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# CHRONOMETRY OF VISUAL WORD RECOGNITION DURING PASSIVE AND LEXICAL DECISION TASKS: AN ERP INVESTIGATION

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*In order to investigate the neuroanatomical chronometry of word processing, two experiments using: Event-Related Potentials (ERPs) have been performed. The first one was designed to test the effects of orthographic, phonologic, and lexical properties of linguistic items on the pre-semantic components of ERPs during a passive reading task and massive repetition used to reduce familiarity effect between words and nonwords. In a second study, the level of familiarity was investigated by varying stimulus repetition and frequency in a lexical decision task. Overall results suggest a functional discrimination between orthographic and nonorthographic stimuli begun as early as 170 ms (N170 component) whereas the next components (N230 and N320) were sensitive to the orthographic nature of the stimuli, but also to their lexical/phonologic proprieties. The N320 associated to phonological processing (Bentin et al., 1999) was modulated by word frequency and massive repetition caused its disappearance. This suggests that this component may reflect a nonobligatory phonologic stage of grapheme-phoneme conversion postulated by the DRC model (Coltheart et al., 2001) or semantic phonologically mediated pathway (Harm & Seidenberg, in press).* Q1

**Keywords** dual-route theory, event-related potentials, N170, N320, N400, PDP models, reading, visual word recognition

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Reading a word is dependent on the identification and integration of several types of information, including orthographic, phonologic, and semantic codes (Massaro & Cohen, 1994). The purpose of reading models is to explain or simulate experimental data at different processing levels as well as their interactions during presentation of words with different characteristics, such as frequency of usage and regularity, as well as nonwords. Two general models have been presented: (1) the connectonist type, such as Parallel Distributed Processing (PDP) (Plaut et al., 1996; Seidenberg & McClelland, 1989) and (2) dual-route theory (Coltheart, Curtis, Atkins & Haller, 1993; Coltheart et al., 2001; Morton & Patterson, 1980). In particular, the Dual-Route Cascaded (DRC) model (Coltheart et al., 2001) postulates the existence of two pathways: a lexical route by means of a phonological lexicon and a sublexical one applying serial grapheme-phoneme transcriptions, especially for reading nonwords and infrequent words.

Although the first PDP model (Seidenberg & McClelland, 1989) was efficient for simulating word frequency, consistency, and their interactions in the absence of grapheme-phoneme conversion rules, it was less efficient for nonword reading. Because of this, Plaut et al. (1996) suggested the existence of an orthography-phonology (OP) and orthography-semantic-phonology (OSP) pathway. It is generally accepted that at least two pathways exist for reading words and nonwords, but their exact nature and their mode of interaction are still actively discussed.

To discriminate between different levels of processing and their underlying brain structures, positron emission tomography (PET) and functional magnetic resonance imagery (fMRI) techniques have delineated specific cortical areas underlying various aspects of reading (Cabeza & Nyberg, 1997, 2000; Posner, et al., 1999; Price, 1998). Although event-related potentials (ERPs) are less accurate in terms of neuroanatomic localization than these techniques, valuable information may be obtained on the timing and interrelations of different processing stages.

The N400 (Kutas & Hillyard, 1980) is considered to be an important language-related component, although observable with nonverbal stimuli as well (Nigam et al., 1992). The topographic distribution of this component depends on the nature of the stimulus, mainly centro-parietal for sentences (Kutas et al., 1988) and more anterior (fronto-central) for isolated words (Bentin, 1987; Bentin et al., 1985; McCarthy & Nobre, 1993) as well as the type of reference electrode. Although the specific process corresponding to the N400 is still a matter of debate (Kutas & Federmeier, 2000), it is probably involved in semantic integration/expectation or lexical search/access (Bentin et al., 1985; McCarthy & Nobre, 1993; Nobre & McCarthy, 1994). The implication of the N400 in phonologic processing has also been documented because this wave was not observed for nonwords obeying no orthographic and phonetic rules of language (Holcomb &. Neville, 1990; Nobre & McCarthy, 1994; Rugg & Nagy, 1987).

Although the N400 has brought considerable information on the brain mechanisms underlying language processes, recent studies have indicated the involvement of earlier components. In a visual discrimination task, Bentin et al. (1999) described for orthographic stimuli a N170 wave maximal at left temporal sites, whereas non-orthographic stimuli gave larger amplitudes in the right hemisphere. Nobre et al. (1994) observed in epileptic patients an intracranial N200 component specific for letter presentation in the posterior fusiform gyrus but unaffected by the nature of the verbal presentation (real word or nonword) and by semantic priming. In their view, orthographic processing begins as early as 200 ms in temporal regions. Moreover, Dehaene (1995) found differences between real words and strings of consonants approximately at 192 ms, corresponding to N170/N200, perhaps reflecting visual word form construction.

A N280 component at left frontal sites has also been described, specific for function-words (prepositions, conjunctions) and pseudowords (Neville et al., 1992; Nobre & McCarthy, 1994), which implies distinct neural organizations depending on the type of word used. The functional significance of the frontal N280 is still debated, but may represent a categorical site (Brown et al., 1999; Osterhout et al., 1997).

In addition, a N320 component, recorded in mid-temporal sites, was reported by Bentin et al. (1999). This wave appeared in a rhyming decision task with an amplitude larger in the left than the right hemisphere. Because the N320 appeared only after reading pronounceable stimuli, the authors hypothesized that this wave represents a form of phonologic processing.

The goal of the present investigation was to delineate the neuroanatomical chronometry of reading at different levels of processing, possibly orthographic for the N170 (or N200), phonologic for the N320, and categorical for the N280. More particularly, the phonologic trace attributed to N320 permits an investigation of its functional representation according either to DRC or PDP models. Indeed, although differing in some aspects, these models have a double pathway in common, with a specificity to nonwords or infrequent words, where the influence of phonology is likely to be important. The DRC model postulates the existence of a grapheme-phoneme (nonlexical) pathway, whereas the PDP model postulates a direct (orthography-phonology) pathway. The relative impact of nonwords and infrequent words may shed light on this question.

## EXPERIMENT 1

### Introduction

Stimuli with different orthographic, phonologic, lexical, and semantic properties were presented in a sub-vocal passive reading task. Word reading and the access to their meaning were assumed to be irrepressible. In this experiment, the study of the neurophysiological consequences of visual information processing for words was attempted at early pre-semantic stages, as N170, N200, N280, and N320 are considered to be pre-semantic components.

Although several studies have been conducted on the neuroimaging effects of word in comparison to nonword processing (Cohen et al., 2000; Compton et al., 1991; Dehaene, 1995; Nobre & McCarthy, 1994; Petersen et al., 1990). Tagamets et al. (2000) suggested that the differences may simply be due to familiarity as opposed to linguistic differences as such. In order to minimize this potentially confounding variable, massive (100 times), non-immediate repetition of stimuli was used in the first study. The stimuli consisted of a string of pseudo-letters, a string of consonants, a pseudo-word, and a concrete word. The comparison between pseudo-letters and the string of consonants isolates the orthographic process. In the same fashion, the comparison between the string of consonants and the pseudo-word isolates the phonologic process and the comparison between the pseudo-word and the frequently used concrete word the lexical process.

As mentioned earlier, DRC and PDP models suggest two routes in reading. In DRC, nonword processing would be assumed essentially by grapheme-phoneme conversion (nonlexical pathway), whereas in the case of PDP these stimuli would involve the OP pathway. Thus, if the N320 component represents phonologic processes, it should be elicited more extensively by nonwords.

## Method

### *Subjects*

A group of 10 French-speaking monolingual subjects (5 men and 5 women) with a mean of 23 years of age participated in the first study. All subjects had normal or corrected-to-normal vision, were right-handed (lateralization test, Oldfield, 1971), and had no history of neuropsychiatric disorders.

### *Stimuli*

The stimuli consisted of a string of pseudo-letters in false fonts, identical to those used by Petersen et al. (1990), a string of consonants whose pronunciation was impossible, a 2-syllable pseudo-word, and a 2-syllable frequently used regular, concrete word. The stimuli contained 5 characters in capital letters with the "Courier" font and similar intercharacter spacing. The stimuli were presented 100 times in a pseudo-random order and never twice in succession.

### *Procedure*

After placing the electrodes, the subjects were comfortably seated in the dark at a distance of 60 cm from a computer screen. The stimuli were white on a dark background with a visual angle subtending 2° and lasted 1 s, followed by a blank period lasting between 900 and 1100 ms in which the subjects stared at a fixation point. The stimuli were presented in series of 20, after which time a 10-s pause was given. A 10-min rest period was allowed whenever needed. The subjects were asked to look attentively at each stimulus and at the fixation point.

### *Recordings*

The EEG was recorded with 32 tin electrodes (electrocaps) from FP1, F7, F3, C3, T3, CP3, TP7, T5, PO5, PO3, P3, O1, XO1, FP2, F8, F4, C4, T4, CP4, TP8, T6, PO6, PO4, P4, O2, XO2, Fz, Cz, Cpz, Pz, Poz, and Oz sites distributed according to the 10-20 system. During acquisition, each electrode was referred to Cz. Electrode resistance was kept under 5 kΩ. The EEG was amplified, digitized at a rate of 256 Hz, filtered (band-pass 0,1 Hz–100 Hz), and stored on Deltamed™ software.

### *Data Analyses*

The EEGs were averaged with a multi-electrode reference (Bertrand et al., 1985) composed of F7, F3, C3, T3, CP3, TP7, T5, P3, F8, F4, C4, T4, CP4, TP8, T6, P4, Fz, Cz, Cpz, and Pz sites. These electrode sites were chosen in order to obtain a uniform distribution on the scalp. Frequencies higher than 48 Hz were rejected. The baseline was calculated as the mean voltage during the 250 ms preceding the stimuli. Approximately 5% of the trials were excluded because of ocular artifacts, defined by amplitudes greater than 100 µV at FP1 and FP2 electrodes.

Three temporal windows were determined by observation of the grand average and respecting the chronometry of each studied component: N170 (141–180 ms), N230 (180–270 ms), and N320 (270–336 ms). The mean amplitude within occipito-temporal areas (TP7, T5, PO5, O1, XO1, TP8, T6, PO6, O2, XO2 electrodes), selected on the basis of the topography of the components, was measured and analyzed by repeated-measure ANOVAs. When either the main factor or interaction was significant, planned comparisons were conducted.

## Results

The first component recorded with a peak amplitude at occipital regions was P100, dependent on the physical characteristics of the stimuli and on selective attention (Hillyard et al., 1998; Johannes et al., 1995; Luck et al., 2000; Martinez et al., 2001). The second component was N170, with a maximal amplitude at posterior temporal sites (T5/T6 electrodes). The third component culminated at 230 ms (N230) and appeared at occipital (O1/2) and temporal (T5/6) regions. A later component (N320) was present only at occipital sites for orthographic stimuli and at left temporal regions for some of them.

All of these components appeared very clearly at left and right occipital levels (O1/O2 electrodes) with orthographic items, whereas at the temporal sites the different components were larger in the left hemisphere than the right. Furthermore, the N320 appeared only on the left side (T5 electrode), so that, in general, the negative waves (N170, N230, N320) were of greater duration on the left side (Figure 1). The N400 (or P400 in posterior regions) was very weak, which may be due to the high number of item repetitions and the passive nature of the task. A slow component appeared between 500–1000 ms, negative/positive at posterior/anterior regions, respectively. This component has been labeled either as a "late positive component" (LPC) (Segalowitz et al., 1997; Swick & Knight, 1997) or else "negative slow wave" (Ackerman et al., 1994; McCarthy & Nobre, 1993).

This article will only focus on the first three negative components, namely N170, N230, and N320. The analysis was made for selected electrodes corresponding to the topographic distribution of the components, namely TP7, T5, PO5, O1, XO1, TP8, T6, PO6, O2, and XO2.

### *N170*

The N170 was optimal at occipito-temporal regions, with the amplitude increasing from occipital to temporal sites, especially in the left hemisphere (Figure 1). The hemisphere main factor was significant ($F[1, 9] = 11.29$; $p < .009$), as the negativity was larger on the left side. The item × side interaction ($F[3, 27] = 3.5$; $p < .03$) was

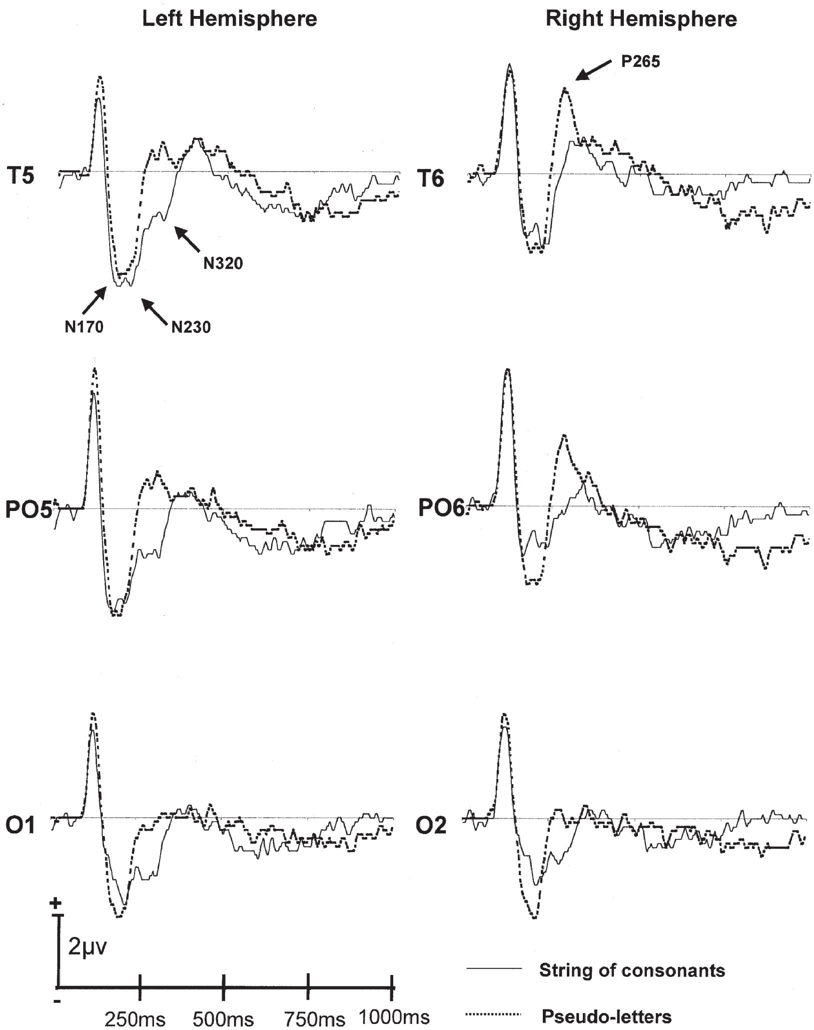


**FIGURE 1.** The negative waves (N170, N230, N320) were of higher amplitude in the left hemisphere than the right. The N320 was absent for pseudo-letters.

also significant (Figures 1 and 2). At the left temporal area (T5 electrode), all 3 stimuli composed of letters triggered larger negativities than pseudo-letters ($p < .05$) (Figure 2). In the right hemisphere, the pattern was reversed at the O2 electrode ($p < .05$), as the N170 was larger for pseudo-letters than for the string of consonants.

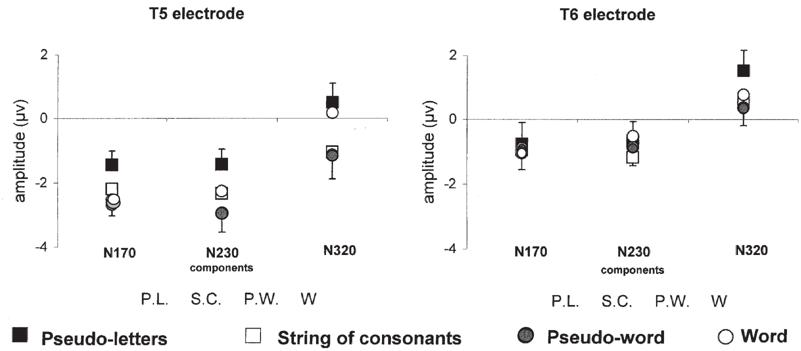


**FIGURE 2.** Mean (± SD) amplitudes obtained in temporal lobe, with higher negativity for N170 and N230 waves at the T5 but not at the T6 electrode for the three types of stimuli composed of letters than for pseudo-letters. Only the string of consonants and the pseudo-word elicited the N320.

### *N230*

As with the previous component, the N230 was larger in the left hemisphere than the right ($F[1, 9]$ 8.38; $p < .02$), particularly at temporal sites (Figures 1 and 2). The significant item × side interaction ($F[3, 27] = 5.51$; $p < .005$) indicates an orthographic effect restricted to the left hemisphere. Contrary to the N170, the pseudo-word triggered a larger negativity than the string of consonants ($F[1, 9] = 18.49$; $p < .002$). In particular, this effect appeared at PO5 and T5 electrodes (Figures 2 and 3).

### *N320*

As with the previous components, the item × side interaction was significant ($F[3, 27] = 3.92$; $p< .02$). However, unlike the previous components, the N320 was triggered only by the string of consonants and by the pseudo-word and not by the other 2 stimuli (Figures 2 and 3). In particular, the amplitude of the string of consonants differed from the string of pseudo-letters ($F[1, 9] = 14.96$; $p < .004$). Indeed, the string of pseudo-letters triggered instead a positive component at approximately 265 ms, with a maximal amplitude at the right temporal site (T6 electrode, see Figures 2 and 3). Moreover, unlike the previous components, the amplitude of the N320 was identical at O1, PO5, and T5 electrodes.

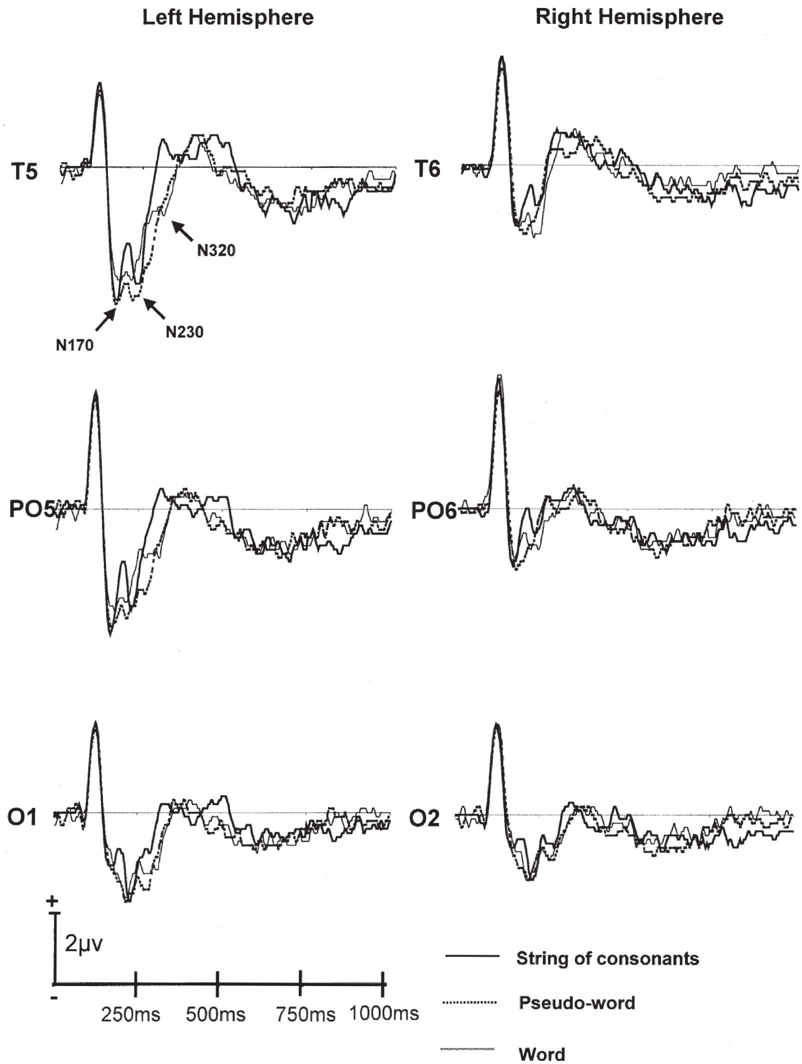


**FIGURE 3.** A greater N230 amplitude was revealed for the pseudo-word than other orthographic stimuli at T5 and PO5 electrodes. Only the pseudo-word and the string of consonants elicited the N320 in the temporal left hemisphere.

On one hand, the appearance of the N320 after presentation of the string of consonants and the pseudo-word but not for the stimulus with false fonts is suggestive of its dependence on orthographic stimuli. On the other, the absence of the same wave after presentation of a real word indicates its sensitivity to the general characteristics of orthographic items. Indeed the concrete word differed from either the pseudo-word ($F[1, 9] = 10.49$; $p < .01$) and the string of consonants ($F[1, 9] = 5.64$; $p < .04$) (Figures 2 and 3), significance being reached at T5, PO5, and O1 sites in the left hemisphere.

In summary, early differences were found between nonwords and words. A functional discrimination between orthographic and non-orthographic stimuli began as early as 170 ms and lasted until the end of recording. The next components (N230 and N320) were sensitive to the orthographic nature of the stimuli, but also by their lexical/phonologic properties.

## Discussion

### *N170 and Orthographic Processing*

The results of this experiment are in accord with the hypothesis that orthographic information is processed very early. Bentin et al. (1999) reported that the N170 wave was maximal for orthographic stimuli at left temporal sites in a visual discrimination task. In the present passive reading task, the amplitude of the N170 was larger at occipito-temporal regions for all three orthographic items than for the string of pseudo-letters. In addition, the increasing amplitude of the N170 in the left but not the right hemisphere from occipital to temporal regions is concordant with the hypothesis of a finer discriminative ability on that side. These results are also in agreement with evidence of orthographic processing in extra-striate regions by fMRI and PET methods (Petersen et al., 1990; Puce et al., 1996; Pugh et al., 1996; Pugh et al., 1997). Nevertheless, although this study's stimuli were presented 100 times, the possibility cannot be excluded that the stimuli also differed in terms of familiarity, as suggested in these types of paradigm by Tagamets et al. (2000). It is for this reason that the effects of repetition and word frequency were evaluated in a second experiment.

### *N230*

As for the previous component, the N230 was lateralized on the left side and was influenced by the nature of the orthographic stimulus. But unlike the previous component, the negativity of the N230 was larger for the pseudo-word than for the string of consonants at left temporal sites. This component may therefore correspond to the intracranial N200 described by Nobre et al. (1994), on the basis of their proximity and their sensitivity to the orthographic status (presence or absence of letters) of stimuli. However, the N230 but not the N200 was affected by the pseudo-word/string of consonants contrast in the left temporal area. It is therefore possible that the N200 is only one of several generators underlying the N230.

Dehaene (1995) and Cohen et al. (2000) reported differences in ERP amplitudes between words and strings of consonants approximately at 200 ms, interpreted as construction of the visual word form. The concept of visual word form was first introduced by Petersen et al. (1990) with the fusiform gyrus as its anatomic substrate (Cohen et al., 2002; Dehaene et al., 2002). Here the authors' observed differences between the string of consonants and the pseudo-word. This result may be due to the fact that the pseudo-word obeys orthographic and phonologic rules, whereas the string of consonants does not. Moreover, as seen later, repetition affects word processing.

### *N320*

Unlike the previous components, the N320 was only observed for two types of stimuli (string of consonants and pseudo-word) and not for the other two (pseudo-letters and concrete word). In particular, the string of pseudo-letters elicited a positive wave. These results show that the N320 is affected by orthographic and lexical properties of the stimuli. This component appears comparable to the N320 described by Bentin et al. (1999), which, according to those Q3 authors, is involved in phonologic processes. This hypothesis is supported by its clear lateralization on the left side. Indeed, studies in dyslexic or split-brain patients (e.g., Schweiger et al., 1989) indicate that only the verbally dominant hemisphere (left for most persons) possesses phonologic properties. The absence of the N320 after presentation of the concrete word may be explained by the high number of repetitions and the passive nature of the task. Thus, the phonologic processing represented by this component does not appear to he obligatory for word reading, excluding a role in lexical processing. Instead, this wave may be involved in grapheme-phoneme conversion (according to the DRC model) or in the phonologic pathway (according to the PDP model). This result implies a more direct non-N320 mediated pathway for the real word than for nonwords. The appearance of the N320 for the string of consonants, which cannot be transcribed at the phonologic level, may be explained by the passive nature of the task and by frequent repetitions, inciting attempts on the part of subjects at either phonologic transcriptions or graphemic analyses.

Overall, the findings of interstimulus differences after a high number of repetitions meant to limit the impact of familiarity are indicative that linguistic differences may be detected by different ERP amplitudes.

## EXPERIMENT 2

### Introduction

In the second study, the level of familiarity was investigated by varying stimulus repetition and frequency in a lexical decision task. The lexical decision task was used in order to evoke deeper processes, apt to generate the N400 (e.g., Chwilla et al., 1995). It has previously been demonstrated that word frequency affects different ERPs, including the N400 (e.g., Rugg, 1990; Van Petten & Kutas, 1990; Young & Rugg, 1992), as well as behavioral performances (Connine et al., 1990; Forster & Chambers, 1973; Monsell et al., 1989).

If the N320 represents the grapheme-phoneme conversions (GPCs) of the DRC model or the OP pathway of PDP models, this wave should be sensitive to stimulus frequency. In the DRC model, the frequency should modulate the application of GPCs, in the sense of more important processing for low frequency words (Coltheart et al., 2001). Likewise, in PDP models, the OP pathway should be sensitive to frequency and consistency. Moreover, the more a word is presented during training procedure, the more important is the semantic contribution and the weaker OP in reading (Plaut et al., 1996). In the previous experiment, the real word did not elicit an N320, possibly due to massive repetition, maximizing the efficiency of the lexical route and causing the disappearance of GPC the (DRC model) or else maximizing the involvement of the semantic pathway (PDP model). The present experiment attempted to shed some light on that point.

## Methods

### *Subjects*

A separate group of 10 subjects (5 men and 5 women) participated in the second study; their mean age was 24 years. As in the previous study, the right-handed subjects' first language was French, with normal or corrected-to-normal vision and no history of neuropsychiatric disorders.

### *Stimuli*

The stimuli consisted of a list of 50 frequent words, a list of 50 infrequent words, and a list of 50 pseudo-words. Each of these lists was presented twice. In addition, three single items (frequent, infrequent, and pseudo-word) with characteristics similar to the lists were presented 100 times under a nonimmediate condition.

The effect of repetition was evaluated by comparing the items presented 100 times to the items presented twice. Although it is possible that once-repeated words already differ from nonrepeated words, such differences are not necessarily linguistic in nature, but may instead reflect memory-related processes.

The effect of frequency was evaluated by comparing frequent to infrequent words. All the presented words were concrete. The number of letters and of syllables as well as the mean position of the orthographic uniqueness point (Kwantes & Mewhort, 1999) for each list did not differ from the single items. The single items consisted of 6 letters and 2 syllables with a late orthographic uniqueness point and with few orthographic similarities to neighboring letters. Word frequency was determined by the BRULEX database (Content et al., 1990). The frequent word list had a mean value of 3,720 occurrences per 100 million and the infrequent word list a value of 149. The single frequent word had a value of 4,556 and the single infrequent word a value of 102. The stimuli were presented in a pseudorandom fashion and no identical stimulus was presented twice in a row. The stimuli appeared with the "Courier" font in capital letters, with similar spacing between each letter.

### *Procedure*

The method of presentation was similar to that of the previous study, except that the subjects were asked to decide whether the stimulus was a word or not (lexical decision) by pressing one of two keys with their right hand. In order to avoid the recording of motor-related ERPs, the subjects responded only after hearing a beep sound. The next item appeared only after a response was made.

### *Recordings and Data Analyses*

The recording and data analyses were identical to those of the first experiment. The same temporal windows were used and the dependent variable was the mean amplitude. Unlike the previous study, the authors were able to analyze the N400 component within the 336-480 ms temporal window at fronto-central areas (FP1, F7, F3, T3, C3, EP2, E8, E4, T4, C4).

The generators of the components were assessed by LORETA software (Pascual-Marqui, 1999; Pascual-Marqui et al., 1994) from the grand average and at maximal Global Field Power of the studied component. These topographic data were obtained from a network of 28 electrodes (FP1, F7, F3, C3, CP3, TP7, T5, PO5, PO3, P3, O1, FP2, F8, F4, C4, CP4, TP8, T6, PO6, PO4, P4, O2, Fz, Cz, Cpz, Pz, Poz, Oz).

## Results

ANOVAs were performed on the following factors: *Repetition* (2 as opposed to 100 times), *Frequency* (high vs. low), *Hemisphere* (left or right), and *Electrodes.*

### *N170*

The two main factors—frequency and hemisphere—were significant. The magnitude of the N170 was larger in the left hemisphere than the right ($F[1, 9] = 18.52$; $p < .0062$) and frequent words elicited a larger negativity than infrequent words ($F[1, 9] = 5.28$; $p < .0472$). The significant repetition x frequency interaction ($F[1, 9] = 12.59$; $p < .0062$) indicates that the frequency effect was due to items presented 100 times and not to items presented twice. Indeed, the amplitude of the more frequent word was higher than that of the infrequent word only for these highly repeated items ($F[1, 9] = 14.30$; $p < .0044$) (Figure 4).

The analysis of the generators of the N170 indicated several possible sources in posterior regions. The first source of high intensity was obtained in the precuneus region (Brodmann areas 7 and 19) of the left hemisphere. A second generator was revealed in the junction of the superior part of midtemporal gyrus and inferior parietal gyrus (BA39) of the left hemisphere of higher intensity with non-frequent words.

### *N230*

The repetition main factor was significant ($F[1, 9] = 10.29$; $p < .011$), characterized by a larger amplitude for words presented twice than words presented 100 times. The significant repetition × frequency interaction ($F[1, 9] = 7.29$; $p < .025$) is due to the higher amplitudes for infrequent words, only for twice-presented and not massively presented words. The repetition × frequency × hemisphere triple interaction ($F[1, 9] = 5.6$; $p < .043$) reveals that this effect was only observed in the left hemisphere, particularly at T5 and PO5 electrodes (Figure 5).

Generator analysis of the N230 indicated the presence of a source at the level of the mid-temporal gyrus (BA37/39) of the left hemisphere.

### *N320*

The N320 appeared at the occipito-temporal level (Figure 5) only for words presented twice. The repetition main factor was significant

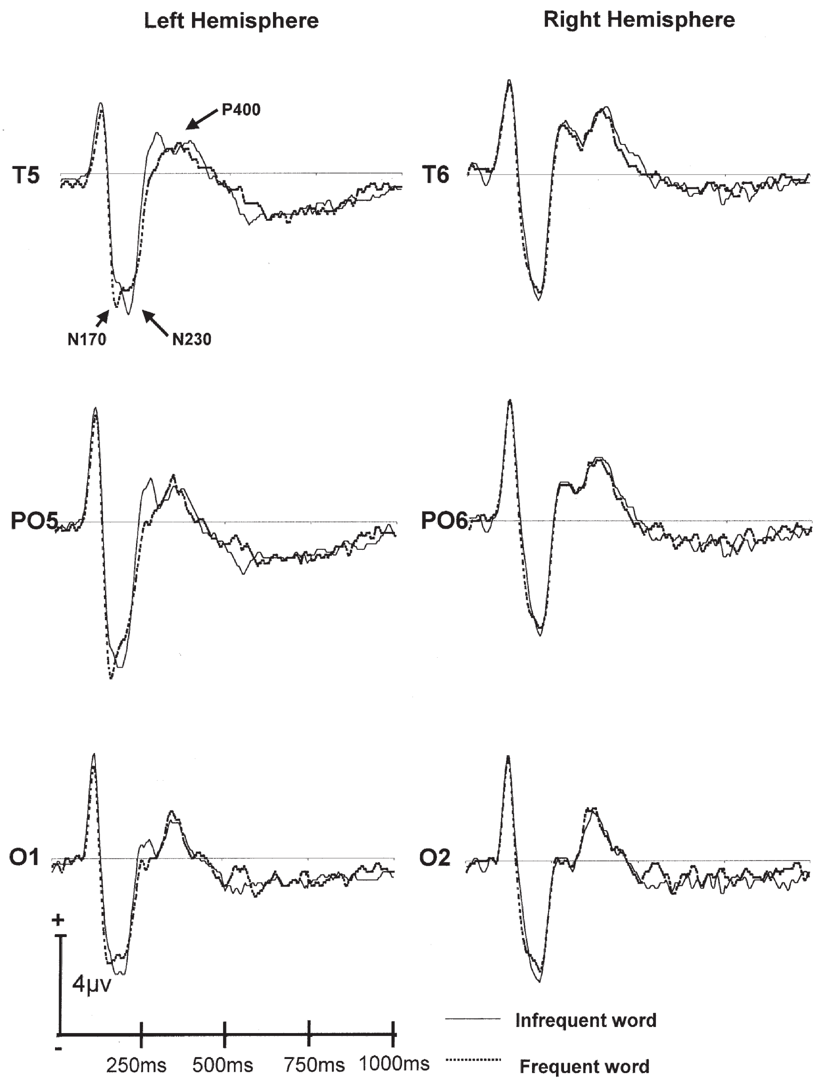


**FIGURE 4.** ERPs elicited by frequent and infrequent massively repeated words. The frequent word elicited a greater N170 amplitude than the infrequent word only at T5 and PO5 electrodes.

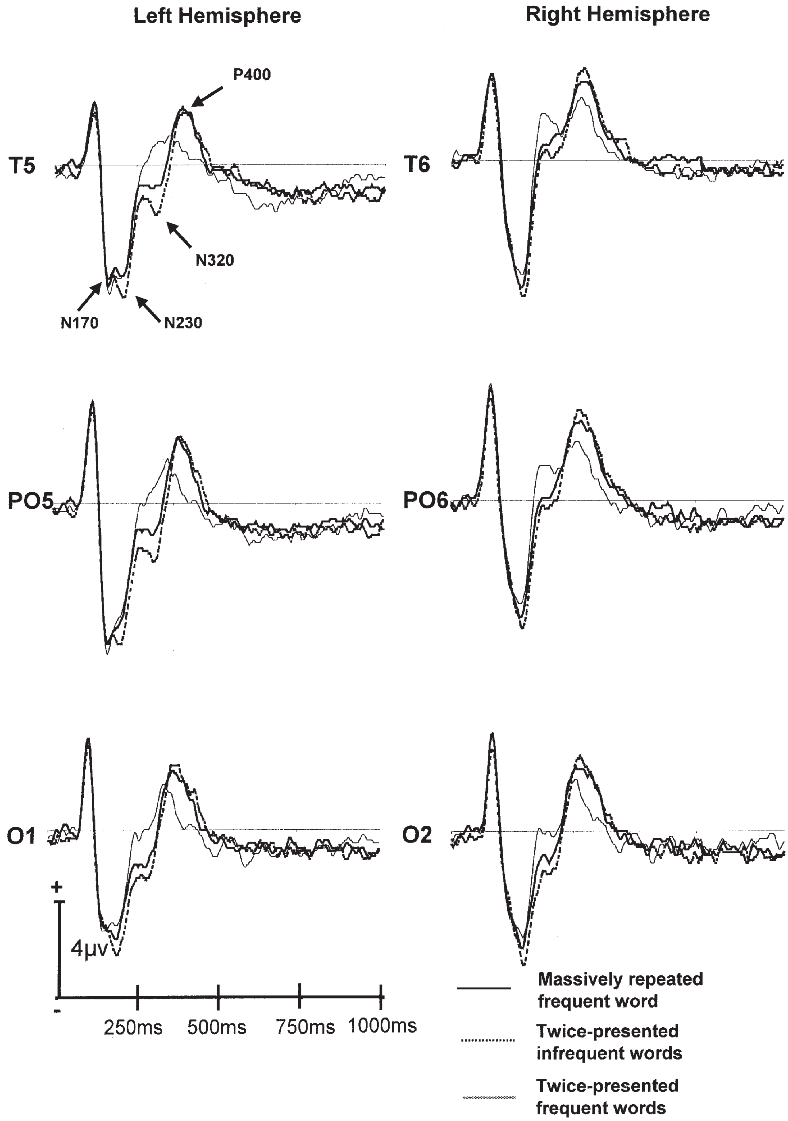


**FIGURE 5.** ERPs indicating frequency effects for twice-presented words on the N230 wave, where the amplitude was greater for infrequent words than frequent words at T5 and PO5 electrodes. The N320 was present only for twice-presented words lists in the left temporal region and its amplitude was prominent for infrequent words.

($F[1, 9] = 32.29$; $p < .0004$), as was the repetition x frequency interaction ($F[1, 9] = 16.16$; $p < .004$), indicating that the N320 amplitude was larger for infrequent than frequent words for these twice-presented words ($F[1, 9] = 16.16$; $p < .003$). The repetition × hemisphere interaction was also significant ($F[1, 9] = 8.91$; $p < .016$), explained by the higher amplitude on the left side ($F[1, 9] = 7.74$; $p < .022$) for words presented only twice than for massively presented words. This asymmetry concerns almost every occipito-temporal site.

The analysis of the generators of the N320 indicated different sources situated in the left hemisphere. The first were situated at the level of the superior part of the mid-temporal gyrus (BA37/39) and of the inferior temporal gyrus (BA20) and were obtained for all lists, whereas activations at the level of the inferior parietal lobule (BA39/40) and lingual gyrus (BA18) were absent for the list of frequent words (Figure 6).

Mid-temporal and inferior parietal gyri have often been associated with phonological treatment (Hagoort et al., 1999; Mazoyer et al., Salamon et al., 1993; Moore & Price, 1999; Peterson et al., 1999; Price et al., 1994; Zatone et al., 1992). The source in the lingual gyrus seems to be involved in visual processing (Kastner & Ungerleider, 2001). According to Hagoort et al. (1999), the lingual gyrus is activated in numerous reading tasks, but its exact function remains to be determined.

### *N400*

The N400 appeared for words presented twice mainly at frontal sites (F3 and F4 electrodes), whereas for words presented 100 times, the N400 was weaker (Figure 7). The N400 was larger in the left hemisphere than the right ($F[1, 9] = 9.94$, $p < .012$), but there was no frequency effect ($p > .05$). The significant repetition × electrode interaction ($F[8, 72] = 2.61 = 2.61$; $p < .015$) indicates that words presented twice elicited larger amplitudes than words presented 100 times at F3 and (B electrodes. The N280 component underlines this repetition effect ($F[1, 9] = 12.98$; $p < .0058$), characterized, contrary to the N400, by a larger negativity for massively presented items than twice-presented items. This difference may reflect an

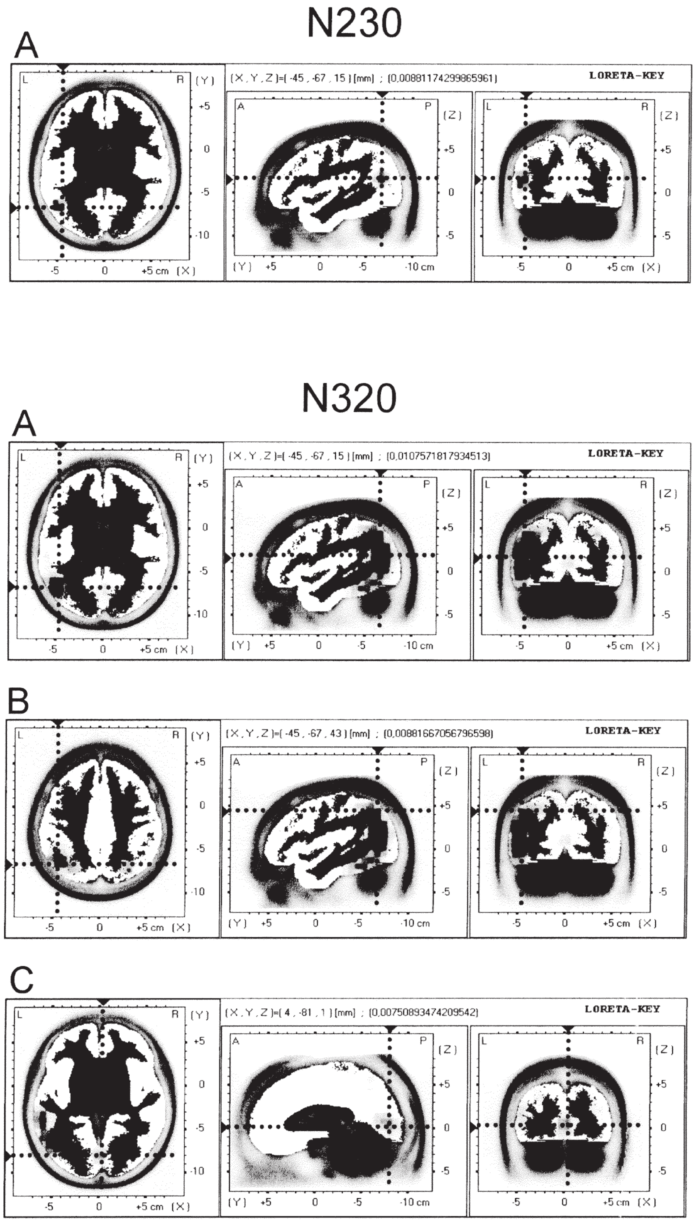


**FIGURE 6.** The principal generators for the N230 and N320 components obtained with LORETA software during presentation of infrequent words: (A) mid-temporal gyrus (BA37/39), (B) inferior parietal lobule (BA39/40), and (C) lingual gyrus (BA18). The Talairach coordinates of these generators are presented, with intersection of line points indicating their location.

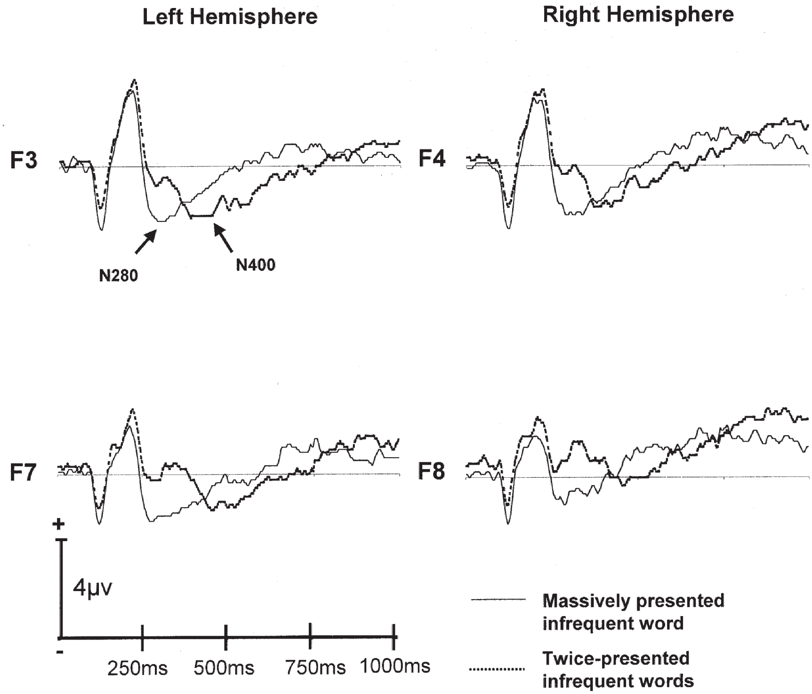


**FIGURE 7.** ERPs indicating that the massively repeated infrequent word was associated with a prominent N280 and a very small N400, whereas this pattern was reversed for twice-presented infrequent words.

earlier lexical-semantic access for massively repeated words compared to single repetition.

In summary, massive repetition had considerable effects on ERPs, leading to a weaker N230 amplitude, the disappearance of the N320, an enhanced N280 amplitude, and a diminished N400. For twice-presented stimuli, N230 and N320 amplitudes were higher for infrequent words. For massively repeated stimuli, the frequency effect began as early as N170 and the frequent word elicited greater amplitudes than the infrequent one.

## Discussion

In general, the amplitudes of the ERPs in the second study were larger than the first, probably due to the presentation of more diverse items and to a more effort-demanding task (Awh et al., 2000).

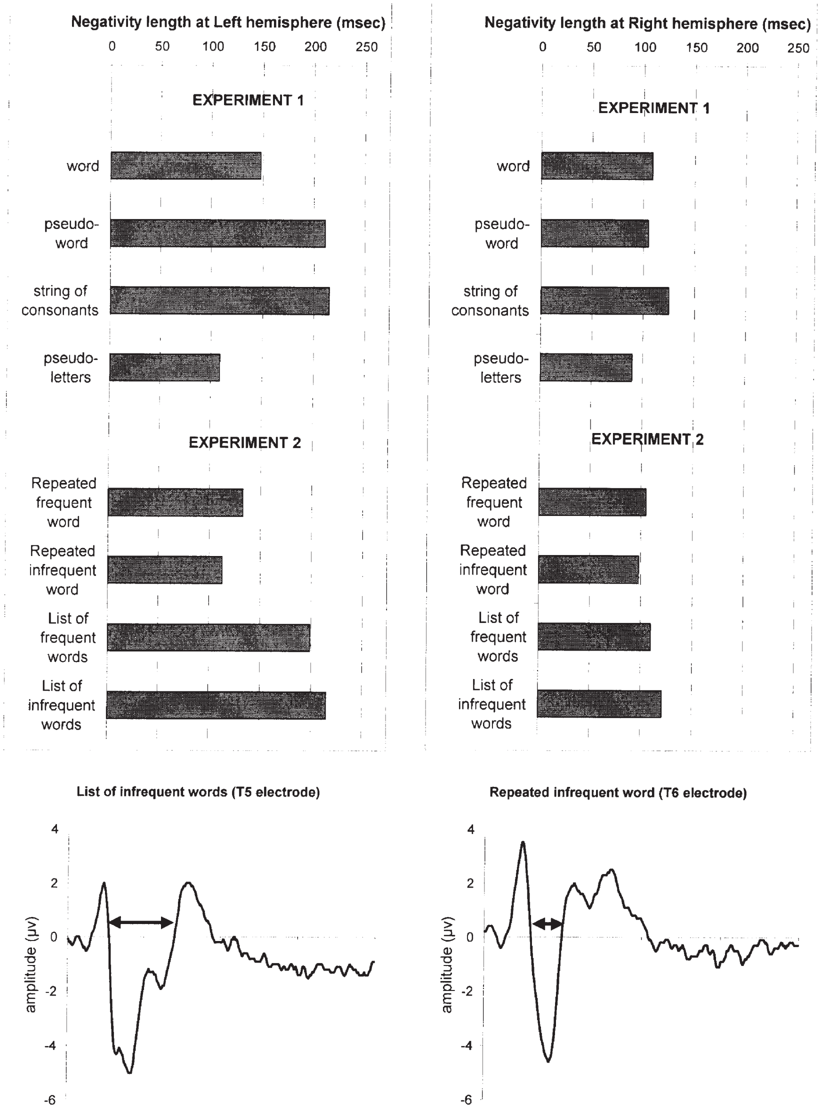


**FIGURE 8.** The duration of negativity for N170, N230, and N320 components at T5 and T6 electrodes. The duration was calculated from the Grand Average, ranging from the beginning of N170 to the return to baseline (either N230 or N320 depending on experimental conditions). The more difficult the stimulus (low frequency or unusual association of letters), the more the negativity spreads in time in left temporal regions.

### *N170—The First Discriminative Step for Reading*

As in the first experiment, the amplitude of the N170 was higher in the left hemisphere than the right, particularly at PO5 and T5 electrodes. In addition, the amplitude of the N170 was higher for the frequent word than for the infrequent word, but this effect occurred only when these words were presented 100 times, and not when word lists were presented only twice. Thus, the massive repetitions seemed to amplify the sensitivity of this wave to word frequency. This result is all the more interesting in regard to recent studies suggesting that this component is sensitive to face familiarity and expertise (Caharel et al., 2002; Rossion et al., 2002). It seems that under favorable (e.g., massive repetition) circumstances, this familiarity effect is present for words as well. In any event, the sensitivity to word frequency together with the larger negativities found for stimuli composed of letters than pseudo-letters in the first study are concordant with the hypothesis that this component reflects orthographic discrimination (Bentin et al., 1999). The different results in massive as opposed to single repetition may also be explained by a more visual processing strategy elicited by the former method. In addition, the N170 (or N1) has been shown to be modulated by selective attention (see Hillyard et al., 1998). For example, when a stimulus appeared in an expected location, the amplitude of the N1 component was enhanced. A parallel may be drawn between selective attention (where the N1 amplitude is high for stimuli in expected locations) and the: high N1 amplitude for very frequent words, but only under massive repetition, for reasons that remain to be determined. Perhaps repetition allowed more “archaic” processing such as logography (Erith, 1985, 1986). The possibility cannot be excluded that this effect reflected a more direct visual word form processing.

The generators for the N170, in particular at the level of the left-sided midtemporal lobe, are of interest in view of the involvement of this region in the storage of visually presented words (Beauregard et al., 1997; Howard et al., 1992). This would support the concept of an orthographic form of processing, where letters can be extracted on the basis of visual patterns (Bentin et al., 1999).

### *N230 and Lexical Processing or Visual Word Form*

In the left hemisphere, massive repetition diminished the amplitude of the N230. Moreover, under the same condition, an infrequent word generated a N230 wave more similar to that evoked by a frequent word (of lower amplitude). Behavioral studies have indicated that under some conditions the repetition of infrequent words generates performances similar to those of frequent words (Bentin et al., 1998). This raises the question as to the implication of the N230 in lexical processing, suggested to occur as early as 200 ms post-stimulus by some authors (Posner & Pavese, 1998). The possible role of N230 in lexical processing is supported by the findings in the first experiment because this component was of maximal amplitude for pseudo-words, whose orthographic and phonologic properties resemble those of words but with no lexical equivalents. These items probably elicit lexical retrieval processes that would be characterized by an elevated N230 amplitude. The repetition effect may also indicate that this component reflects lexical processing. Indeed, an infrequent word is more liable to be retrieved when repeated a great number of times.

Although as yet uncertain, the possibility of the intracranial N200 (Nobre et al. 1994) as a source of the N230 may be proposed. The authors obtained a generator in the mid-temporal gyrus of the left hemisphere for all stimuli, in the absence of any evidence of a source at the level of the fusiform gyrus. Should that be confirmed, this would indicate that the intracranial N200 is not a source for the N230, as the former was located in the fusiform area. The left mid-temporal gyrus has been shown to be involved in some forms of phonological processing during visual word recognition (e.g., Price et al., 1994; Hagoort et al., 1999). According to Indefrey and Levelt (2000), the posterior segment of the superior and midtemporal gyri is the storage site of word phonological representations. The mid-temporal gyrus has also been associated with lexico-semantic processing (Pugh et al., 1996) and as a site for the "visual word form area" (Howard et al., 1992; Beauregard et al., 1997). The latter interpretation appears unlikely, however, indeed, recent studies indicate that the area of visual word form is situated at the level of the fusiform gyrus (Cohen et al., 2000) and is not affected by word frequency (Fiebach et al., 2002). But studies suggesting the involvement of the midtemporal gyrus in phonological and/or lexical processes are in agreement with a role of the N230 in the lexical pathway proposed by the DRC model. It can therefore be postulated that the N230 reflects lexical retrieval, probably of a phonological nature.

### *N320 and Grapheme-Phoneme Conversions*

One of the major aims of this study was to determine whether the N320 reflects the GPC route postulated by the DRC model or the OP pathway postulated by PDP models. In the first study, the N320 was triggered only by the string of consonants and by the pseudoword and not by the concrete word or the string of pseudo-letters. Thus, the appearance of the N320 was specific for some orthographic items.

As in the first study, the N320 was absent after massive presentation of concrete words in the lexical decision task. However, this wave was observable for twice-presented concrete words, the amplitude being larger for infrequent than for frequent words. Bentin et al. (1999) reported a N320 suggested to be involved in phonologic processes. The disappearance of this component under massive repetition can be interpreted in different ways. First, this wave may be the result of a more visual strategy based on visual word form as suggested for the N230. However, repetition may allow a direct lexical access, by-passing the phonologic transcription step (DRC) or a more direct orthographic to semantic processing as suggested by the N400 data (see later). This hypothesis is supported by the finding that reading difficulty (words of low frequency or an unusual association of letters) is associated with longer negativities until the end of either the N230 or the N320 in left but not right temporal sites (Figure 8). The presentation of word lists and/or the lexical nature of the task may require phonologic transcription, permitting expression of the N320. In the DRC model, the use of phonologic transcription would be more important for infrequent words (e.g., Coltheart & Rastle, 1994), and this result was found in the present investigation, as the N320 amplitude was greater for infrequent words. These results are also in agreement with PDP models, because the phonologic pathway should be more important for less frequent words.

Concerning possible generators of the N320, a source was identified at the level of the left midtemporal gyms (at the same location than the generator of the N230) often described in phonological processes (see earlier discussion). A grapheme-phoneme transcription consists in relating orthographic elements (the graphemes) with phonological elements (the phonemes). For this reason, it is reasonable to emit the hypothesis that at least two generators of grapheme-phoneme conversions must exist, the first for the activation of orthographic elements and the second for the phonemes.

The orthographic coding of stimuli presumably achieved at approximately 200 ms. Indeed, with intracranial electrodes, Nobre et al. (1994) reported an activation of the fusiform area only after presentation of letters at this latency. With scalp electrodes, Bentin et al. (1999) showed that the N170 was of a higher amplitude in the left hemisphere that the right for stimuli composed of letters, whereas pseudo-letters evoked the opposite effect. It can therefore be assumed that orthographic coding has already been completed before 320 ms. Although some studies suggest that the lingual gyrus has a role in orthographic processing (Chen et al., 2002), the generator for the N320 obtained at the level of the lingual gyrus for some items in this study may therefore not constitute the orthographic encoding of the item (extraction of letters from print). This activation would rather reflect the persistent trace of orthographic information, for the purpose of executing a phonological transcription. It is of special interest to note that this generator is absent for the list of frequent words that are assumed to solicit less the nonlexical or phonologic mediation pathway. Moreover according to Small et al. (1998), the activation of the lingual gyms (BA18) would be associated with the use of sublexical grapheme-phoneme conversion strategies during reading after training in a patient with phonologic acquired dyslexia. At least Mechelli et al. (2000) indicated that during reading, increases in word length elevated the activation of the lingual gyrus. According to Coltheart et al. (2001), word length would be the expression of serial processes. Now, in the DRC model, only GPCs are serially applied. Thus, the N320 may be the electrophysiological correlate of GPCs and the lingual gyms would be one of its generators, reflecting the activation and retrieval of the stimulus under its orthographic form.

In a similar manner to the lingual gyrus, the generator of the N320 at the level of the inferior parietal lobule (BA40) was not elicited during reading of frequent words. This region is associated with phonological encoding (e.g., Moore & Price, 1999; Peterson et al., 1999). According to Booth et al. (2002), the angular and supramarginal gyri represent heteromodal zones involved in the conversion of written words into phonology. The results on the generators of the N320 are concordant with the hypothesis that the inferior parietal lobule is involved in GPCs.

### *N400 and Word Meaning*

As in previous studies, the N400 appeared for isolated words and was larger at frontal regions in the left hemisphere (Bentin, 1987; Bentin et al., 1985; Boddy, 1986; McCarthy & Nobre, 1993). In a similar manner to the N320, the N400 was not apparent after massive presentation of concrete words, either due to the number of repetitions or to the nature of the task (Bentin, 1989; Bentin et al., 1985; Chwilla et al., 1995; Kutas & Hillyard, 1989; Rugg, 1985). But for massively repeated words, an early negativity at approximately 280 ms appeared predominant, consisting perhaps of a N400-type wave of earlier onset. One possible explanation is that the higher number of presentations facilitated access to lexical or semantic memory. In the Young and Rugg (1992) study, repetition did not affect the N400. However, in their experimental paradigm, words were repeated only four times, perhaps not sufficient to engage lexico-semantic processing. An important question to be addressed in the future is whether the N280 represents an N400 with earlier onset or whether the two components have distinct functional characteristics.

As reported by Harm and Seidenberg (in press), one of the central questions in reading studies is to understand the processes involved Q4 in extracting meaning from printed words. Is there a direct (orthographic-semantic) or else a phonologically mediated (orthographic-phonologic-semantic) pathway? These authors proposed an intermediate position, in which the accessed pathway is dependent on word frequency, regularity, and other properties. If the present authors hypothesize that the N320 represents phonologic and N400 semantic processing, it seems that under some circumstances (such as massive repetition), the phonologically mediated way (with appearance of the N320) can be suppressed.

## CONCLUDING REMARKS

The results of these experiments demonstrate that the appearance of three negative components (N170, N230, and N320) correspond to crucial stages in the processing of visual word recognition. The N320 may represent a more specific type of processing, sensitive to word frequency, appearing only for certain orthographic stimuli and disappearing under the condition of massive repetition. This component may reflect either a nonobligatory phonologic stage of grapheme-phoneme conversion postulated by the DRC model (Coltheart et al., 2001) or else the semantic phonologically mediated pathway (Harm & Seidenberg, in press). Q4

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