) ¹. In addition, the words from each of these categories were split between those whose initial /CV/ sequence corresponded to a syllable of high or low frequency (see Table 1). This design results in two cases, one in which the frequency disparity of the /CV/ sequence is syllabically matched, with an initial /CV/ syllable, and those where it is unmatched, having a /CVC/ initial syllable. Word frequency, word length, /CVC/ syllable frequency and orthographic neighborhood size (the number of words that can be created by changing one letter of the stimulus, preserving letter positions) were matched across conditions. The syllable frequencies previously described were non-positional, calculated as the sum of the lexical frequency for all words found in Lexique containing a syllable consisting of the initial /CV/ or /CVC/ sequence of the stimuli. However, additional positional statistics for the stimuli were also calculated and presented in Table 1, describing the frequency of lexical cohort with the same initial /CV/ syllable or bi-phone as the stimuli. For example, for the stimulus “gateau” (“cake”), the syllabic cohort frequency would be the total frequency of all words with the initial syllable /ga/. This frequency is a subset of the phonemic cohort frequency which consists of the total frequency of all words with the phoneme /g/ in first position and /a/ in second position. As might be expected, a comparison of syllabic and phonemic cohort frequencies across all the /CV/ syllables revealed that there was a significant correlation between these frequencies ($r=0.36$, $t(62)=3.1$, $p=0.0015$). An additional 32 disyllabic probe words were also generated, each the name of a common animal, half of the form /CV.CV(C)/ the other half /CVC.CV(C)/. ERP data collected during the presentation of these 32 probe words were not used in subsequent analyses.

¹French syllable structure in this study will be referenced from the syllabification model of Laporte (1992), shown to accurately represent the preferential syllable segmentation responses of French listeners in metalinguistic tasks (Goslin and Frauenfelder, 2001).

2.1.3. Procedure—Participants were presented with stimuli words in white lower case letters against a black background in which animal names served as probe items in a go/no-go semantic categorization task. Participants were required to press a response button beneath their right thumb as quickly as possible if they considered the word to be the name of an animal, all other words required no response. Each of the words was preceded by a fixation point (+) which remained on the screen for 1 s, followed by a blank screen for 200 ms. The stimulus word remained on the screen for 1500 ms or until the participant pressed the response button. The word was followed by a blank screen for 300 ms followed by a symbol that invited them to blink their eyes which remained on screen for 1 s followed a blank screen of 300 ms before the start of the next trial. Stimuli presentation order was randomized for each participant, separated into four blocks between which the participants were invited to take a small pause. A practice session was administered before the main experiment to familiarize the participant with the procedure.

2.1.4. ERP data acquisition and analysis—The electroencephalogram (EEG) was recorded from 29 active tin electrodes held in place on the scalp by an elastic cap (Electrode-Cap International). Scalp locations included those over the left and right fronto-polar (FP1/FP2), frontal (F3/F4, F7/F8), frontal–central (FC1/FC2, FC5/FC6), central (C3/C4), temporal (T5/T6, T3/T4), central–parietal (CP1/CP2, CP5/CP6), parietal (P3/P4), and occipital (O1/O2) areas and five midline sites over the frontal pole (FPz), frontal (Fz), central (Cz), parietal (Pz), and occipital (Oz) areas (see Fig. 1). In addition, four electrodes were attached to the face and neck area: one below the left eye (to monitor for vertical eye movement/ blinks), one to the right of the right eye (to monitor for horizontal eye movements), one over the left mastoid (reference), and one over the right mastoid (recorded actively to monitor for differential mastoid activity). All EEG electrode impedances were maintained below 2.5 k Ω (impedance for eye electrodes was less than 10 k Ω). The EEG was amplified by an SA Bioamplifier with a bandpass of 0.01 and 40 Hz, and the EEG was continuously sampled at a rate of 200 Hz.

Averaged ERPs were formed off-line from trials free of ocular and muscular artifact. Separate waveforms were calculated by averaging ERPs across the various experimental conditions. ERPs were quantified by measuring mean amplitudes in five post-target onset latency windows (150–300 ms, 300–550 ms, 550–600 ms, and 600–800 ms) each baselined to the average activity in the 100 ms pre-stimulus epoch. For each time window, repeated measures analyses of variance (ANOVAs) were conducted using the within-subject factors of syllable structure (matched-/CV.CV(C)/ vs. unmatched-/CVC.CV(C)/) and /CV/ syllable frequency (high vs. low). To thoroughly analyze the scalp distribution of ERP effects, separate analyses were performed for each of four columns of electrodes (see Fig. 1) that each included an anterior–posterior factor of electrode site. These included: midline (FPz, Fz, Cz, Pz, Oz), column 1 (FC1, C3, CP1, FC2, C4, CP2), column 2 (F3, FC5, CP5, P3, F4, FC6, CP6, P4), and column 3 (FP1, F7, T3, T5, O1, FP2, F8, T4, T6, O2). For columns 1, 2, and 3, we also included a factor of hemisphere (left/right). Where appropriate, the Geisser–Greenhouse correction (Geisser and Greenhouse, 1959) was applied for violation of the assumption of sphericity. In cases of interaction with either electrode location or hemisphere, the data were re-analyzed after z-normalization.

2.2. Results

Grand average waveforms, seen in Fig. 2, reveal a broadly distributed N1–P2 complex which is followed by an N400 component at most scalp sites. Visual inspection suggests that an effect of syllable frequency occurs as early as 300 ms, however, at this point, it is limited to the matched syllabic condition (those with an initial /CV/ syllable). As can be seen in Fig. 3, early activity due to increased syllable frequency is regional, resulting in increased positivity in left anterior electrodes and increased negativity in central posterior electrodes. In later epochs, the

increased positivity spreads to the anterior electrodes until the effect peaks between 550 and 600 ms with a general increase in positivity with syllable frequency. At this final epoch, there is also a general effect of syllable frequency, common to both matched and mismatched conditions, although it is significantly stronger in the former condition.

2.3. Significant ERP effects

2.3.1. 150–300 ms latency window—ANOVA revealed no significant ($p < 0.05$) main effects or interactions.

2.3.2. 300–550 ms latency window—ANOVAs between 300 and 550 ms revealed a significant interaction between syllable structure, syllable frequency, and electrode location in the C2 column of electrodes ($F(3,60) = 4.84, p = 0.004$, after normalization $F(3,60) = 5.69, p = 0.0017$). Further examination of this interaction revealed that the effect of /CV/ syllable frequency and electrode location was only significant when the structure of the carrier was matched (/CV.CV(C)/: $F(3,60) = 6.56, p < 0.001$, after normalization $F(3,60) = 7.34, p < 0.001$) and not when unmatched (/CVC.CV(C)/: $F(3,60) = 0.52, p = 0.66$). As can be seen in Fig. 2 (top), this effect took the form of a larger positivity for high frequency syllables at more anterior sites and a larger negativity for these same items at the more posterior electrodes.

2.3.3. 550–600 ms latency window—Between 550 and 600 ms, the interaction between syllable structure and syllable frequency seen in the previous epoch was now generally significant across electrode locations in midline ($F(1,20) = 4.60, p = 0.044$), C1 ($F(1,20) = 7.89, p = 0.01$), and C2 ($F(1,20) = 7.73, p = 0.011$) columns. As before, the effect of syllable frequency was only significant in matched (matched: midline ($F(1,20) = 8.46, p = 0.008$), C1 ($F(1,20) = 7.08, p = 0.015$), C2 ($F(1,20) = 8.47, p = 0.009$), unmatched: midline ($F(1,20) = 0.04, p = 0.83$), C1 ($F(1,20) < 0.001, p = 0.98$), and C2 ($F(1,20) = 0.03, p = 0.86$)) syllabic conditions across all electrode columns. In the C3 electrode column, a general effect of syllable frequency was found ($F(1,20) = 4.42, p = 0.048$). Finally, a significant effect of target type was found in the midline ($F(1,20) = 4.40, p = 0.049$) and a significant interaction between target type and electrode location in the C2 line ($F(3,60) = 3.94, p = 0.031$, after normalization $F(3,60) = 4.28, p = 0.021$).

2.3.4. 600–800 ms latency window—ANOVA revealed no significant ($p < 0.05$) main effects or interactions.

2.4. Discussion of Experiment 1

In this experiment, we found significant differences in ERPs associated with changes in the frequency of the initial /CV/ syllables of words. Between 300 and 550 ms, these differences were only significant when the initial syllable of the target word was also /CV/ rather than mismatched initial /CVC/ syllable words. These results indicate that syllabic units have some role to play in French and that this activation respects known syllable segmentation behavior. As can be seen in Fig. 3, this syllabic activity is initially characterized by a significant bi-polar response with increased positivity due to high frequency syllables in anterior electrodes and increased negativity in posterior electrodes.

As time passes, the increased negativity in the posterior electrodes reduces until, in the 550–600 ms epoch, the relationship between EEG and syllable frequency is generally positive. As can be seen in Fig. 2, it is in this final epoch that we find the greatest syllabic activity, with a strong negative deflection associated with low frequency syllables. However, while the effect of syllable frequency was limited to the matched condition in most electrode sites, in the C3 line of electrodes, there were significant effects of syllable frequency in both matched and unmatched conditions. The presence of /CV/ syllable frequency effects in mismatched, /

CVC.CV(C)/, targets could point towards phonemic activation, due to the association between the /CV/ syllable and bi-phone cohort frequencies. However, it is also possible that the frequency effects in the mismatched condition were syllabic and stemmed from syllabification variability. In this experiment, the target stimuli were segmented using an algorithm that has been shown to reflect the preferred segmentation of French listeners. However, while the preferred segmentation may account for the majority of listeners responses, there still exists a significant minority of cases where listeners segment a given intervocalic consonant cluster differently (Goslin and Frauenfelder, 2001). This variation is known to be particularly prevalent in syllable offset detection (e.g., Content et al., 2001), i.e., when attempting to decide when a syllable should end rather than when one should start. Therefore, it is possible that in a minority of cases our participants might have segmented the mismatched targets as /CV.CCV(C)/ rather than /CVC.CV (C)/, causing the observed syllable frequency effect.

Another effect observed in the 550–600 ms time window was that of target type, where potentials along the midline of electrodes were more positive for /CVC.CV(C)/ target words than /CV.CV(C)/ words. While it is possible that this effect is associated with either syllable complexity or boundary placement, it is also possible that this effect is also due to a frequency differential. As can be seen in Table 1, the average frequency of /CV/ syllables found in the stimuli is more than an order of magnitude greater than /CVC/ syllables. However, a problem with this explanation is that the polarity of this potential frequency effect is the opposite to that of /CV/ frequency also seen in this experiment.

This preponderance of later syllabic effects, coupled with the lack of any significant activity before 300 ms after the presentation of the stimulus, is at odds with the previous ERP studies of syllable which indicated the possible pre-lexical activation of syllabic units. In the studies of Barber et al. (2004) and Hutzler et al. (2004), significant syllable frequency effects were found in time windows starting at 150 and 190 ms respectively. In both of these studies, syllabic effects were found well before those attributed to lexicality, indicated by lexical frequency effects in the former study and lexical status effects in the latter, in time windows starting at 350 ms. While there are significant differences between our study and those conducted previously, notably the task and electrode organization used in the present study, the lack of any significant ERP effects associated with syllable frequency before 350 ms in our own study does not allow us to rule out either a lexical or post-lexical locus for this syllabic activity.

Temporal differences aside, another important deviation between the ERP effects associated with syllable frequency in this and previous studies is the polarity of this effect. In the previous studies, syllables words with high frequency syllables produced an increase in the amplitude of the N400 in anterior electrodes, an increase in negative potentials compared to syllables with low frequency. This was interpreted as representing a difference in general semantic activation caused by the spread of activation from the cohort of words sharing the initial syllable as the target words. However, in our study, high frequency syllables led to a reduction of the N400 in anterior electrodes, the opposite effect to that found in the previous studies.

We suggest that both the time frame and polarity of the syllable frequency effects seen in our study are more consistent with the activation of syllabic units that are directly involved in the perception and production of speech but only indirectly involved in visual word recognition. However, there still remains the possibility that the source of these findings could be purely orthographic. Analyses revealed that the positional bigram frequency of the initial two graphemes of the stimuli, shown in Table 1, is significantly correlated with phonological syllable frequencies ($r = 0.31$, $t(238) = 4.95$, $p < 0.0001$). Therefore, the selection of the stimuli into high and low phonological frequency categories in this experiment also yields a similar orthographic frequency grouping. Both of these hypotheses will be enlarged upon later in this study.

3. Experiment 2: /CVC/ syllable frequency

The purpose of Experiment 2 is to establish whether the syllabic effects noted in the previous experiment are syllable generic and are not simply limited to /CV/ syllables. The /CV/ syllable is widely held as forming the core syllable, used as a primitive and innate representational pattern used in speech production and perception. Evidence to support this theory comes from analyses of both Spanish and German infants production from the age of 0;9 to 2;1 (LLeo and Prinz, 1996). At the earliest stages, the majority of produced syllabic structures in both languages are /CV/. During development, this representation is gradually built upon, increasing in complexity through the progressive branching of syllabic constituents. Initially, the coda will be defined, and then an extension in the number of available slots in the onset and coda position will take place, giving rise to the following order of complexity: CV–CVC–CVCC–CCVCC.

In Experiment 2 we examine whether the findings of Experiment 1 with the canonic /CV/ syllables can also be seen with more complex /CVC/ syllables by reversing the matched/ mismatched conditions and examining the effect of /CVC/ syllable frequency. Generic syllabic activity should be indicated by similar findings in both experiments, indicated by differences in electrophysiological data between high and low frequency syllables only in the matched syllabic conditions.

3.1. Methods and materials

3.1.1. Participants—Thirty-one university students, all right-handed native speakers of French, took part in the experiment (20 women) aged between 18 and 28 (mean 21.61 years).

3.1.2. Stimuli—A list of 280 disyllabic words was selected according to criteria similar to that used in Experiment 1. The only departure from the previous design was in the selection of words with high and low frequency /CVC/ initial syllables (see Table 2) rather than /CV/ syllables used in the previous experiment. Therefore, in this experiment, the frequency disparity between stimuli pairs will be syllabically matched in /CVC.CV(C)/ and not in /CV.CV(C)/ words, the opposite to that of Experiment 1. Likewise, the initial /CV/ syllable frequency of stimuli was matched across conditions rather than /CVC/ frequency in the previous experiment. Again, the frequency of both the syllabic and phonemic cohort for the stimuli was calculated and is shown in Table 2 as in Experiment 1 a significant correlation was found between these frequencies ($r=0.81$, $t(161)=17.51$, $p<0.001$). The 32 animal probe words previously used in Experiment 1 were also used in this experiment and, as before, the ERP data collected during the presentation of these words were not used in subsequent analyses.

3.1.3. Procedure—The procedures is the same as in Experiment 1, but with a reversal of matched (now /CVC.CV(C)/ words) and unmatched conditions (now /CV.CV(C)/ words).

3.1.4. ERP data acquisition and analysis—The ERP data acquisition and analysis is the same as in Experiment 1 except that the ANOVA for each time window was conducted with the within-subject factor of /CV/ frequency instead of /CVC/ frequency.

3.2. Results

Grand average waveforms, seen in Fig. 4, reveal an N1–P2 complex followed by an N400 component. In early epochs, high /CVC/ syllable frequency can be seen to decrease the N1 and increase the P2 deflections compared to low /CVC/ frequencies in both the syllabically matched and unmatched target words. However, as can be seen in Fig. 5, this effect is largely limited to frontal electrode sites and can, in the case of the P2 deflection, lead to a reversal of the effect in posterior electrodes.

In later epochs, the effect of syllable frequency is limited to words with a matched syllable structure, that is, increased /CVC/ syllable frequency results in greater positivity only in words with an initial matched /CVC/ syllable structure (/CVC.CV(C)/). Between 300 and 800 ms, high frequency syllables reduced the negative deflection (more positive) compared to those with low frequency although, as can be seen in Figs. 2 and 3, between 300 and 550 ms, these differences appear to be localized to the right anterior electrodes.

3.3. Analyses of ERP data

3.3.1. 150–300 ms latency window—Analyses revealed an interaction between syllable frequency and electrode location that was significant in C1 ($F(2,60)=3.91, p=0.025$, after normalization $F(2,60)=4.28, p=0.018$), marginal in C2 ($F(3,90)=2.66, p=0.053$, after normalization $F(3,90)=5.21, p=0.002$), and midline ($F(4,120)=2.39, p=0.054$, after normalization $F(4,120)=3.73, p=0.007$), but not significant in C3 ($p>0.05$).

3.3.2. 300–550 ms latency window—Analyses for waveforms between 300 and 550 ms revealed a significant interaction between target type, syllable frequency, hemisphere, and electrode location in the C2 line of electrodes ($F(3,90)=2.81, p=0.044$, after normalization $F(3,90)=3.45, p=0.020$). Further examination of the interaction between frequency and hemisphere revealed that it was only significant when the structure of the carrier was matched (/CVC.CV(C)/: $F(1,28)=9.81, p=0.004$, after normalization $F(1,28)=11.18, p=0.002$) and not when unmatched (/CV.CV(C)/: $F(1,28)=1.79, p=0.19$).

3.3.3. 550–600 ms latency window—Between 550 and 600 ms, the interaction between target type and syllable frequency seen between 300 and 550 ms is now generally significant across electrode locations in midline ($F(1,28)=7.12, p=0.012$), C1 ($F(1,28)=5.28, p=0.029$), C2 ($F(1,28)=5.88, p=0.022$), and C3 ($F(1,28)=6.57, p=0.016$) lines. As before, the effect of syllable frequency was only significant in matched (matched: midline ($F(1,28)=5.59, p=0.025$), C1 ($F(1,28)=4.11, p=0.052$), C2 ($F(1,28)=4.67, p=0.039$), C3 ($F(1,28)=5.92, p=0.021$), unmatched: midline ($F(1,28)=1.5, p=0.23$), C1 ($F(1,28)=1.08, p=0.31$), C2 ($F(1,28)=0.54, p=0.46$) and C3 ($F(1,28)<0.001, p=0.99$) syllabic conditions. Furthermore, a main effect of target type was found in the C3 line ($F(1,28)=4.44, p=0.044$) and an interaction between target type and electrode locations in midline ($F(4,112)=4.87, p=0.01$, after normalization $F(4,112)=6.04, p=0.004$) and C1 ($F(2,56)=4.33, p=0.02$, after normalization $F(2,56)=3.65, p=0.032$) lines.

3.3.4. 600–800 ms latency window—In the final window, a significant interaction was found between syllable frequency and electrode location in midline ($F(4,112)=4.93, p=0.012$, after normalization $F(4,112)=4.45, p=0.022$) and C2 ($F(3,84)=4.05, p=0.028$, after normalization $F(3,84)=4.19, p=0.024$) lines, with a three-way interaction between these factors and hemisphere in the C3 line ($F(4,112)=2.69, p=0.049$, after normalization $F(4,112)=2.71, p=0.048$). In addition, a four-way interaction between syllable frequency, target type, hemisphere, and electrode location was found in C1 ($F(2,56)=4.98, p=0.01$, after normalization $F(2,56)=3.2, p=0.048$) and C2 lines ($F(3,84)=3.97, p=0.017$, after normalization $F(3,84)=3.74, p=0.014$). However, further examination revealed that when examined in isolation the effects of /CVC/ frequency did not reach significance with either matched or unmatched carriers ($p>0.05$).

3.4. Discussion of Experiment 2

The main aim of this experiment was to verify whether the syllable frequency ERP effects seen with initial /CV/ syllables in Experiment 1 could be replicated with more complex /CVC/ syllables. We found that the syllabic findings from both of the experiments were largely comparable. As in the previous experiment between 300 and 550 ms, the effects of syllable

frequency were limited to matched target words, represented by a bi-polar response with high frequency syllables leading to increased positivity in anterior electrodes and increased negativity in posterior electrodes. Similarly, by the 550–600 ms time window, the effect of high /CVC/ frequency was also represented by general positivity, again, this was limited to matched targets. The effect of target type found in this time window was also replicated in this experiment, with high positivity for targets with initial /CVC/ rather than /CV/ syllables. In agreement with the previous experiment, these indicators of valid syllabic activity do not arise before 300 ms after the presentation of the stimuli, with syllabic activity peaking with a negative deflection between 550 and 600 ms in words with low frequency initial syllables. These findings show that the activity shown in the previous experiment with /CV/ initial syllables can be extended to more complex /CVC/ syllables. However, the findings of both experiments point towards a late role for syllabic representations, suggesting that they are only indirectly involved in processing printed words.

As we have seen, indicators of syllabic activity, indicated by frequency effects found only in the syllabically matched condition, are highly similar in both experiments, with a 350–600 ms window of syllabic activity for both /CV/ and /CVC/ syllables. However, there are marked differences in both the timing and prevalence of general frequency effects between Experiments 1 and 2. As previously discussed, when syllable frequency effects are found in both the syllabically matched and unmatched conditions (a general syllable frequency effect), the locus of these effects is more likely to be phonemic than syllabic. In Experiment 1, general syllable frequency effects were isolated to the C3 line of electrodes in the 550–600 ms time window. However, in Experiment 2, this late effect of syllable frequency was delayed and was found to be significant in the 600–800 ms time window in both mid and C2 electrode lines. In addition, an early general effect of syllable frequency was also found in the 150–300 ms time window of Experiment 2 in the C1 line of electrodes, a finding which is inconsistent with early activation of syllabic representations, as it can be seen in the mismatched syllabic condition. This finding is indicative of the activation of frequency sensitive phoneme representations. However, as in Experiment 1, analyses revealed that positional orthographic and phonological frequencies for the stimuli in this experiment were correlated ($r=0.58$, $t(278)=11.99$, $p<0.0001$), meaning that this effect could also result from differences in orthographic typicality.

4. General discussion

The two experiments reported in this study examined effects of syllable frequency on ERPs to visually presented French words. We found that there were consistent ERP effects associated with the activation of syllabic representations between 300 and 600 ms after target word presentation. This finding was indicated by significant differences in ERP amplitude between words with high or low frequency initial syllables. The locus of this effect was verified by testing for syllable frequency effects in target words whose initial syllable provided either a match or mismatch with the syllable under analysis. As the initial phonemic representation of the target was coincident with the syllable under analysis in both conditions, then a general frequency effect over both conditions would have pointed towards phonemic processing. However, over this time window, syllable frequency effects were largely limited to the matched condition, which is indicative of syllabic phonological processing.

While this finding would appear to support some form of syllabic processing in the processing of printed words in French, the latency of these effects would suggest a relatively indirect influence compared with the influence of phonemic representations. In both the previous ERP studies of syllable frequency, conducted in Spanish (Barber et al., 2004) and German (Hutzler et al., 2004), the early onset of syllable frequency effects, between 150 and 200 ms, provided support for pre-lexical syllabic processing as they occurred before the onset of lexical

frequency effects at around 350–400 ms. In our own study of French visual word recognition, no significant effects of /CV/ frequency were seen in this early time window, between 150 and 350 ms. However, in Experiment 2, we did find significant effects of /CVC/ syllable frequency, but in both the mismatched and matched syllabic conditions. As has been discussed, this finding is more consistent with the use of phonemic pre-lexical processing in French, rather than syllabic representations, as the frequency effect did not respect the syllable boundaries of the target word. This conclusion is also supported by the lack of this early effect in Experiment 1 where /CV/ syllable frequency was manipulated. According to the syllabic hypothesis put forward by Carreiras et al. (1993), lexical access can be mediated through the activation of pre-lexical syllabic representations. However, under this hypothesis, the phonemic length of particular syllables should have no effect upon spread of bottom-up activation as syllables of all lengths are represented as single pre-lexical unit. Conversely, under the phonemic hypothesis, the amount of activation transmitted to the cohort of lexical candidates would increase as a proportion of the overlap between the target and candidates. This might explain why general frequency effects were only seen in Experiment 2 as the overlap for the /CVC/ sequences under analysis in this experiment was greater than the /CV/ sequences in Experiment 1.

An alternative explanation for the presence of syllable frequency effects in unmatched syllabic conditions in our own study could stem from variability in the syllabification of the target words. In this case, the syllabic locus of general frequency effects could be maintained if we assume that in a significant number of cases our participants syllabified mismatched target words such that it matched the syllable type under analysis. Unfortunately, this assumption also has serious detrimental implications for the use of syllabic classification units in French, a concept postulated by Carreiras et al. (1993) for Spanish visual word recognition. In a study of English, Cutler and Norris (1988) introduced an important distinction between segmentation and classification roles for the syllable, stating that these processes are logically distinct and that while classification requires segmentation the reverse is not true. They insisted that the role of the syllable lies in segmentation, rather than classification, as embodied in the Metrical Segmentation Strategy (Cutler and Norris, 1988), where lexical look-up is initiated at the onset of strong syllables. A similar hypothesis has also been forwarded by Content et al. (2001) in French, who propose that there are distinct processes involved in the detection of syllable onsets and offsets, with syllable onsets serving as alignment points for lexical search. This hypothesis stemmed from the results of syllable repetition experiments where it was found that syllable onset detection was significantly more consistent than offset detection and also from later studies of syllable onset and offset misalignment in word spotting (Dumay et al., 2002). These findings have important implications in the syllable as a classification unit as this role requires a boundary conception of segmentation. Therefore, any segmental inconsistencies, leading to pre-lexical to lexical mismatch, or disparities between syllable onset and offset detection, leading to ambisyllabic behavior, would seriously undermine the effectiveness of pre-lexical syllabic classification.

Finally, a possible alternative to these two phonological explanations is that the locus of the early general frequency effects is purely orthographic. In both experiments, analyses revealed a significant correlation between phonological syllabic frequency and corresponding orthographic bi- and trigrams. Indeed, a recent study of English orthographic typicality by Hauk et al. (2006) showed ERP effects associated with differences in positional bi and trigram frequencies at latencies of 100 and 284 ms after stimulus onset. However, while the latter latency falls into the same range as that of our early syllabic activity (150–350 ms), the polarity of these two effects was the opposite. In the study by Hauk et al., words with high initial bi- or trigram frequency were more negative than those with lower frequency, whereas the relationship between ERP amplitude and our early frequency effects was generally positive. While this disparity cannot preclude a purely orthographic locus for our earlier frequency

effects, it does call this hypothesis into question. Similarly, when considering the locus of the later syllable frequency effects seen in our study, with latencies between 350 and 650 ms, it must be noted that Hauk et al. did not observe any effects of orthographic typicality later than 284 ms after the onset of the stimulus.

Another indicator of the locus of the later syllable frequency comes from the finding that they are generally only found in syllabically matched conditions, meaning that they respected known phonological syllabification principles. Because French has a deep orthography, where the relationship between spelling and sound can be opaque, the phonological mechanisms used to segment syllables do not always respect orthographic segmentation. Furthermore, in French, orthographic knowledge has been shown to interfere with the syllabification of spoken words. This phenomena was seen in a study by Goslin and Floccia (under revision), who compared the segmentation of spoken words between pre-literate children and literate adults. They found that, although syllable segmentation was largely stable throughout the course of development, the disparities between orthographic and phonological representations caused confusion in adult participants. For example, in the word “taxi”, the children reliably split the intervocalic consonant cluster /ks/ between the first and second syllable. However, in adults the single graphemic representation of this cluster resulted in an abnormally high proportion of tautosyllabic responses.

Not only do these findings highlight the phonological locus of syllable segmentation in French, but they may also indicate why we failed to find evidence of pre-lexical syllabic activation in French, unlike that found in similar ERP studies of Spanish (Barber et al., 2004) and German (Hutzler et al., 2004). As both Spanish and German have a shallow orthographic system, the simple relationship between orthographic and phonological representations would facilitate the direct activation of syllabic units in visual word recognition, without the requirement of a phonemic intermediary. However, as we have seen, in French, there are cases in which syllable segmentation requires the use of phonemic knowledge, requiring the activation of a phonemic pre-lexical representation. In this case, it becomes more difficult to argue for a further, syllabic stage during the pre-lexical processing of French words.

Taking these factors into consideration, we suggest that our findings point towards the possibility of a pre-lexical processing in visual word recognition in French using phonemic, rather than syllabic, phonological units. Phonemes would play a central role in the processing of visible language given the key role they play during the process of learning to read (Ziegler and Goswami, 2005). Syllable representations, on the other hand, would play a central role in the processing of spoken language and would only be activated by a printed word via activation of the word’s constituent phonemes. Thus, according to this account, phoneme representations (and their corresponding grapheme representations) provide the central interface between written and spoken language, whereas syllables are more strongly tied to the processing of spoken language.

This proposal fits with the recent finding of Grainger et al. (in press) showing phonological influences on visual word recognition as early as 200 ms post-target onset in a masked priming ERP study. Primes that were pseudo-homophones of target words (e.g., brane-BRAIN) generated ERP waveforms that diverged from the orthographic control primes (e.g., brant-BRAIN) starting around 200 ms post-target onset. This phonological effect was interpreted as reflecting fast grapheme-to-phoneme conversion following presentation of a pronounceable string of letters. The estimated timing of this phonological priming effect therefore fits with the present proposal that syllable representations are contacted following phoneme activation with an estimated onset of syllable effects at around 300 ms post-stimulus onset.

These findings also offer further support for the conclusions of Ferrand et al. (1996), whose study of French visual word recognition showed that syllable priming was significant in reducing latencies in naming, but not lexical decision tasks². They suggested that the disparity found between these tasks was not consistent with pre-lexical syllabic processing in visual word recognition as the effects were only found when the participants articulated their response. Indeed, the naming task involves generating a speech output and therefore necessarily involves representations that are central to the processing of speech. Visual lexical decision, on the other hand, does not necessarily involve such representations.

Furthermore, if the syllable representations that are responsible for syllable frequency effects are only activated via phoneme representations, then this implies that it is phonologically defined and not orthographically defined syllables that are the basis of syllable effects found in visual word recognition. In line with this reasoning, Conrad et al. (in press) have recently shown that the pattern of behavioral results generated by a syllable frequency manipulation in French is driven by phonologically defined and not orthographically defined syllables. Thus, it is the number of other words that share the same initial phonological syllable that is important, independently of whether or not the initial syllable is spelled the same way.

This interpretation of the present results is compatible with a number of models of speech perception and production that have postulated a central role for the syllable. Although the role of the syllable in speech perception (e.g., Mehler et al., 1981; Cutler and Norris, 1988; Content et al., 2001) is more controversial than its role in the production of speech (e.g., Dell, 1986, 1988; Levelt et al., 1999), this debate is not critical for the present interpretation and is certainly beyond the scope of the present study. What is important with respect to our proposed interpretation of the present results is that syllables are considered to be critical units at some point in the processing of spoken language.

In summary, the manipulation of syllable frequency in French target words in our experiments resulted in ERP effects between 350 and 600 ms after target onset that were consistent with syllabic activation. We suggest that activity in this time frame, along with the positive relationship between the measured potential and syllable frequency, is indicative of access to phonological syllable representations that play a central role in the processing of spoken language. The early ERP effects seen in our study, on the other hand, more likely reflect pre-lexical phonemic processing.

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²But see Carreiras and Perea (2002) for alternative results in Spanish.

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Fig. 1.
Electrode montage used in Experiments 1 and 2.

/CV.CV(C)/ (Unmatched)

/CVC.CV(C)/ (Matched)

Fig. 2.

Average ERP waveforms for /CV.CV(C)/ and /CVC.CV(C)/ words with high and low initial /CV/ syllables.

Fig. 3. Scalp distributions of initial /CV/ syllable frequency effects (high–low frequency) with /CV.CV(C)/ (matched) and /CVC.CV(C)/ (unmatched) carrier words between 150 and 800 ms. Bottom diagram describes the distribution of the effect of carrier word (/CV.CV(C)/–/CVC.CV(C)/) between 550 and 600 ms.

Fig. 4.
Average ERP waveforms for /CV.CV(C)/ and /CVC.CV(C)/ words with high and low frequency initial /CVC/ syllables.

Fig. 5. Scalp distributions of initial /CVC/ syllable frequency effects (high–low frequency) with /CV.CV(C)/ (unmatched) and /CVC.CV(C)/ (matched) carrier words between 150 and 800 ms. Bottom diagram describes the distribution of the effect of carrier word (/CV.CV(C)/–/CVC.CV(C)/) between 550 and 600 ms.

Table 1

Mean values of non-positional /CV/ and /CVC/ syllable frequency, lexical frequency, positional CV bigram frequency, orthographic neighbors, word length, and syllabic and phonemic cohort frequency for the words in each condition of Experiment 1

	/CV.CV(C)/ words		/CVC.CV(C)/ words	
	High /CVC/ syllable frequency	Low /CVC/ syllable frequency	High /CVC/ syllable frequency	Low /CVC/ syllable frequency
/CVC/ syllable frequency (/10 ⁶ ; non-positional)	2149.39	26.04	1902.33	16.77
Syllabic cohort frequency (/10 ⁶ ; non-positional)	570.50	12.13	453.76	3.28
CVC trigram frequency (/10 ⁶ ; positional)	2460.91	255.46	2911.80	860.14
Phonemic cohort frequency (/10 ⁶ ; positional)	1730.56	151.70	1855.67	135.17
/CV/ syllable frequency (/10 ⁶ ; non-positional)	5491.53	5087.92	5747.80	4956.77
Orthographic neighbors	0.40	0.37	0.66	0.64
Word length	7.19	7.49	6.73	6.33
Lexical frequency (/10 ⁶)	3.73	2.81	3.71	3.53

Table 2

Mean values of non-positional /CVC/ and /CV/ syllable frequency, lexical frequency, positional CVC trigram frequency, orthographic neighbors, word length, and syllabic and phonemic cohort frequency for the words in each condition of Experiment 2

	/CV.CV(C)/ words		/CVC.CV(C)/ words	
	High /CVC/ syllable frequency	Low /CVC/ syllable frequency	High /CVC/ syllable frequency	Low /CVC/ syllable frequency
/CVC/ syllable frequency (/10 ⁶ ; non-positional)	2149.39	26.04	1902.33	16.77
Syllabic cohort frequency (/10 ⁶ ; non-positional)	570.50	12.13	453.76	3.28
CVC trigram frequency (/10 ⁶ ; positional)	2460.91	255.46	2911.80	860.14
Phonemic cohort frequency (/10 ⁶ ; positional)	1730.56	151.70	1855.67	135.17
/CV/ syllable frequency (/10 ⁶ ; non-positional)	5491.53	5087.92	5747.80	4956.77
Orthographic neighbors	0.40	0.37	0.66	0.64
Word length	7.19	7.49	6.73	6.33
Lexical frequency (/10 ⁶)	3.73	2.81	3.71	3.53