The Speed of Orthographic Processing during Lexical Decision: Electrophysiological Evidence for Independent Coding of Letter Identity and Letter Position in Visual Word Recognition

Marina Mariol[1], Corentin Jacques[1,2], Marie-Anne Schelstraete[1], and Bruno Rossion[1,2]

Abstract

■ Adults can decide rapidly if a string of letters is a word or not. However, the exact time course of this discrimination is still an open question. Here we sought to track the time course of this discrimination and to determine how orthographic information—letter position and letter identity—is computed during reading. We used a go/no-go lexical decision task while recording event-related potentials (ERPs). Subjects were presented with single words (go trials) and pseudowords (no-go trials), which varied in orthographic conformation, presenting either a double consonant frequently doubled (i.e., ''ss'') or never doubled (i.e., ''zz'') (identity factor); and a position of the double consonant was which either legal or illegal (position factor), in a 2 × 2 factorial design. Words and pseudowords clearly differed as early as 230 msec. At this latency, ERP waveforms were modulated both by the identity and by the position of letters: The fronto-central no-go N2 was the smallest in amplitude and peaked the earliest to pseudowords presenting both an illegal double-letter position and an identity never encountered. At this stage, the two factors showed additive effects, suggesting an independent coding. The factors of identity and position of double letters interacted much later in the process, at the P3 level, around 300–400 msec on frontal and central sites, in line with the lexical decision data obtained in the behavioral study. Overall, these results show that the speed of lexical decision may depend on orthographic information coded independently by the identity and position of letters in a word. ■

INTRODUCTION

Following years of exposure to written language, adults become experts in word recognition, being able to read words efficiently and effortlessly in a few hundreds of milliseconds. It is now largely assumed that letters constitute the basic perceptual units in visual word recognition, and that during the first stages of visual word recognition, letter identity is extracted and then processed in an abstract way (i.e., regardless of font, size, or case; Pelli, Farell, & Moore, 2003; Grainger & Jacobs, 1996; Besner & McCann, 1987).

In alphabetic systems such as English or French with 26 letters, thousands of words can be formed that conform to the orthotactic constraints of the language. A word can be discriminated from another word by means of the *identity* of the letters that compose the string, and also by their arrangement or *position* within the string. For instance, we can differentiate between two orthographic neighbors like ''trail'' and ''train'' based on letter identity, whereas letter position is particularly important to distinguish between anagrams such as, for instance, ''liar'' and ''rail'' or ''lair.'' Therefore, words are recognized based on two crucial source of information: letter identity and letter position within the word; and their combination must conform to the orthographic constraints specific to the language.

According to an interactive activation model (IA), letter identity and letter position are computed at the same time so that the coding unit is not the letter per se but the letter at a given position (Paap, Newsome, McDonald, & Scvaneveldt, 1982; McClelland & Rumelhart, 1981). However, masked priming studies have found position-independent orthographic priming effects, suggesting that letters are coded in relative rather than in absolute position (Schoonbaert & Grainger, 2004; Peressotti & Grainger, 1999; Humphreys, Evett, & Quinlan, 1990). These observations led to the proposal of a coding of letter identity and position with the ''open-bigram'' coding (Grainger & Van Heuven, 2003). This account hypothesizes a first stage in word recognition, the alphabetic array, which is supposed to be composed of letter detectors that process letter identities in a parallel and in an independent way but still location-specific. Thus, the alphabetic array codes for the presence of a letter at a given

[1]Université catholique de Louvain, Louvain-la-Neuve, Belgium,
[2]Université catholique de Louvain, Bruxelles, Belgium

location relative to eye fixation. The location invariance is achieved at the next stage of orthographic processing and involves the computation of relative position information. At this stage, bigrams are formed across adjacent and nonadjacent letters in the correct order and use a hierarchical parallel activation. For example, the word ''table'' is coded by the bigrams /TA/ /TB/ /TL/ /TE/ /AB/ /AL/ /AE/ /BL/ /BE/. Whitney's (2001) SERIOL model is also based on a relative coding of nonadjacent letters but differs from the open-bigram account in how the bigrams are activated. The SERIOL model, as well as the SOLAR model (Davis, 1999), proposes an ordered, serial activation process from left to right.

Although word orthography can be defined by their letter identity and position, *how* and *when* these two factors are processed during word recognition remains largely unknown. More specifically, are letter identity and position computed together, as proposed in the IA model, or rather independently, as proposed in the ''open-bigram'' or SERIOL models? If the second proposal is true, then what is the exact time course of their respective processing? Another important and related question concerns the role that letter position and identity play in the discrimination between words and pseudowords conforming or not to the orthotactic constraints.

The goal of the present study was to test the effect of orthographic conformation on word/pseudoword discrimination (i.e., conformation about the identity and the position of letters). By manipulating these two factors orthogonally, and using event-related potentials (ERPs) in normal readers, we aimed to clarify which of these two factors, if any, is extracted first, and when are they bound together into a visual word representation. In order to dissociate between identity and position in orthographic information, we took advantage of the fact that, in French, the use of double consonants is highly constrained with respect to their identity and position in a word: Only certain consonants can be doubled (i.e., ''ll,'' ''ss'' but not ''hh'' or ''zz''), and there is never a double consonant at the beginning or at the end of a word. Thus, these two constraints should play a role in determining the speed at which strings of letters are recognized as a word or not, and can be used experimentally.

To clarify the time course of word recognition, a number of studies have recorded ERPs or magnetoencephalography (MEG) during written word stimulation. Recording with intracranial electrodes in a region of the left posterior fusiform gyrus responding preferentially to alphabetic stimuli, Nobre, Allison, and McCarthy (1994) reported a negative component peaking around 200 msec (N200), which was of equal amplitude to words and nonwords (letter strings). Recording on the human scalp, Bentin, Mouchetant-Rostaing, Giard, Echallier, and Pernier (1999) also described a posterior negative component peaking around 170 msec after stimulus onset (N170). This component was larger to alphabetic items than to nonalphabetic strings (symbols and forms), but there were no differences between words, pseudowords, and consonant strings before 300 msec. In a divided visual field experiment, Cohen et al. (2002) did not find any difference between alphabetic stimuli at the N170 level, but larger negativity to words than to consonant strings in the left occipito-temporal site after 230 msec. In line with the findings of Bentin et al. (1999) and Nobre et al. (1994), recent MEG studies of visual recognition also show negligible differences in the early brain responses (i.e., up to 200–250 msec poststimulus) to words, anagrams, nonwords, and random consonant strings (Pammer et al., 2004; Cornelissen, Tarkiainen, Helenius, & Salmelin, 2003; Tarkiainen, Helenius, Hansen, Cornelissen, & Salmelin, 1999). Altogether, these studies suggest that the posterior N170 is sensitive to alphabetic stimuli processes but not sensitive to orthographic characteristics of the stimuli. However, Compton, Grossenbacher, Posner, and Tucker (1991) showed task-dependent differences between word stimuli and consonant strings at about 150 to 225 msec. In that study, words elicited larger responses than consonant strings before 200 msec during passive reading, and the opposite was found during lexical decision. In the same vein, McCandliss, Posner, and Givon (1997) found larger response to consonant strings than words in a semantic task. Furthermore, these authors explored the role of learning on the brain mechanisms involved in orthographic processing in an ERP study with adults who spent 5 weeks learning a miniature artificial language. A posterior left-lateralized component at about 200 msec was sensitive to orthographic regularities, being larger in amplitude for the more regular items. In a one-back matching task, Maurer, Brandeis, and McCandliss (2005) also reported differences between words and pseudowords in English at the N170 level, with words more negative than pseudowords.

At present, these discrepancies between studies about the time course of word versus nonwords discrimination cannot be explained satisfactorily. It may well be that words and nonwords activate highly similar networks of nearby areas and, therefore, do not provide clearly distinct electrophysiological responses on the scalp. More fundamentally, behavioral studies suggest that there may not be a unique answer to the question of the speed at which words are discriminated from nonwords in the human brain (Ellis, 2004), and this issue is at the heart of the study carried out here. In order to avoid or minimize difficulties in tracking the time course of word/pseudoword discrimination, we designed an ERP paradigm in which words and pseudowords were associated with different overt behavioral responses, thereby allowing looking for an explicit electrophysiological marker of their distinction in time. More precisely, we used a go/no-go paradigm in which participants were instructed to respond on definite stimuli (go trials), but withhold their response on other stimuli (no-go trials).

ERP studies using a go/no-go response paradigm with visual stimulation have usually reported two main differences between go and no-go trials. The first difference is a fronto-central negative deflection in the ERP elicited by no-go trials peaking around 200–400 msec, the ''no-go N2'' (Bruin, Wijers, & van Staveren, 2001; Tekok-Kilic, Shucard, & Shucard, 2001; Falkenstein, Hoormann, & Hohnsbein, 1999; Filipovic, Jahanshahi, & Rothwell, 1999; Van't Ent & Apkarian, 1999; Kopp, Mattler, Goertz, & Rist, 1996; Thorpe, Fize, & Marlot, 1996; Eimer, 1993; Jodo & Kayama, 1992; Pfefferbaum & Ford, 1988; Kok, 1986; Pfefferbaum, Ford, Weller, & Kopell, 1985). The second difference between go and no-go trials is a positive shift, the ''no-go P3,'' maximal at fronto-central sites occurring with a latency of 300–500 msec. The P3 topographical distribution is more anterior for no-go stimuli compared to go stimuli (Pfefferbaum et al., 1985). This ''no-go N2–P3 complex'' has been suggested to reflect inhibition-related processes (Falkenstein et al., 1999) or to reveal a conflict arising from competition between the execution and the inhibition of a response (Donkers & van Boxtel, 2004; Nieuwenhuis, Yeung, Van den Wildenberg, & Ridderinkhof, 2003).

Here we coupled a go/no-go paradigm with a lexical decision task in order to determine the relative speed at which our parameters of interest (identity and letter position) influence the time course of word/pseudoword discrimination. Furthermore, by allocating pseudowords to no-go trials, we were able to measure the strength of inhibition needed to withhold the response relative to the response observed for real words (go trials).

In summary, the main goal of the present study was to track the time course of word/pseudoword discrimination and to test for the role of letter position and identity in this process. By manipulating these two factors, we addressed the issues of which of these two factors is processed first, and when both are bound together to take into account orthotactic constraints. Thus, contrary to previous studies, our investigation is based on the assumption that there is no unique answer to the question of the speed at which words are discriminated from pseudowords, but that it rather depends on the orthographic conformation of these pseudowords defined both by letter identity and letter position. We carried out both a behavioral study and an ERP experiment. The aim of the behavioral study was to inform about the relative speed at which pseudowords are rejected, depending on the factors of identity and position of double consonants. The ERP study aimed at disambiguating the early influence and weight of these two parameters in word/pseudoword discrimination by using a sensitive paradigm able to provide an explicit electrophysiological marker of their distinction in time with no overlap in the processing.

METHODS

Stimuli

We used the same set of stimuli in both the behavioral and the ERP experiments. The stimulus set comprised 960 items of eight letters, half words and half pseudowords (see Table 1). The words were selected from the lexical computerized database for written French, Brulex (Content, Mousty, & Radeau, 1990) as following: half frequent eight-letter words (mean $\log_{10}$ of frequency/million = 3.3, range 2.8–4.5) and half rare words (mean $\log_{10}$ of frequency/million = 1.4, range 0.7–1.9) (see Table 1A). Half of the words contained a double consonant. The selection constraints were (1) that the word did not contain the double consonant tested in the pseudowords (i.e., ''ll,'' ''ss''); this criterion was set in order to prevent interferences in the pseudowords processing and (2) that the word be part of the passive vocabulary of high school graduated students as evaluated by a judgment task.

We constructed 480 pseudowords including eight letters. We manipulated the consonant type on the existence of the doublet format (CCf: double consonant frequently doubled, i.e., ''ll,'' ''ss''; CCn: consonant never doubled, i.e., ''hh,'' ''zz''). Moreover, we also varied the position in which the different bigrams occurred: a legal position (median, inner letters) and an illegal position (end and beginning of items, outer letters) (see Table 1B). All the pseudowords were pronounceable and had no orthographic neighbor as defined by Coltheart, Davelaar, Jonasson, and Besner (1977).

Experimental Tasks and Procedures

Behavioral Study: Lexical Decision Task

A lexical decision task was used. Stimuli were presented using EPrime 1.1 on a 17-in. PC computer monitor. Each trial began with a fixation cross in the center of the screen for 400 msec, which then disappeared when the target string was presented. Targets were briefly presented for

Table 1. (A) Examples of Words Stimuli Extracted from the Brulex Database (Content et al., 1990) as a Function of Lexical Frequency (High vs. Low Frequency). (B) Examples of Pseudowords Stimuli as a Function of *Position* (Illegal vs. Legal) and *Identity* (Frequent vs. Never) of the Target Double Consonant (CC)

A

High Frequency	*Low Frequency*
biologie (240 items)	poudrier (240 items)

B

Identity Position	*CC Frequent (ll, ss)*	*CC Never (hh, zz)*
Legal (inner letters)	allinent (120 items)	ahhinent (120 items)
Illegal (outer letters)	llainent (120 items)	hhainent (120 items)

150 msec, at the center of the screen, subtending 5° of visual angle using the font verdana, 30 points, at a maximum contrast (written in white lowercase letters on a black background). The interval between stimuli varied randomly between 1500 and 1800 msec. The participant's task was to decide, as quickly and as accurately as possible, whether the stimulus was a legal French word or a nonword. The experiment's set comprised 960 stimuli split up into 10 blocks composed of 96 items each (48 pseudowords and 48 words) with balanced representation of each condition across blocks. Equal numbers of words and pseudowords were used in the stimulus set to encourage processing up to the lexical level (e.g., Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001) and to prevent the probability of the go stimuli to influence the amplitude of the no-go N2 in the ERP experiment (Bekker, Kenemans, & Verbaten, 2005). Blocks and items were presented in random order. The responses consisted in pressing one of two keys, one for a real word and the other for a nonword using the index fingers. The response's buttons assignment was counterbalanced across subjects.

ERP Study: Go/No-go Task

A go/no-go paradigm sensitive to fast recognition processes was used. Participants were instructed to respond only when a real word was presented. They were invited to be as accurate and as fast as possible. An infrared diode sensitive apparatus was used to measure the onset of button releases (Thorpe et al., 1996). Other than this response's apparatus, the procedure and stimuli were identical to the behavioral study.

Behavioral Study: Lexical Decision Task

Participants

Twenty right-handed normal adult (7 men, range = 19–32 years old) native French speakers, with no history of language impairment and with normal or corrected-to-normal vision, participated in the behavioral experiment. Participants were graduate and undergraduate students from the Université catholique de Louvain; Undergraduates received credits for their participation.

Data Analysis

Repeated measures analyses of variance (ANOVAs) were at first performed on responses separately for words and pseudowords. Analyses were conducted on the responses to words (reaction times on correct responses: RT, and accuracy: CR) with *lexical frequency* (frequent vs. rare) as a within-subjects factor. For the pseudowords, ANOVAs were computed for the reaction times on correct responses for the pseudowords with a double consonant in an illegal position with *location of the regularity violation* (beginning vs. end) of the double consonant as a within-subjects factor. Then, analyses were conducted on pseudoword responses (reaction times on correct responses: RT, and accuracy: CR) with *position* (legal vs. illegal) and *identity* (frequent vs. never) as within-subjects factors. Finally, we compared words and pseudowords with *lexicality* (words vs. pseudowords) as a factor, and we also performed pairwise comparisons in order to compare words and pseudowords for every condition.

ERP Study: Go/No-go Task

Participants

Nineteen normal adults (5 men, 1 left handed, range = 15–37 years old) who are native French speakers, with no history of language impairment and with normal or corrected-to-normal vision, participated in the ERP experiment. They were paid for their participation.

ERP Recording Procedure

Electroencephalogram (EEG) recording was conducted in a dimly lit room. Following electrode application, participants were seated in a comfortable chair. They were instructed to refrain blinking and remain as still as possible to prevent corresponding artifacts to interfere with the EEG recording. They were asked to focus on the center of the screen during stimuli presentation.

Continuous EEG activity was recorded from 58 tin scalp electrodes, arranged according to the extended 10–20 system, using an elastic cap (Quick-Cap, Neuromedical Supplies). Four additional electrodes were used to monitor eyes' movements and blinks. Horizontal EOG recording electrodes were placed at the outer canthi of the eyes and vertical EOG recording electrodes were placed above and below the left eye. The on-line reference was an electrode placed on the left earlobe. The ground electrode was placed on the forehead. Electrode impedance was kept below 5 kΩ during recording. Electrical activity was amplified and digitized at a sampling rate of 1000 Hz with an antialiasing digital filter of 0.27× sampling rate (therefore, at 1000 Hz sampling rate, the usable bandwidth is 0 to 270 Hz).

EEG data were analyzed using EEProbe 3.3 (ANT). Offline, the EEG was filtered between 0.1 and 20 Hz. The high-pass cutoff (0.1 Hz) was used to get rid of drifts and the low-pass cutoff (20 Hz) was used to smooth the waves and facilitate automatic peak detection on ERP waveforms. Then EEG and EOG artifacts were removed using a [−40; +40 μV] deviation over 200-msec intervals on all electrodes. Epochs with eye blinks were detected and corrected by subtracting from the EEG the PCA-transformed EOG components for each electrode, weighted according VEOG propagation factors (computed via linear regression, Nowagk & Pfeifer, 1996). Data was then re-referenced off-line to a common average reference. Although the common average reference, recommended by the guidelines for psychophysiological research (Picton et al., 2000), is optimal for visual components, in particular, the N170 (Joyce & Rossion, 2005), an earlobe or mastoid reference is traditionally used in studies focusing on go/no-go differences and on later components such as the P3 (i.e., Roche, Garavan, Foxe, & O'Mara, 2005; Mathalon, Whitfield, & Ford, 2003). Thus, these latter components or differences on the waveforms are also reported using the average of the earlobes.

Averages were generated for each subject and each condition in epochs of −200 to 800 msec, time-locked to the stimulus onset. Only trials with correct behavioral responses and artifact-free were used for the ERP average. The number of trials was balanced across no-go conditions and these procedures resulted in a mean number of 91 (± 3.9) trials per condition (4 = Legal Frequent, Legal Never, Illegal Frequent, Illegal Never) for pseudowords. For words, the mean number of trials per condition (2 = frequent vs. rare) was of 198 (± 5.5).

Data Analysis

Behavioral data. ANOVAs were performed on behavioral responses (reaction times on correct responses: RT, and accuracy: CR) on words, with *lexical frequency* (frequent vs. rare) as within-subjects factor and on the percent of false alarms (FA) corresponding to a mistaken response to a pseudoword (no-go trials) with *position* (legal vs. illegal) and *identity* (frequent vs. never) as within-subjects factors.

ERP data. After visual examination of both grand-average ERP waveforms and topographical maps of all conditions, the different ERP components were identified. A different number of electrodes for the different components were included in the analyses, depending on their distribution on the scalp. For each subject and each condition, C1 latency and amplitude values were extracted at the peak on two posterior electrodes on the midline, POz and Pz, where the component was the most prominent during the time period of 60–90 msec. P1 parameters were extracted for five pairs of parieto-occipital electrodes (P7/8, P5/6, P3/4, PO7/8, PO5/6) between 80 and 140 msec. For the N170, values were extracted on six pairs (P7/8, P5/6, PO3/4, PO7/8, PO5/6, O1/2) during the 110–200 msec epoch. The component N2-no-go had a restricted topography and was measured in a time period of 200–400 msec on a fronto-central lead (FCz), where it was maximal (Figure 6). Finally, the late positivity P3 was measured in a time period of 300–550 msec on four central leads (Pz, CPz, Cz, and FCz) and three other pairs of centro-parietal electrodes (C1/2, C3/4, CP1/2).

When several electrodes were taken into account, the latencies and amplitude values were averaged over these channels (2 central electrodes averaged for the C1; 5 electrodes for the P1 for each hemisphere; 6 electrodes for the N170 in each hemisphere; 1 central electrode for the N2-no-go; 3 electrodes on each hemisphere for the P3 and 4 central electrodes). This procedure was used to take into account the distribution of the components over multiple channels, but the statistical analyses did not include any electrode factor and were thus comparable for the different components.

A series of repeated measure ANOVAs were performed on peak latencies and amplitudes, separately for each component. For pseudowords, the factors were: *position* (illegal/legal) and *identity* (frequent/never) of the double consonants, and for words, the factor of *lexical frequency* was included. We also compared words and pseudowords including the factor *lexicality* (words vs. pseudowords). The additional factor was *hemisphere* of recording (LH = left hemisphere; RH = right hemisphere; M = Midline when necessary). Planned comparisons were performed to evaluate the specific *position* and *identity* impact. Significant interactions between experimental variables were clarified by either breaking them into simple effects or by means of post hoc comparisons, and were considered significant at $p < .05$. The time course of words versus pseudowords discrimination was analyzed by computing an ERP difference waveform *go minus no-go trials*, independently of condition, for each participant, on two posterior sites (PO7/PO8), were the N170 was the most prominent, in order to track the first differential activity between words and pseudowords. Moreover, the time course of processing of frequent words compared to rare words was also analyzed in a same way. Intrasubject t tests ($df = 18$) were performed at the $p < .05$ level between −100 and 800 msec on the differential waveforms. Overall, an effect was considered to be significant if 30 consecutive t values (30 msec here) were below the $p < .05$ level (Rugg, Doyle, & Wells, 1995).

RESULTS

Behavioral Data (Lexical Decision in the Behavioral Study)

Mean reaction times on correct responses and percentage of correct responses are presented in Figure 1 for both words and pseudowords. The behavioral responses were fast and accurate even though performance varied across conditions.

Reaction Times

Repeated measures ANOVAs on mean reaction times for words revealed that *lexical frequency* had a significant effect [$F(1, 19) = 76.7$, $p < .0001$] with high-frequency words (541 ± 14 msec) responded faster than low frequency ones (607 ± 20 msec), as shown in Figure 1B. *Lexicality* had a significant influence on reaction times

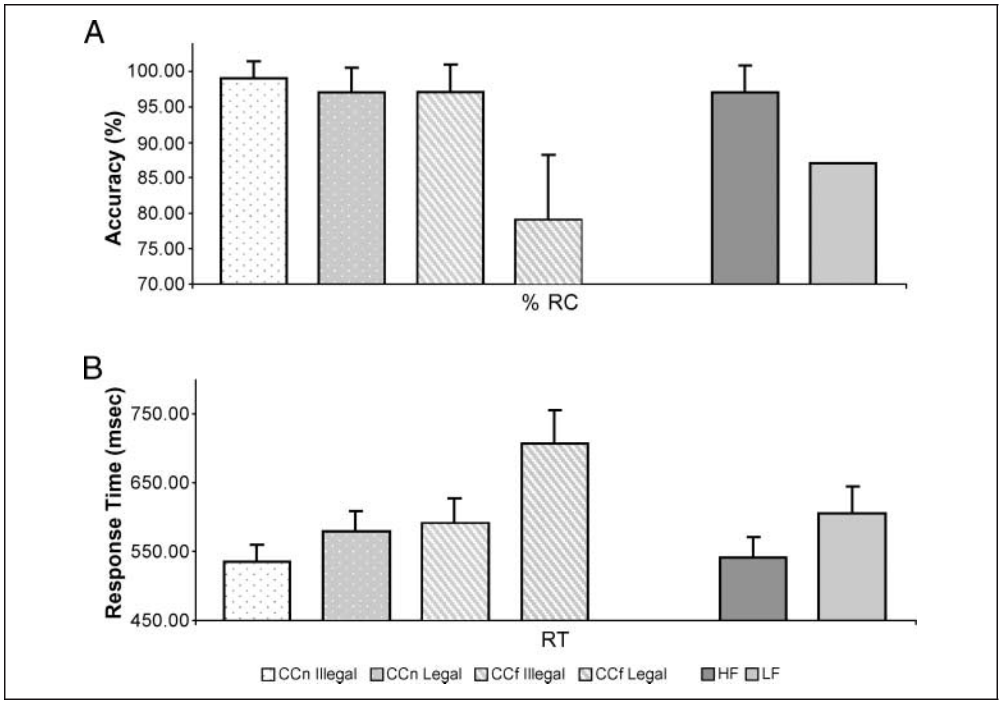

Figure 1. Lexical decision data obtained in the behavioral study. (A) Mean percentage of correct responses and *SEM* for pseudowords (CCn and CCf in legal or illegal position) and words (high vs. low frequency: HF vs. LF). (B) Mean response times and *SEM* (msec) for pseudowords and words.

[$F(1, 19) = 7.24, p < .01$] with words (574 ± 16.95 msec) responded faster than pseudowords (603 ± 18.1 msec).

For the pseudowords with a double consonant in an illegal position, we tested, at first, the location of the regularity violation (beginning vs. end of the pseudowords). As no effect of *location of the regularity violation* was found ($F < 1$), we then do not take this factor into account in the further analyses and, therefore, for the illegal position, reaction times on end and beginning of the pseudowords are grouped.

Response times on pseudowords significantly differed across the *position* conditions [$F(1, 19) = 113.7, p < .0001$]. They increased from the illegal condition (563 ± 15.3 msec) to the legal condition (643 ± 21.1 msec). The main effect of *identity* was also significant [$F(1, 19) = 63.3, p < .0001$]. Pseudowords containing a frequent double consonant (649 ± 23.3 msec) were responded more slowly than pseudowords including a never doubled consonant (556 ± 13.3 msec). These effects were qualified by a highly significant interaction between *position* and *identity* [$F(1, 19) = 38.1, p < .0001$] because the frequently doubled consonants were more affected by the position ($p < .0001$) with a difference of 116 msec between legal and illegal, than the never doubled consonants (44 msec, $p < .0001$).

Because there was an effect of *lexicality* and of *lexical frequency* for words, and *position* and *identity* had also an effect on pseudowords, we performed pairwise comparisons. Almost all pairwise comparisons reached significance (ps < .002), except for the frequent words that did not differ from pseudowords including never doubled consonants in an illegal position ($p < .5$) and for the rare words that did not differ from the pseudowords including frequent double consonant in an illegal position ($p < .3$). Words differed from pseudowords containing never doubled consonants in an illegal position ($p < .0001$), but not when in a legal position ($p < .8$), and words also differed from pseudowords including frequently doubled consonants in a legal position ($p < .0001$), whereas they not differed when in an illegal position ($p < .2$).

Accuracy (Mean Percentage of Correct Responses)

Repeated measures ANOVAs on percentage of correct responses for words revealed that *lexical frequency* had a significant effect [$F(1, 19) = 55.5, p < .0001$] with a higher accuracy on frequent words (97 ± 0.55%) compared to rare words (87 ± 1.7%), whereas *lexicality* had no significant effect ($F < 1$) on accuracy, which may be due to a ceiling effect.

For pseudowords *letter position* had a significant influence on task performance [$F(1, 19) = 46.8, p < .0001$], with pseudowords containing a double consonant in an illegal position (97.5 ± 0.5%) being responded more accurately than those containing a double consonant in a legal position (88 ± 1.62%). The main effect of *identity* of the double consonants was also significant [$F(1, 19) = 59.3, p < .00001$], indicating more accurate responses on double consonants never found in French (97.8 ± 0.46%) than on frequently doubled consonants (87.6 ± 1.6%). There was a significant interaction between *position* and *identity* [$F(1, 19) = 49.7, p < .0001$]. As illustrated in Figure 1A, position had a higher impact on accuracy for the frequently doubled consonants, which were responded significantly more accurately ($p < .0001$) in the illegal (96.4 ± 0.66%) than in the legal position (78.9 ± 2.8%). For consonants never doubled, the difference was much smaller, even though it was also significant due to ceiling effects ($p < .007$; illegal: 98.6 ± 0.44%; legal: 97.1 ± 0.58%).

In summary, the results of the behavioral experiment indicated classical lexical effects on words and an influence of both *identity* and *position* of double consonants on the latency and accuracy of responses on pseudowords (see Figure 1). When a pseudoword contained a double consonant that did not conform to orthographic rules (i.e., a consonant never doubled or in an illegal position), subjects responded faster and more accurately. However, frequently doubled consonants were more affected by *position* than never doubled consonants. Thus, a pseudoword composed by strictly the same letters but in different positions (i.e., ''allinent'' vs. ''llainent'') led to different performances, illustrating the impact of the orthographic characteristics of the stimuli on subject's performance.

Behavioral Data (Go/No-go Task in the ERP Study)

Behavioral responses recorded on words were fast (mean RT: 538 ± 25.7 msec) and accurate (mean CR: 90 ± 1.4%), indicating that our task effectively tapped express word recognition. As in the behavioral study, task performance on words (go trials) was significantly influenced by *lexical frequency*. Frequent words (97 ± 1%) were recognized as words more accurately than rare words (84 ± 2%) [$F(1, 18) = 44.5, p < .0001$]. Moreover, high-frequency words (504 ± 23 msec) were responded faster than low-frequency (572 ± 28 msec) ones [$F(1, 18) = 88.7, p < .0001$]. The sensitive pad used in the go/no-go task could have allowed fastest responses compared to the press button used in the previous behavioral lexical decision task. Moreover, the go/no-go paradigm offers faster response times than the classical lexical decision task (Perea, Rosa, & Gomez, 2002).

On no-go trials (pseudowords), as indicated in Figure 2, *position* of the double consonant influenced the behavior on no-go trials [$F(1, 18) = 47.6, p < .0001$], such that the legal position (13.8 ± 1.9%) induced more false alarms than the illegal position (3.9 ± 0.7%). *Identity* also had an impact on behavior [$F(1, 18) = 55.6, p < .0001$], such that items containing frequently doubled consonants were responded mistakenly more often (14.4 ± 2%) than those containing never doubled consonants (3.2 ± 0.7%). There was a significant interaction between these two factors [$F(1, 18) = 43.9, p < .0001$] due to the fact that frequent doubled consonants were more affected by *position* ($p < .0001$) than never ones ($p < .005$).

In summary, the behavioral responses collected during EEG recording mirrored the results of the behavioral lexical decision task, and confirmed the important role of *identity* and *position* of double consonants when readers have to discriminate written words from pseudowords at a glance.

ERP Data

Grand-average ERPs over the 19 subjects showed five major components identified after stimulus onset (i.e., C1, P1, N170, N2-no-go, P3-no-go). ERP waveforms for words and pseudowords are illustrated in Figure 3 and ERP waveforms for each condition are plotted in Figures 4 and 5. The scalp topographies between conditions started to differ after 200 msec and the distribution of the late components N2 and P3 no-go are shown in Figure 6 and will be described in details below.

The first negative deflection, largest at posterior midline electrode sites, the C1, had an average peak latency of about 80 msec for all the conditions. The P1, a positive deflection at lateral occipital sites, was found to peak around 100 msec in all conditions but with a clear right lateralization on amplitude. The N1 or N170, a negative lateral occipital component, had an average onset

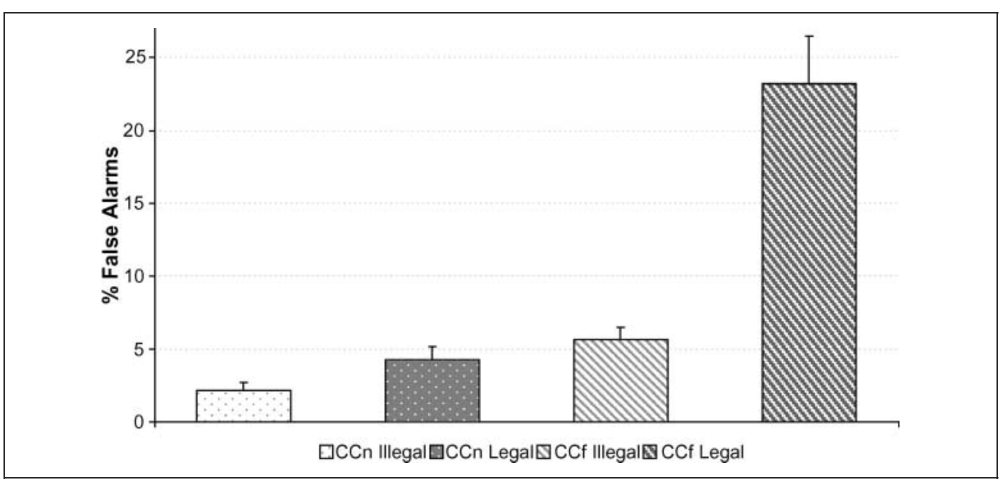

Figure 2. ERP study. Percentages and *SEM* of false alarms (FA) observed in response to pseudowords (no-go trials) across conditions (CCn and CCf in legal or illegal position).

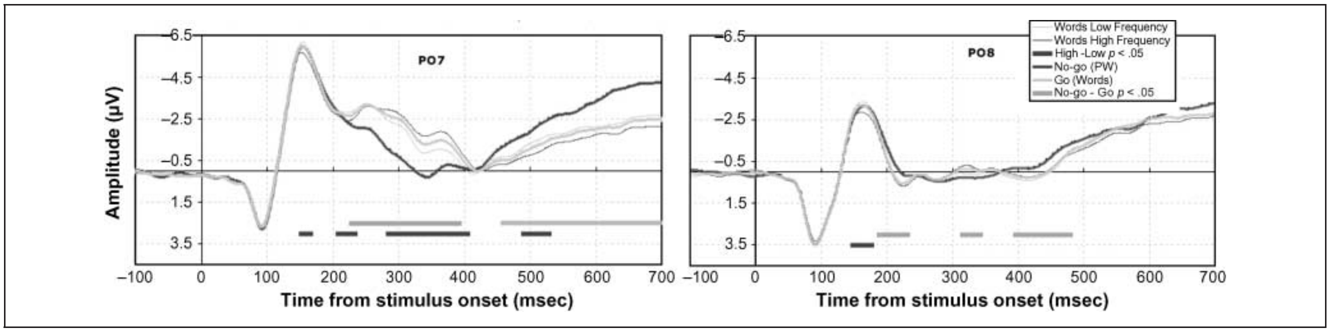

Figure 3. Grand-averaged ERPs elicited by words (go trials) and pseudowords (no-go) stimuli. Words are also plotted in respect with their lexical frequency (low frequency and high frequency). ERPs recorded on the left and right hemisphere at inferior occipito-temporal electrodes (PO7/PO8) in the go and no-go trials. Gray line indicates significant t tests point by point between no-go and go trials. Darkest line indicates significant t tests point-by-point between high- and low-frequency words.

latency of about 110–115 msec in the left hemisphere, whereas in the right hemisphere the average onset latency was around 130–135 msec. The average peak latency was around 160 msec for both hemispheres. The N170 was most prominent in the left hemisphere than in the right hemisphere (see Table 2).

Thereafter, as can be seen on Table 3 and Figure 4A, a negative deflection on fronto-central sites, the N2 in response to no-go trials, had an average peak latency of about 300 msec. The peak amplitude (see Figure 4B) and latency (see Figure 4C) depended on the condition and were delayed from the earlier latency found on illegal never with the largest amplitude to the legal frequent with the latest latency and the smallest amplitude. Finally, the N2 was followed by a large positivity in the time range between 300 and 550 msec, which can be identified as a P3 component (see Figure 5A). This P3-complex was most prominent at central leads and peaked around 460 msec (see Table 3 and Figure 5).

Early Visual Components (80–200 msec)

C1 (60–90 msec) and P1 (80–140 msec). For early visual components, no significant effects were found, neither on the mean amplitude nor on the mean latency for any of the factors ($F < 1$), but a main effect of hemi-

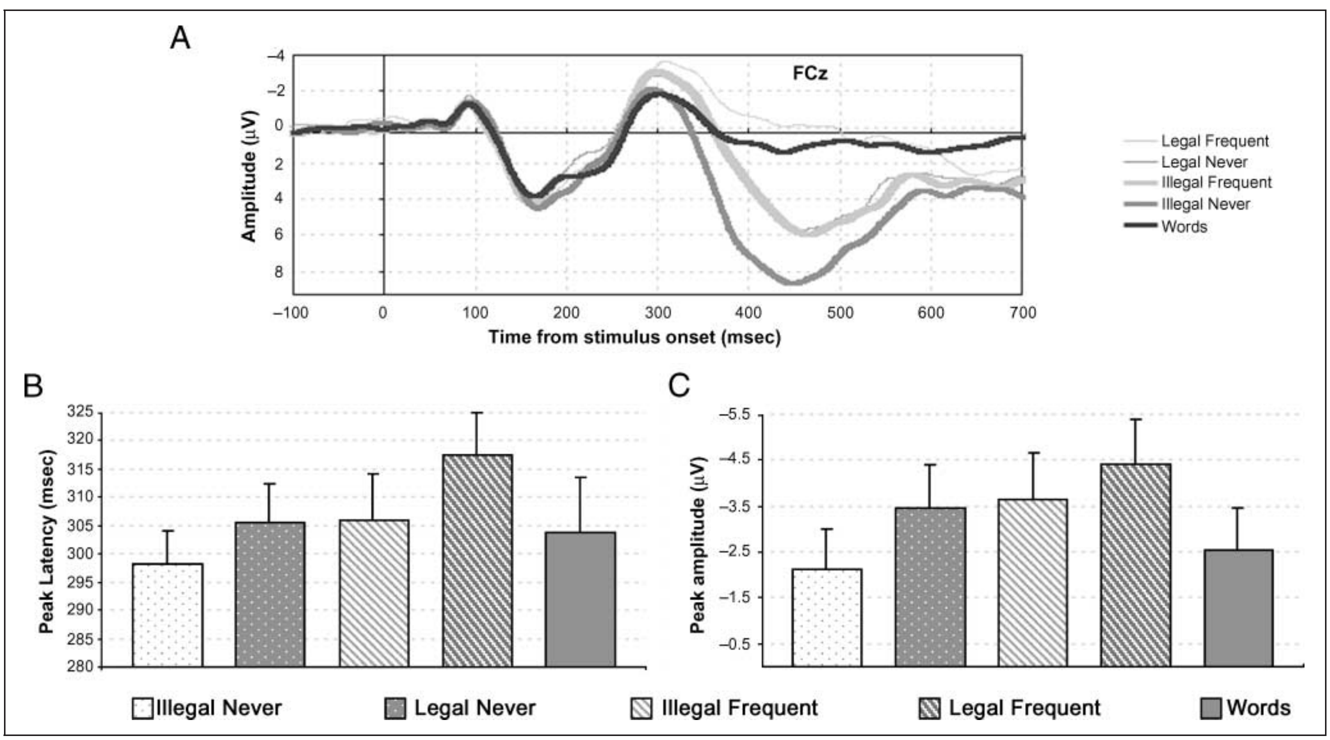

Figure 4. (A) Grand-averaged ERPs recorded at a fronto-central electrode on the midline (FCz), where the N2-no-go component was maximal. All the conditions are plotted together (words were also plotted to give the baseline). (B) Amplitude of the N2 component recorded at a fronto-central electrode on the midline (FCz) was plotted for each condition. (C) Latency of the N2 component recorded at a fronto-central electrode on the midline (FCz) was plotted for each condition.

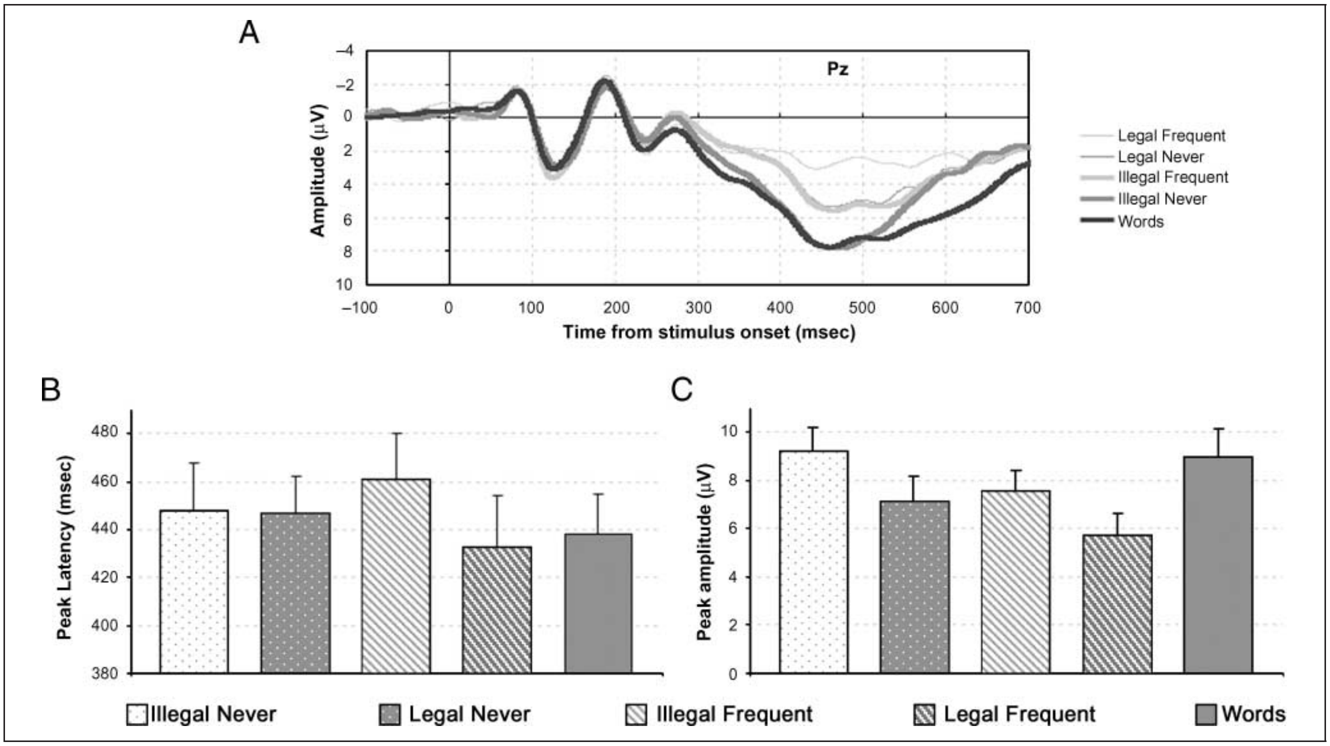

Figure 5. (A) Grand-averaged ERPs recorded at a posterior electrode on the midline (Pz), where the P3-no-go component was maximal. All the conditions are plotted together (words were also plotted to give the baseline). (B) Amplitude of the P3 component recorded at a posterior electrode on the midline (Pz) was plotted for each condition. (C) Latency of the P3 component recorded at a posterior electrode on the midline (Pz) was plotted for each condition.

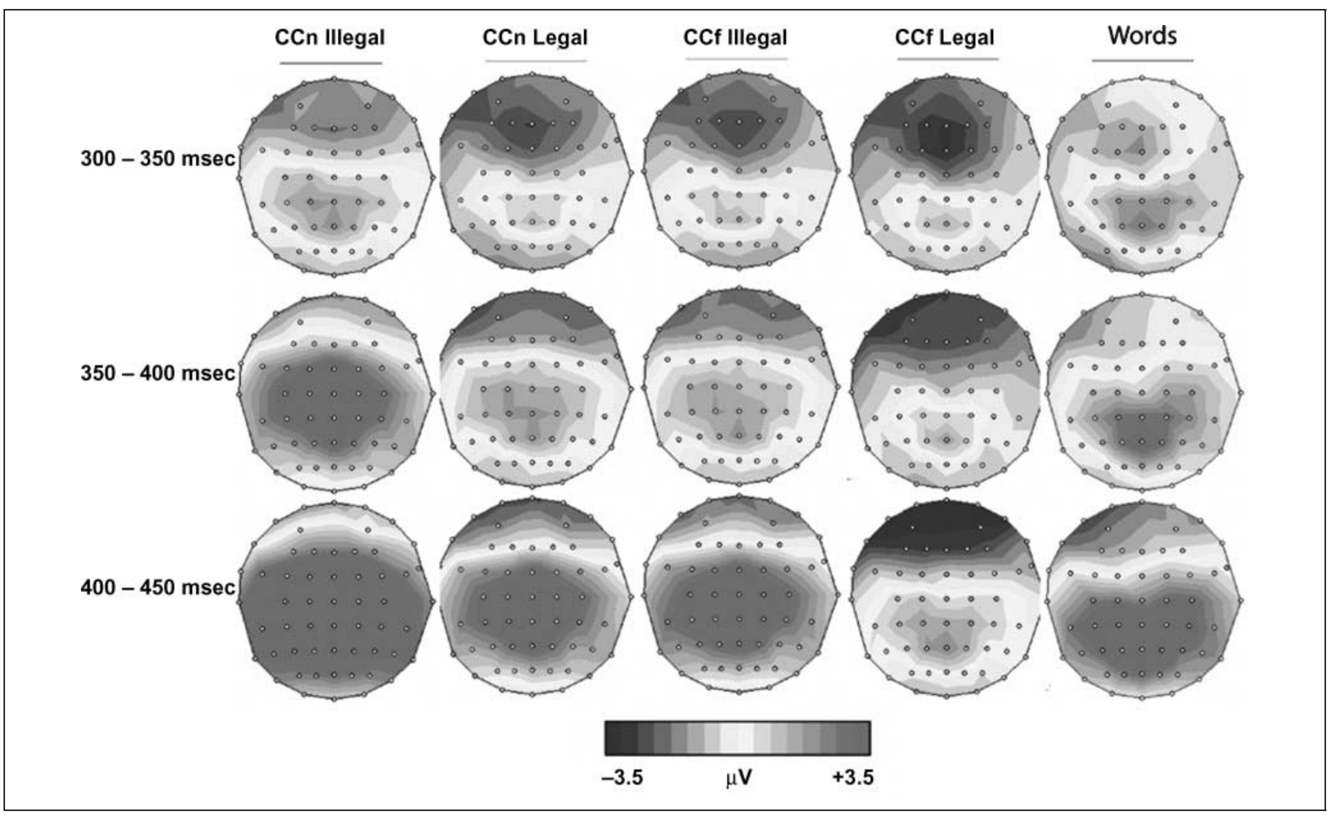

Figure 6. Scalp topographies at peak maximum for each condition. The first row corresponds to the N2 component at fronto-central sites, with maximum amplitude for CCf legal condition, the second and third rows display the P3 who starts first and had the greatest amplitude in response to CCn illegal condition.

Table 2. Mean (*SEM*) Latency (msec) and Amplitude (μV) of the C1, P1, and N1 at Peak Maximum

		Legal		Illegal	
	Words	Frequent	Never	Frequent	Never
C1					
Latency (msec)	80 (±1.6)	80 (±2)	78 (±2)	80 (±2)	80 (±2)
Amplitude (μV)	−1.5 (±0.3)	−1.6 (±0.3)	−1.6 (±0.4)	−1.7 (±0.3)	−1.8 (±0.3)
P1					
Latency					
L	102 (±3)	102 (±3)	101 (±3)	100 (±3)	100 (±3)
R	105 (±3)	105 (±4)	105 (±3)	107 (±4)	105 (±3)
Amplitude					
L	2.7 (±0.4)	2.9 (±0.5)	2.7 (±0.4)	2.9 (±0.4)	2.8 (±0.5)
R	4 (±0.5)	4.3 (±0.6)	4.2 (±0.5)	4.2 (±0.6)	4.1 (±0.6)
N1					
Latency					
L	160 (±3)	161 (±3)	161 (±3)	160 (±3)	164 (±4)
R	163 (±4)	163 (±4)	165 (±4)	164 (±3)	160 (±4)
Amplitude					
L	−6.3 (±1)	−6 (±0.9)	−6.4 (±1)	−6.2 (±1)	−6.2 (±1)
R	−4.1 (±0.8)	−3.9 (±0.8)	−4.3 (±0.8)	−4.2 (±0.8)	−4.2 (±0.9)

L = left hemisphere; R = right hemisphere.

sphere on the P1 mean amplitude was found [$F(1, 18) = 6.043$, $p < .024$], due to a larger peak amplitude on the right hemisphere than on the left (4.2 ± 0.56 and 2.8 ± 0.42 μV respectively).

N170 (110–200 msec). Neither latency nor amplitude effects were found ($F < 1$) for the factors lexicality, position and identity. There was no effect of hemisphere [$F(1, 18) = 1.073$, $p < .3$] for latencies. However, on mean amplitude, a difference between hemispheres was found [$F(1, 18) = 9.245$, $p < .007$] due to a significantly larger amplitude on the left (−6.3 ± 0.95 μV) compared to the right hemisphere (−4.1 ± 0.83 μV). For words, a lexical frequency effect was found on amplitude [$F(1, 18) = 6.2$, $p < .02$] with a larger amplitude for rare words (−5.3 ± 0.84 μV) compared to frequent words (−4.99 ± 0.85 μV) and a hemisphere effect [$F(1, 18) = 9.8$, $p < .006$] with larger amplitude on the left (−6.3 ± 0.96 μV) than on the right (−4.04 ± 0.86 μV) hemisphere. However, no interaction was found between these two factors ($F < 1$) (see Figure 3).

Sample-by-sample *t* tests showed that differential ERP activity between go and no-go trials was not found on this time window but started to differ from zero ($df = 18$, $p < .05$) at 230 msec in the left hemisphere, as can be seen in Figure 3.

Summary of the results. As reported on Table 2, for the early visual components, all types of items elicited almost the same pattern of response. The first difference was found on the P1 with greater peak amplitude on the right hemisphere, whereas at the level of the N1, the amplitude was larger on the left hemisphere. As illustrated in Figure 3, before 200 msec, only lateralization effects were found for the different kinds of alphabetic stimuli. However, a lexical frequency effect was found bilaterally at the N170 level. The first difference between go and no-go trials started around 230 msec at occipito-temporal sites.

No-go Trials (200–550 msec)

No-go N2 (200–400 msec). At the level of the N2, on no-go trials, position of double consonants had a clear influence on amplitude [$F(1, 18) = 17.5$, $p < .001$], with a larger amplitude for the legal condition (−3.9 ± 0.93 μV) compared to the illegal condition (−2.9 ± 0.91 μV). Mean

Table 3. Mean (*SEM*) Latency (msec) and Amplitude (μV) Values of the N2 and P3 No-go at Peak Maximum Measured on FCz Fronto-central Lead

	Legal		*Illegal*	
	Frequent	*Never*	*Frequent*	*Never*
N2 No-go				
Latency (msec)	317 (±7)	306 (±7)	306 (±8)	298 (±6)
Amplitude (μV)	−4.41 (±0.99)	−3.45 (±0.94)	−3.62 (±1.02)	−2.45 (±0.87)
P3 No-go				
Latency (msec)				
FCz	456 (±15)	470 (±8)	467 (±12)	448 (±11)
L	434 (±24)	467 (±15)	477 (±12)	475 (±9)
M	437 (±23)	465 (±11)	463 (±14)	458 (±12)
R	423 (±18)	476 (±4)	474 (±13)	473 (±12)
Amplitude (μV)				
FCz	2.23 (±0.96)	6.7 (±1.11)	7.43 (±1.24)	9.75 (±1.18)
L	4.9 (±0.66)	7.8 (±0.84)	8.2 (±0.8)	10.2 (±0.73)
M	4.4 (±0.69)	7.5 (±0.91)	8 (±0.9)	10.08 (±0.88)
R	4.7 (±0.62)	7.6 (±0.83)	8.1 (±0.84)	10.11 (±0.8)

L = left hemisphere; M = Midline; R = right hemisphere.

amplitude also varied across identity levels [$F(1, 18) = 7.8$, $p < .012$], with a decrease from frequently doubled consonants (−4 ± 0.98 μV) to never doubled consonants (−2.8 ± 0.9 μV). These two factors did not interact ($F < 1$) with each other (see Figure 4B).[1]

The latency of the N2-no-go (see Figure 4C) showed a similar pattern as for amplitudes.[2] Illegal items (302 ± 7 msec) elicited an earlier N2 than legal ones (312 ± 6.7 msec), as confirmed by a significant main effect of position [$F(1, 18) = 8.1$, $p < .011$]. A significant main effect of identity [$F(1, 18) = 8.8$, $p < .008$] was due to an earlier N2 peak for frequent (302 ± 6.3 msec) than for never doubled consonants (312 ± 7.3 msec). There was no interaction between position and identity ($F < 1$) on peak latency as shown in Figure 4.

No-go P3 (300–550 msec). For the P3 amplitude[3] (see Figure 5B), there was a main effect of position [$F(1, 18) = 33.27$, $p < .0001$], with larger amplitudes on illegal (9.12 ± 0.8 μV) compared to legal (6.14 ± 0.7 μV) items. We also found a main effect of identity [$F(1, 18) = 29.67$, $p < .0001$], with larger amplitude for never (8.88 ± 0.7 μV) than for frequent (6.38 ± 0.6 μV) double consonants. However, these factors did not interact ($F < 1$). There was no effect of hemisphere, and no significant interaction between factors ($F < 1$).

For the P3 latency[4] (see Figure 5C), the main effect of position was significant [$F(1, 18) = 4.6$, $p < .045$], whereas no significant main effect of identity was found [$F(1, 18) = 2.9$, $p > .1$]. The legal items peaked earlier (450 ± 14.8 msec) than the illegal items (470 ± 9.8 msec). The interaction between position and identity was almost significant [$F(1, 18) = 4.3$, $p < .053$]. For the never doubled consonants, position had no influence ($p > .8$) on latency, whereas for frequent double consonants, position had an effect ($p < .04$) with an earlier latency for legal (431 ± 20.12 msec) than illegal (471 ± 12.5 msec) position. There was no other effect on P3 latency ($F < 1$).

Summary of the results. As illustrated in Figures 3, 4, 5, and 6 and Table 3, differences between conditions appeared after 200 msec. At the N2-no-go level, position and identity had clear effects on amplitude and latency, but these two factors did not interact at this latency. These results suggest additive effects of the two parameters. However, the interaction between the two factors was present at the level of the P3 latency, in line with the overt response time obtained in the lexical decision task in the behavioral study.

DISCUSSION

The first and general aim of the present study was to track the time course of the discrimination between words and pseudowords in a language (i.e., French) that is relatively transparent in reading, using both a classical lexical decision in the behavioral study and an ERP go/no-go paradigm. We contrasted go to no-go trials in order to maximize the ERP differences between these two types of responses and, therefore, to obtain a reliable marker of the onset of lexical effects. The behavioral results obtained in the classical lexical decision showed a classical frequency effect with an advantage for frequent words compared to rare words. The pseudowords containing frequently doubled consonants in a legal position led to the slowest response times and the less accurate responses, whereas the never doubled consonants in an illegal position were responded faster and more accurately. There was an interaction between the position and identity of doubled consonants. Indeed, the frequently doubled consonants were more affected by position than by the never doubled consonants, illustrating the impact of the orthographic characteristics of the stimuli on subject's performance. The main ERP results showed a first difference, around 230 msec, maximal at left posterior sites, between words and pseudowords. Following these differences, the data showed additive effects of the factors identity and position at the N2 level. In line with the lexical decision data obtained in the behavioral study, there was an interaction at a much later latency, at the P3 level, between identity and letter position.

Early Visual Components and Left Lateralization

In the ERP data, no difference between stimuli were found at the level of the early visual C1 and P1 components, which are thought to originate mainly from the primary visual cortex and extrastriate areas, respectively (e.g., Clark, Fan, & Hillyard, 1995). Whereas the P1 had larger amplitude on the right hemisphere, the N1, or N170, was strongly left lateralized. The left lateralization of the N1 to letter strings is consistent with evidence from previous scalp (Rossion, Joyce, Cottrell, & Tarr, 2003; Schendan, Ganis, & Kutas, 1998) and intracranial ERP studies (Allison, Puce, Spencer, & McCarthy, 1999; Nobre et al., 1994). Earlier studies suggested that the main distinctive feature of reading-related N170 specialization lies in its left-lateralized topography (Maurer, Brem, Bucher, & Brandeis, 2005; Rossion et al., 2003; Bentin et al., 1999), contrasting with the bilateral or right-lateralized topographies for objects and faces, respectively (Rossion et al., 2003). However, the left-lateralized topographic effect did not fully generalize to pseudowords in English (Maurer, Brandeis, et al., 2005), whereas it did in German (Maurer, Brem, et al., 2005), a more regular language. To account for these findings, Maurer, Brandeis, et al. (2005) and Maurer, Brem, et al. (2005) suggested that the left-lateralized topographic N170 effect would be associated with functional properties related to language specificities that are especially relevant in pseudoword reading, that is, phonological codes are automatically activated as suggested by eye-movement priming paradigm (Rayner, Sereno, Lesch, & Pollatsek, 1995). Our results of a left lateralization of the N170 to pseudowords are consistent with this interpretation of an automatic mapping between graphemes and phonemes, showing that a full generalization to pseudowords appeared in French, a relatively shallow language in reading with consistent mapping between graphemes and phonemes. Indeed, our pseudowords, even if they were not all orthographically acceptable, were all pronounceable. Moreover, such an interpretation could also fit with the fact that we did not find any difference in amplitude between words and pseudowords at the N170 level, as in earlier studies in regular languages such as French (Bentin et al., 1999) and Finnish (Wydell, Vuorinen, Helenius, & Salmelin, 2003). This lack of difference could be due to the fact that French is quite regular in the relationship between grapheme and phoneme, whereas English is a deeper language.

However, in Bentin et al.'s (1999) study, a left lateralization was found for all kinds of alphabetic stimuli (somewhat inappropriately named orthographic because consonants strings are not orthographic items). That is, in a shallow language, a left lateralization for words, pseudowords, and consonants strings that are not pronounceable can be found. This left-lateralized specialization for all kinds of alphabetic stimuli suggests that the sensitivity to letter strings is independent of their pronounceability, but is rather sensitive to the alphabetic character of the material or letter sensitive. This interpretation is supported by the fact that, in Bentin et al.'s study, the phonological effects were found later, at the N320 level. Moreover, as described in the Introduction, recent MEG studies of visual recognition also show negligible differences in the early brain responses (i.e., up to 200–250 msec poststimulus) to words, anagrams, nonwords, and random consonant strings (Pammer et al., 2004; Cornelissen et al., 2003; Tarkiainen et al., 1999).

In sum, the N170 is known to be sensitive to the processing of alphabetic material but not always to pronounceability or orthographic regularity of letter strings (Bentin et al., 1999) and is also known to be related to expertise through exposure to alphabetic stimuli (Maurer, Brem, et al., 2005). Consequently, this component could be viewed as the electrophysiological counterpart of the activation of the letter array, proposed by Grainger and Van Heuven (2003), which they hypothesized to develop through exposure to print and to be insensitive to orthographic regularity or to phonology. Given that there was no difference across conditions (i.e., words and pseudowords varying in orthographic regularity), the strong left lateralization found in the present study, as in previous studies, can be related to aspects of visual expertise in pattern recognition (i.e., strings of letters) and not to linguistic processes per se, although at this stage a low-level interpretation cannot be completely ruled out.

The Speed of Lexical Access

Using behavioral measures, we observed that words and pseudowords were discriminated at around 570 msec. In comparison, in the ERP study, the first difference between words and pseudowords appeared around 230 msec poststimulus onset, largely preceding the motor output (which occurred at about 500 msec for high frequency words on average). This latency is in line with MEG observations, showing that the visual word form area does not reach a significant (i.e., detectable) level of activation until around 200 msec poststimulus (Pammer et al., 2004). This result also fits the temporal data observed in intracranial potential recordings (Nobre et al., 1994), as well as the scalp recordings (Hauk et al., 2006; Cohen et al., 2002; Nobre et al., 1994). These studies, in line with our findings, show that nonwords can be distinguished from real words at around 210–250 msec post stimulus with pseudowords producing more negative potentials than words. Thus, this first ERP differential activity can be viewed as an index of the lexical access in normal adult readers, following the N170.

However, some studies have reported very early lexical effects in English. Sereno, Rayner, and Posner (1998) tested a very large sample of subjects (40) and reported a larger P1 (100–132) to words than consonant strings, which was only marginally significant when words were compared to pseudowords. Yet, this effect was small and was found on a single electrode site, and it is unclear whether the same site showed a difference for words over pseudowords and consonant strings. Furthermore, these results are incompatible with Maurer, Brandeis, et al. (2005), Maurer, Brem, et al. (2005), and Bentin et al.'s (1999) findings showing no difference at this level when comparing nonalphabetic and alphabetic stimuli.

Another potential index of lexical access is also the frequency effect. We found a bilateral difference between frequent and rare words as early as at the N170 level, with larger amplitude for rare words and a left-lateralized difference starting at 200 msec after stimulus onset, just preceding the word/pseudoword distinction. The effect of lexical frequency is observed relatively later in a large number of studies, using different languages, namely, Brown, Hagoort, and ter Keurs (1999): around 250 msec; Rugg (1990): around 300 msec; Barber, Vergara, and Carreiras (2004), Hutzler et al. (2004); Vanpetten and Kutas (1990): between 350 and 400 msec; Polich and Donchin (1988): around 500 msec. However, again, some studies reported earlier frequency effects. For instance, in line with our findings, Sereno et al. (1998) reported a difference between 132 and 192 msec, at the N170 level, with larger amplitude for low-frequency words compared to high-frequency words. Proverbio, Vecchi, and Zani (2004) found a frequency effect on the P150 component at centro-parietal sites with larger amplitude in high-frequency words than in low-frequency ones in the 135–175 msec time window. Hauk and Pulvermuller (2004) also reported early (150–190 msec) effects of word frequency in a global field power analysis. Yet, contrary to the clear difference we found at 230 msec between words and pseudowords, none of the studies cited here, which reported word frequency effects, showed a left lateralization of the effect. It was bilateral in all studies, including ours, but with a right lateralization in the experiment of Proverbio et al. (2004). This lack of left lateralization may suggest that the effect does not reflect a linguistic process per se, but rather a visual familiarity effect. Indeed, the visual N1 or N170 may show increased amplitude for highly familiarized object categories (Rossion et al., 2003; Curran, Tanaka, & Weiskopf, 2002).

Taken together, all these results suggest that the first strong evidence of lexical access can be evaluated to take place at about 200 msec. In any case, an early difference between words and nonwords may well mark the onset of lexical access, but lexical activity extends over a wide time range. A particular interest of the present study is that it allows identifying a time point at which enough evidence has been accumulated to take a correct lexical decision, and we found converging evidence with lexicality effects and frequency effects, left lateralized around 200 msec. To put it differently, our findings of a 230-msec difference does not reflect the earliest difference or the onset of lexical access but a threshold reflecting enough process for taking an accurate lexical decision. Moreover, and most importantly, we show for the first time that this time threshold is variable, depending on the plausibility of pseudowords in terms of letter position and identity.

No-go N2 and P3: Early Independent and Additive Effects

In accordance with the literature (for a review, see Falkenstein et al., 1999), we found a typical no-go effect on the N2. That is, we observed a more negative effect on the fronto-central N2 compared to go trials, on the Fz/FCz electrode. For the P3, no-go trials were not larger as compared to go trials on Pz in our study, but this effect is not always reliably observed in the literature. For instance, Fallgatter and Strik (1999) tested 27 subjects and found only a trend in larger parietal P3 amplitude for no-go compared to go stimuli. However, and interestingly, what is more characteristic of the P3 effect to no-go trials is its anterior shift (see Falkenstein et al., 1999), as we observed here also. Indeed, most of studies report a P3 that exhibits topographical differences across go and no-go conditions (i.e., Bruin et al., 2001). As a matter of fact, Fallgatter and Strik (1999) and Fallgatter, Brandeis, and Strik (1997), computing a data reduction relying on all the channels, yielded a single topographical parameter (no-go anteriorization, NGA), which allowed discriminating go from no-go conditions in all the subjects.

At the N2 level, the waveforms were modulated by letter identity and position independently. Most interestingly, the latency and amplitude modulations of the N2 no-go fit with behavioral responses times, even if the electrophysiological results do not show any interaction between the factors manipulated at this latency. ERPs were more negative to no-go trials compared to go trials, except for illegal never items who had a similar amplitude to the go trials. As mentioned in the Introduction, the N2 no-go effects have been interpreted to reflect response inhibition (e.g., Falkenstein et al., 1999). It has also been argued that the no-go-N2 amplitude could vary depending on the neuronal activity required for response inhibition. Here, the N2 amplitude increased with word-likeness, and then with orthographic regularity. In the present study, the amplitude and latency of this component can thus be considered as a measure of the orthographic distance with words. These results are in agreement with the inhibition hypothesis because the more the stimulus is legal orthographically, the more the response has to be inhibited. In consequence, this component can be viewed as an index of the upper processing time limit at which a lexical decision is performed in normal French adult readers. These results are inconsistent with a conjunctive coding of the two parameters as proposed by slot-based account (McClelland & Rumelhart, 1981). Indeed, observing additive effects of identity and position factors argues against this hypothesis and is rather in favor of an early independent coding, as with the description of orthographic processing proposed by Grainger and Van Heuven (2003). An alternative interpretation would be that of a sequential processing allowing the fastest response for initial positions. Nonetheless, this result could be hardly explained by a sequential process from left to right because no differences were found between a regularity violation at the beginning and at the end of an item. The illegal position comprised the initial and the final positions and led to the fastest responses compared to the legal median position. This result is in line with the local-context coding account that hypothesizes a hierarchical parallel activation, but the spatial coding account referring to a serial activation implicating a beginning-to-end positional bias cannot account for our data. Moreover, these results are consistent with the function linking letter-in-string identification accuracy and position-in-string that is W-shaped (Stevens & Grainger, 2003) with a decreased in visual acuity with distance from fixation and a decreased lateral inhibition for outer letters (first and last letters of a word).

Finally, this interpretation in terms of the existence and selectivity of the letter position coding is strengthened by neuropsychological evidence. For instance, Friedmann and Gvion (2001) reported the case of two Hebrew-speaking acquired dyslexic patients with occipito-parietal lesions who suffer from a highly selective deficit to letter position encoding. As a result of this deficit, they predominantly make errors of letter migration within words (such as reading ''broad'' for ''board'') in a wide variety of tasks: oral reading, lexical decision, same–different decision, and letter location. The deficit was specific to orthographic material, and was manifested mainly in medial letter positions. In other languages, evidence has been rather indirect, that is, position preservation in migrations between words in attentional dyslexia.

Orthographic Processing: Letter Identity and Letter Position Information Bounding

In the behavioral study reported here, illegal never pseudowords were responded significantly earlier than words, suggesting that subjects were able to perform the lexical decision task based on purely orthographic properties rather than on lexicality. This clearly indicates that sufficient processing was accomplished to take a decision, and that this processing can precede lexical access. Moreover, legal never and illegal frequent pseudowords led to a faster decision than frequent words, whereas legal frequent pseudowords (i.e., which conform to the orthographic rules) led to the slowest responses, suggesting a failure in lexical search. Hence, two stimuli sets containing exactly the same letters but organized in a different order do not lead to identical response times. Taken together, these results reveal that the rejection of an item can be based on orthographic criteria before the lexicon is accessed and, importantly, the speed of rejection is graded as function of orthographic conformation. This suggests that these effects are subtended by regularities operating at the level of sublexical orthographic representations (orthographic constraints). According to the sublexical–orthography account, letter perceptibility is improved when the adjacent letters form a typical orthographic context for a given letter in a given position (Massaro & Cohen, 1994). This pattern of results suggest that it might reflect activity in the visual word form area, a left fusiform region thought to be involved in orthographic processing of written words and to be prelexical (Cohen et al., 2002; Dehaene, Le Clec'H, Poline, Le Bihan, & Cohen, 2002).

Conclusions

This study shows differential electrophysiological and behavioral responses to stimuli varying in orthographic regularity, suggesting the important and early role of this factor during visual word recognition. The manipulation of orthographic properties leads to a striking consistency in the results of the behavioral and electrophysiological studies regarding the hierarchy of responses. The orthographic effect in behavior is the final product of the two. Overall, these results fit with a local-context coding account of letter identity and letter position computation and further investigations will be requested to study the neural substrates of letter binding into a visual whole-word unit.

Acknowledgments

We thank Agnesa Pillon for helpful comments on an earlier draft. B. R. and C. J. are supported by the Belgian National Research Foundation.

Reprint requests should be sent to Marina Mariol, Unité Cognition et Développement (CODE), UCL, Place Cardinal Mercier, 10, 1348 Louvain-la-Neuve, Belgium, or via e-mail: marina.mariol@uclouvain.be.

Notes

1. Note that with an average reference, the results were equivalent to those found with an earlobe reference. We obtained a position effect [$F(1, 18) = 12.3$, $p < .002$] with a larger amplitude in legal condition (-5.255 ± 1 μV) compared to illegal condition (-4.13 ± 0.98 μV) and an identity effect [$F(1, 18) = 10$, $p < .005$] with a decrease from frequently doubled consonants (-5.4 ± 1.1 μV) to never doubled consonants (-4.6 ± 1 μV). These two factors did not interact ($F < 1$).
2. With an average reference, results did not reach significance but showed the same trends as those found with an earlobe reference. Illegal items (304 ± 6.9 msec) elicited an earlier N2 than legal ones (310 ± 7.5 msec) even if the effect of position did not reach significance ($F < 1$). The N2 peaked earlier for frequent (302 ± 6.9 msec) than for never doubled consonants (312 ± 6.9 msec) and there was a nonsignificant trend for the identity effect [$F(1, 18) = 3.4$, $p < .08$]. There was no interaction between the factors ($F < 1$).
3. With an average reference, results were highly similar. There was a main effect of position [$F(1, 18) = 46.84$, $p < .0001$], with larger amplitudes on illegal (9.03 ± 0.6 μV) compared to legal (5.7 ± 0.6 μV) items. We also found a main effect of identity [$F(1, 18) = 35.16$, $p < .0001$], with larger amplitude for never (8.76 ± 0.75 μV) than for frequent (6.01 ± 0.61 μV) double consonants. However, these factors did not interact [$F(1, 18) = 3.5$, $p < .077$].
4. With an average reference, the results on the latencies results were almost the same. The main effects were not significant ($F < 1$). However, the same pattern was found. The legal items tend to peak earlier (467 ± 9.4 msec) than the illegal items (474 ± 9.3 msec). The interaction between position and identity did not reach significance [$F(1, 18) = 1.6$, $p < .2$], although the frequent double consonant was more affected by position than the never ones.

REFERENCES

Allison, T., Puce, A., Spencer, D. D., & McCarthy, G. (1999). Electrophysiological studies of human face perception. I. Potentials generated in occipitotemporal cortex by faces and non-face stimuli. *Cerebral Cortex, 9,* 415–430.

Assadollahi, R., & Pulvermuller, F. (2003). Early influences of word length and frequency: A group study using MEG. *NeuroReport, 14,* 1183–1187.

Barber, H., Vergara, M., & Carreiras, M. (2004). Syllable-frequency effects in visual word recognition: Evidence from ERPs. *NeuroReport, 15,* 545–548.

Bekker, E. M., Kenemans, J. L., & Verbaten, M. N. (2005). Source analysis of the N2 in a cued go/nogo task. *Cognitive Brain Research, 22,* 221–231.

Bentin, S., Mouchetant-Rostaing, Y., Giard, M. H., Echallier, J. F., & Pernier, J. (1999). ERP manifestations of processing printed words at different psycholinguistic levels: Time course and scalp distribution. *Journal of Cognitive Neuroscience, 11,* 235–260.

Besner, D., & McCann, R. S. (1987). Word-frequency and pattern distortion in visual word identification and production—An examination of 4 classes of models. *Attention and Performance, 12,* 201–219.

Brown, C. M., Hagoort, P., & ter Keurs, M. (1999). Electrophysiological signatures of visual lexical processing: Open- and closed-class words. *Journal of Cognitive Neuroscience, 11,* 261–281.

Bruin, K. J., Wijers, A. A., & van Staveren, A. S. J. (2001). Response priming in a go/nogo task: Do we have to explain the go/nogo N2 effect in terms of response activation instead of inhibition? *Clinical Neurophysiology, 112,* 1660–1671.

Clark, V. P., Fan, S., & Hillyard, S. A. (1995). Identification of early visual evoked potential generators by retinotopic and topographic analyses. *Human Brain Mapping, 2,* 170–187.

Cohen, L., Dehaene, S., Naccache, L., Lehericy, S., Dehaene-Lambertz, G., Henaff, M. A., et al. (2002). Language-specific tuning of visual cortex functional properties of the visual word form area. *Brain, 125,* 1054–1069.

Coltheart, M., Davelaar, E., Jonasson, J. T., & Besner, D. (1977). Access to the internal lexicon. In S. Dornic (Ed.), *Attention and performance* (Vol. 6, pp. 535–555). London: Academic Press.

Coltheart, M., Rastle, K., Perry, C., Langdon, R., & Ziegler, J. (2001). DRC: A dual route cascaded model of visual word recognition and reading aloud. *Psychological Review, 108,* 204–256.

Compton, P. E., Grossenbacher, P., Posner, M. I., & Tucker, M. D. (1991). A cognitive–anatomical approach to attention in lexical access. *Journal of Cognitive Neuroscience, 3,* 304–312.

Content, A., Mousty, P., & Radeau, M. (1990). Brulex. Une base de données lexicales informatisée pour le français écrit et parlé. *L'Année Psychologique, 90,* 551–566.

Cornelissen, P., Tarkiainen, A., Helenius, P., & Salmelin, R. (2003). Cortical effects of shifting letter position in letter strings of varying length. *Journal of Cognitive Neuroscience, 15,* 731–746.

Curran, T., Tanaka, J. W., & Weiskopf, D. M. (2002). An electrophysiological comparison of visual categorization and recognition memory. *Cognitive, Affective, & Behavioral Neuroscience, 2,* 1–18.

Davis, C. J. (1999). *The self-organising lexical acquisition and recognition (SOLAR) model of visual word recognition*. Australia: University of New South Wales.

Dehaene, S., Le Clec'H, G., Poline, J. B., Le Bihan, D., & Cohen, L. (2002). The visual word form area: A prelexical representation of visual words in the fusiform gyrus. *NeuroReport, 13,* 321–325.

Donkers, F. C. L., & van Boxtel, G. J. M. (2004). The N2 in go/no-go tasks reflects conflict monitoring not response inhibition. *Brain and Cognition, 56,* 165–176.

Eimer, M. (1993). Effects of attention and stimulus probability on ERPS in a Go/Nogo task. *Biological Psychology, 35,* 123–138.

Ellis, A. W. (2004). Length, formats, neighbours, hemispheres, and the processing of words presented laterally or at fixation. *Brain and Language, 88,* 355–366.

Falkenstein, M., Hoormann, J., & Hohnsbein, J. (1999). ERP components in Go/Nogo tasks and their relation to inhibition. *Acta Psychologica, 101,* 267–291.

Fallgatter, A. J., Brandeis, D., & Strik, W. K. (1997). A robust assessment of the NoGo-anteriorisation of P300 microstates in a cued continuous performance test. *Brain Topography, 9,* 295–302.

Fallgatter, A. J., & Strik, W. K. (1999). The NoGo-anteriorization as a neurophysiological standard-index for cognitive response control. *International Journal of Psychophysiology, 32,* 233–238.

Filipovic, S. R., Jahanshahi, M., & Rothwell, J. C. (1999). Cortical potentials related to decision-making: Comparison of two types of go/no-go decision. *NeuroReport, 10,* 3583–3587.

Friedmann, N., & Gvion, A. (2001). Letter position dyslexia. *Cognitive Neuropsychology, 18,* 673–696.

Grainger, J., & Jacobs, A. M. (1996). Orthographic processing in visual word recognition: A multiple read-out model. *Psychological Review, 103,* 518–565.

Grainger, J., & Van Heuven, W. (2003). Modeling letter position coding in printed word perception. In P. Bonin (Ed.), *The mental lexicon* (pp. 1–24). New York: Nova Science Publishers.

Hauk, O., Patterson, K., Woollams, A., Watling, L., Pulvermuller, F., & Rogers, T. T. (2006). [Q:] When would you prefer a SOSSAGE to a SAUSAGE? [A:] At about 100 msec. ERP correlates of orthographic typicality and lexicality in written word recognition. *Journal of Cognitive Neuroscience, 18,* 818–832.

Hauk, O., & Pulvermuller, F. (2004). Effects of word length and frequency on the human event-related potentials. *Clinical Neurophysiology, 115,* 1090–1103.

Humphreys, G. W., Evett, L. J., & Quinlan, P. T. (1990). Orthographic processing in visual word identification. *Cognitive Psychology, 22,* 517–560.

Hutzler, F., Bergmann, J., Conrad, M., Kronbichler, M., Stenneken, P., & Jacobs, A. M. (2004). Inhibitory effects of first syllable-frequency in lexical decision: An event-related potential study. *Neuroscience Letters, 372,* 179–184.

Jodo, E., & Kayama, Y. (1992). Relation of a negative ERP component to response-inhibition in a go/no-go task. *Electroencephalography and Clinical Neurophysiology, 82,* 477–482.

Joyce, C., & Rossion, B. (2005). The face-sensitive N170 and VPP components manifest the same brain processes: The effect of reference electrode site. *Clinical Neurophysiology, 116,* 2613–2631.

Kok, A. (1986). Effects of degradation of visual stimuli on components of the event-related potentials (ERP) in go/nogo reaction tasks. *Biological Psychology, 23,* 21–38.

Kopp, B., Mattler, U., Goertz, R., & Rist, F. (1996). N2,P3 and the lateralized readiness potential in a nogo task involving selective response priming. *Electroencephalography and Clinical Neurophysiology, 99,* 19–27.

Massaro, D. W., & Cohen, M. M. (1994). Visual, orthographic, phonological, and lexical influences in reading. *Journal of Experimental Psychology: Human Perception and Performance, 20,* 1107–1128.

Mathalon, D. H., Whitfield, S. L., & Ford, J. M. (2003). Anatomy of an error: ERP and fMRI. *Biological Psychology, 64,* 119–141.

Maurer, U., Brandeis, D., & McCandliss, B. D. (2005). Fast, visual specialization for reading in English revealed by the topography of the N170 ERP response. *Behavioral and Brain Functions, 1,* 13.

Maurer, U., Brem, S., Bucher, K., & Brandeis, D. (2005). Emerging neurophysiological specialization for letter strings. *Journal of Cognitive Neuroscience, 17,* 1532–1552.

McCandliss, B. D., Posner, M. I., & Givon, T. (1997). Brain plasticity in learning visual words. *Cognitive Psychology, 33,* 88–110.

McClelland, J. L., & Rumelhart, D. E. (1981). An interactive activation model of context effects in letter perception: Part 1. An account of basic findings. *Psychological Review, 88,* 375–407.

Nieuwenhuis, S., Yeung, N., Van den Wildenberg, W., & Ridderinkhof, R. K. (2003). Electrophysiological correlates of anterior cingulate function in a go/no-go task: Effects of response conflict and trial type frequency. *Cognitive, Affective & Behavioral Neuroscience, 3,* 17–26.

Nobre, A. C., Allison, T., & McCarthy, G. (1994). Word recognition in the human inferior temporal-lobe. *Nature, 372,* 260–263.

Nowagk, R., & Pfeifer, E. (1996). Unix implementation of the ERP evaluation package (EEP 3.0). In A. D. Friederici & D. Y. von Cramon (Eds.), *Annual report of the Max-Planck Institute of Cognitive Neuroscience* (pp. 124–126). Leipzig, Germany: Max-Planck Institute.

Paap, K. R., Newsome, S. L., McDonald, J. E., & Scvaneveldt, R. W. (1982). An activation-verification model of letter and word recognition: The word superiority effect. *Psychological Review, 89,* 473–485.

Pammer, K., Hansen, P. C., Kringelbach, M. L., Holliday, I., Barnes, G., Hillebrand, A., et al. (2004). Visual word recognition: The first half second. *Neuroimage, 22,* 1819–1825.

Pelli, D. G., Farell, B., & Moore, D. C. (2003). The remarkable inefficiency of word recognition. *Nature, 423,* 752–756.

Perea, M., Rosa, E., & Gomez, C. (2002). Is the go/no-go lexical decision task an alternative to the yes/no lexical decision task? *Memory & Cognition, 30,* 34–45.

Peressotti, F., & Grainger, J. (1999). The role of letter identity and letter position in orthographic priming. *Perception & Psychophysics, 61,* 691–706.

Pfefferbaum, A., & Ford, J. M. (1988). ERPs to stimuli requiring response production and inhibition—Effects of age, probability and visual noise. *Electroencephalography and Clinical Neurophysiology, 71,* 55–63.

Pfefferbaum, A., Ford, J. M., Weller, B. J., & Kopell, B. S. (1985). ERPs to response production and inhibition. *Electroencephalography and Clinical Neurophysiology, 60,* 423–434.

Picton, T. W., Bentin, S., Berg, P., Donchin, E., Hillyard, S. A., Johnson, R., et al. (2000). Guidelines for using human event-related potentials to study cognition: Recording standards and publication criteria. *Psychophysiology, 37,* 127–152.

Polich, J., & Donchin, E. (1988). P300 and the word-frequency effect. *Electroencephalography and Clinical Neurophysiology, 70,* 33–45.

Proverbio, A. M., Vecchi, L., & Zani, A. (2004). From orthography to phonetics: ERP measures of grapheme-to-phoneme conversion mechanisms in reading. *Journal of Cognitive Neuroscience, 16,* 301–317.

Rayner, K., Sereno, S. C., Lesch, M. F., & Pollatsek, A. (1995). Phonological codes are automatically activated during reading—Evidence from an eye-movement priming paradigm. *Psychological Science, 6,* 26–32.

Roche, R. A. P., Garavan, H., Foxe, J. J., & O'Mara, S. M. (2005). Individual differences discriminate event-related potentials but not performance during response inhibition. *Experimental Brain Research, 160,* 60–70.

Rossion, B., Joyce, C. A., Cottrell, G. W., & Tarr, M. J. (2003). Early lateralization and orientation tuning for face, word, and object processing in the visual cortex. *Neuroimage, 20,* 1609–1624.

Rugg, M. D. (1990). Event-related brain potentials dissociate repetition effects of high- and low-frequency words. *Memory & Cognition, 18,* 367–379.

Rugg, M. D., Doyle, M. C., & Wells, T. (1995). Word and non-word repetition within- and across-modality: An event-related potential study. *Journal of Cognitive Neuroscience, 7,* 209–227.
Schendan, H. E., Ganis, G., & Kutas, M. (1998). Neurophysiological evidence for visual perceptual categorization of words and faces within 150 ms. *Psychophysiology, 35,* 240–251.
Schoonbaert, S., & Grainger, J. (2004). Letter position coding in printed word perception: Effects of repeated and transposed letters. *Language and Cognitive Processes, 19,* 333–367.
Sereno, S. C., Rayner, K., & Posner, M. I. (1998). Establishing a time-line of word recognition: Evidence from eye movements and event-related potentials. *NeuroReport, 9,* 2195–2200.
Stevens, M., & Grainger, J. (2003). Letter visibility and the viewing position effect in visual word recognition. *Perception & Psychophysics, 65,* 133–151.
Tarkiainen, A., Helenius, P., Hansen, P. C., Cornelissen, P. L., & Salmelin, R. (1999). Dynamics of letter string perception in the human occipitotemporal cortex. *Brain, 122,* 2119–2131.
Tekok-Kilic, A., Shucard, J. L., & Shucard, D. W. (2001). Stimulus modality and Go/NoGo effects on P3 during parallel visual and auditory continuous performance tasks. *Psychophysiology, 38,* 578–589.
Thorpe, S., Fize, D., & Marlot, C. (1996). Speed of processing in the human visual system. *Nature, 381,* 520–522.
Vanpetten, C., & Kutas, M. (1990). Interactions between sentence context and word-frequency in event-related brain potentials. *Memory & Cognition, 18,* 380–393.
Van 't Ent, D., & Apkarian, P. (1999). Motoric response inhibition in finger movement and saccadic eye movement: A comparative study. *Clinical Neurophysiology, 110,* 1058–1072.
Whitney, C. (2001). How the brain encodes the order of letters in a printed word: The SERIOL model and selective literature review. *Psychonomic Bulletin & Review, 8,* 221–243.
Wydell, T. N., Vuorinen, T., Helenius, P., & Salmelin, R. (2003). Neural correlates of letter-strings length and lexicality during reading in a regular orthography. *Journal of Cognitive Neuroscience, 15,* 1052–1062.