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Perceptual and lexical effects in letter identification: An event-related potential study of the word superiority effect

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ABSTRACT

Most classical models of visual word recognition are based on sequentially organized levels of representation and involve feedback mechanisms to various extents. In this study, we aim at clarifying which of the early processing stages of visual word recognition are modulated by top-down lexical effects. We studied the identification of letters embedded in briefly presented words (e.g., TABLE) and illegal nonwords (e.g., GTFRS) using event-related potentials (ERPs). Participants were involved in the Reicher–Wheeler paradigm: they were asked to indicate which of two letters displayed above and below a string of hashes was flashed immediately before at fixation within a letter string, which was either a word or a nonword. Event-related potentials were significantly modulated by the lexical status of stimuli around 200 ms after stimulus onset, i.e., in the peaking window of the N1 component. In light of our results, we propose that visual word form representations can constrain letter identification at a prelexical stage i.e., during the extraction of letter-shape information. In addition, we show that this facilitatory top-down effect is sensitive to stimulus exposure duration.

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1. Introduction

Since the 1980s, cognitive models have hypothesized the existence of sequentially organized stages in visual word recognition involving hierarchically organized levels of processing and feedback mechanisms. Although the involvement of processing stages of progressively higher complexity/abstraction (i.e., ‘bottom-up’ processing) has been studied extensively, the mechanisms by which higher levels impact upon lower levels (i.e., ‘top-down’ processes) remain largely underspecified. Here, using event-related potentials (ERPs), we address the time course of top-down effects of lexical

representations on letter identification in words and nonwords during reading.

The present study is based on the ‘Interactive Activation Model’ (IAM) of early processes in reading (McClelland and Rumelhart, 1981; Rumelhart and McClelland, 1982). The IAM model comprises three levels of information processing: (1) the feature level; (2) the letter level; and (3) the word level. ERP studies have shown that midline occipital electrophysiological events between 50 and 150 ms poststimulus are particularly sensitive to variations occurring at the first level (Cornelissen et al., 2003). It is in this time window that the analysis of the low-level visual features of printed words (main lines and

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curves making up letters) is thought to take place (Serenio and Rayner, 2003). The second level corresponds to a prelexical phase of word recognition in which alphabetic and nonalphabetic stimuli can be distinguished. It is thought to unfold between 150 and 200 ms after stimulus onset and involves bilateral occipito-temporal regions (Bentin et al., 1999; Cornelissen et al., 2003; Nobre et al., 1994; Pammer et al., 2004; Salmelin et al., 2000). The third level, a lexical phase in which words can successfully be distinguished from nonwords, seems to intervene between 200 and 250 ms after stimulus onset and involve left-sided temporal regions mainly (Cohen et al., 2000; Pammer et al., 2004; Proverbio et al., 2002; Salmelin et al., 1996; Tarkiainen et al., 1999). However, the timing of such phases is not widely acknowledged. Word frequency effects, for instance, which can only be observed in situations where lexical access has occurred, have been reported as early as 100–120 ms after stimulus onset, both during silent reading and lexical decisions (Serenio and Rayner, 2003; Serenio et al., 1998) while others have reported that the earliest effects of lexical frequency were detectable only 350–600 ms after stimulus onset in lexical decision tasks (Polich and Donchin, 1988). Moreover, the level of top-down modulation involved in reading, i.e., the strength of feedback mechanisms of higher levels onto lower levels during visual word recognition has received little attention so far.

Here we aim at identifying which of the processing stages put forward by models of visual word recognition are modulated by top-down lexical effects. It has been shown that a letter is better identified when it is presented within a word than in isolation (Reicher, 1969; Wheeler, 1970) or within a nonword (Grainger et al., 2003; Jacobs and Grainger, 1992; McClelland, 1976), because an orthographic stimulus that has an entry in the mental lexicon facilitates the identification of any of its constituent letters (McClelland and Rumelhart, 1981). This effect is known as the “word superiority effect” (WSE), first established as a basic characteristic of reading by Cattell (1886). The WSE has been taken as evidence for the existence of top-down modulation of the mental lexicon onto lower levels of visual word form recognition. It was shown to be independent of working memory load and guessing strategies (Reicher, 1969).

McClelland (1979) and McClelland and Rumelhart (1981) proposed two ways in which a letter-based model of visual word recognition could account for the WSE. One hypothesis involves a feedback mechanism from the word representation level onto the letter representation level (McClelland and Rumelhart, 1981). Another explanation is based on the cascaded nature of activation flow in interactive activation networks (McClelland, 1979). Cascaded activations provide the theoretical possibility that activation at higher levels of representation (words) can develop in parallel with activation of lower levels of representation (letters). Thus, letters can be either identified directly on the basis of activity at the letter representation level (letter read-out) or inferred on the basis of word identification (word read-out; see Grainger and Jacobs, 1994).

We used event-related potentials (ERPs) to compare the time-course of electrophysiological events taking place during letter identification within words and nonwords. We chose to use unpronounceable nonwords (consonant strings) rather than pseudowords in order to maximize the word superiority

effect measured with ERPs. Considering the explanatory framework of the WSE given by McClelland and colleagues, we hypothesized that top-down lexical effects would be measurable in the time range of prelexical processing (e.g., at the level of letter representation). Previous studies have suggested that prelexical ERP modulation is confined to the [150–200] ms time window, i.e., in the peaking range of the N170 (Bentin et al., 1999; Cornelissen et al., 2003). We therefore considered that a modulation of the N170 component by the lexical status of the stimuli would reflect the neural onset of top-down lexical effects. We also investigated how stimulus duration influences electrophysiological counterparts of letter identification in words and nonwords since this parameter appears to have significant effects on behavioral performance and brain activity (Price et al., 1994).

2. Results

2.1. Behavioral results

Behavioral results are depicted in Fig. 1. Error rates were lower for letter identification in words (mean = 14% ± 18) than nonwords (mean = 31% ± 13) as indicated by a significant main effect of lexicality on error rates ($F[1,9] = 15.46$, $P < 0.01$). Error rates were also lower for the 66 ms (mean = 21% ± 16) than the 50 ms stimulus exposure duration (mean = 24% ± 17) ($F[1,9] = 15.5$, $P < 0.01$). The two factors did not interact. Reaction times were significantly shorter in the word (mean = 647 ms ± 173) than in the nonword (mean = 735 ms ± 213) context as shown by a main effect of lexicality on reaction times ($F[1,9] = 8.5$, $P < 0.02$). The stimulus exposure duration factor did not affect reaction times significantly and there was no interaction.

2.2. Event-related potentials

Three main peaks (P1, P1', N1) were observed in the [0–300] ms time window over the parieto-occipital region bilaterally in all

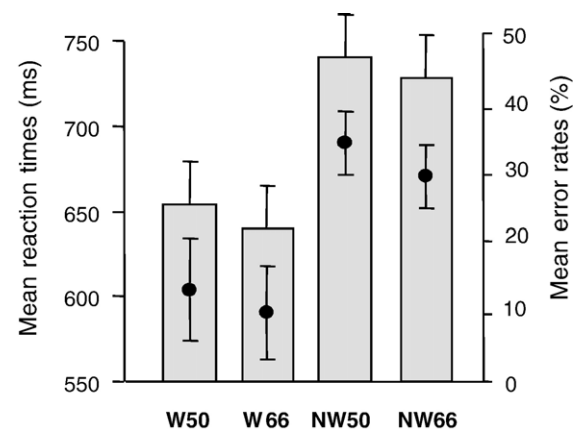


Fig. 1 – Behavioral results. W50 and W66 refer to words displayed or 50 ms and 66 ms, respectively. NW50 and NW66 refer to nonwords displayed for 50 and 66 ms, respectively. Bars display mean reaction times and circles indicate mean error rates. Error bars depict standard errors.

conditions (Fig. 2a for the 50 ms exposure duration condition and Fig. 2b for the 66 ms exposure duration condition).

The first positive component (P1) peaked at 99 ± 13 ms on average and was larger over the right parieto-occipital region than the left ($F[1,9] = 5.45$; $P < 0.05$). The mean latency and amplitude of this wave were not affected by stimulus exposure duration (latency: $F[1,9] = 0.03$; $P = 0.861$; amplitude: $F[1,9] = 4.12$; $P = 0.073$) nor lexicality (latency: $F[1,9] = 0.61$; $P = 0.455$; amplitude: $F[1,9] = 1.48$; $P = 0.254$).

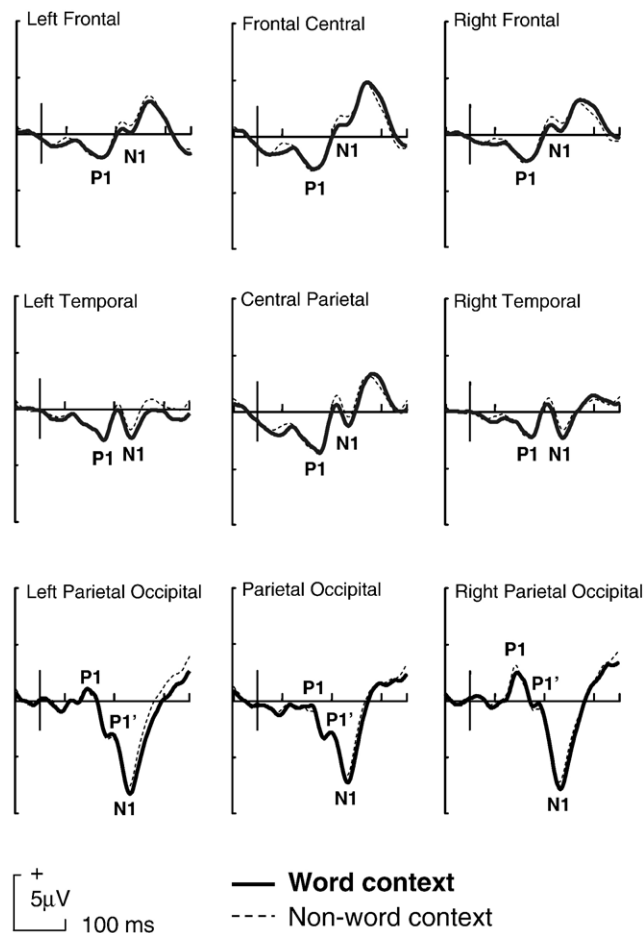
Another positive modulation (P1') peaked at 136 ± 6 ms on average in the 50 ms stimulus exposure condition and 144 ± 12 ms on average in the 66 ms stimulus exposure condition. The P1', thought to be elicited by the poststimulus mask, was unaffected by the lexicality factor. This event was not studied in detail as it was not induced by language-related stimuli.

A negative component (N1) was unaffected in latency by lexicality ($F[1,9] = 3.024$; $P = 0.116$) and peaked at 184 ± 15 ms on average in the 50 ms stimulus exposure condition and 210 ± 19 ms on average in the 66 ms stimulus exposure condition. The N1 was significantly delayed and reduced in

the 66 ms as compared to the 50 ms condition (Latency: $F[1,9] = 16.19$; $P < 0.01$; Amplitude: $F[1,9] = 13.78$; $P < 0.01$). Differences between the 50 and 66 ms exposure duration conditions, as indicated by ms-by-ms paired *t* tests, were significant from 156 to 190 ms and from 202 to 278 ms over the left parieto-occipital region, and from 148 to 190 ms and from 204 to 286 ms over the right parieto-occipital region.

The N1 wave was unaffected in mean amplitude by lexicality ($F[1,9] = 2.96$; $P = 0.119$) but there was a significant interaction between lexicality and duration ($F[1,9] = 7.36$; $P < 0.05$). Post hoc analyses revealed that in the 50 ms condition, the N1 peak was not affected in mean amplitude by lexicality ($P = 1.0$). In the 66 ms condition, however, there was a main effect of lexicality on the amplitude of the N1, which was significantly larger for words than nonwords ($P < 0.01$). Comparisons of word and nonword ERPs in the 66 ms stimulus exposure duration condition using paired *t* tests revealed significant differences from 200 to 306 ms at left PO electrodes, and from 202 to 244 ms at right PO electrodes (Fig. 3a for the topography of the main components and Fig. 3b for the ERP waves).

a. 50 ms exposure duration condition



b. 66 ms exposure duration condition

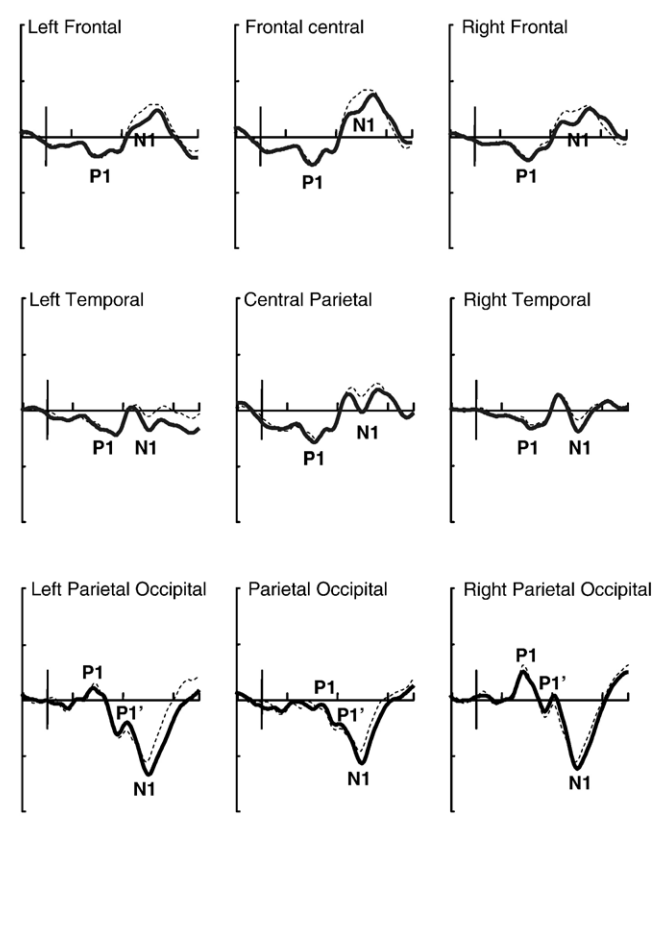


Fig. 2 – Event-related potential results for 9 scalp regions (left frontal; frontal central; right frontal; left temporal; central parietal; right temporal; left parietal occipital; parietal occipital; right parietal occipital). (a) 50 ms exposure duration condition. (b) 66 ms exposure duration condition. In both exposure duration conditions, three peaks were observed, very similar across lexical context conditions (P1; P1'; N1) in the [200–300] ms time window.

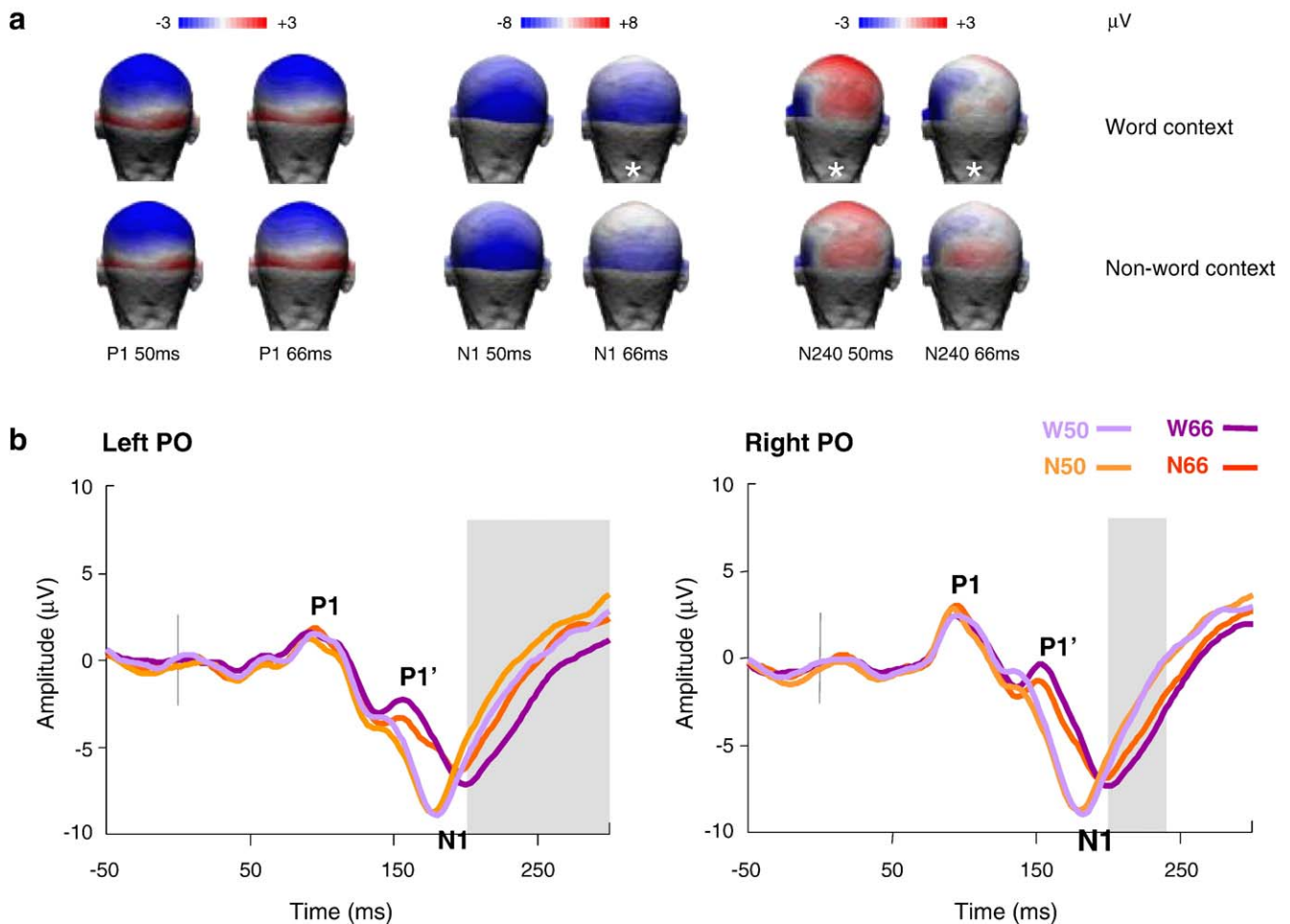


Fig. 3 – Event-related potential results. (a) Topography of the main components observed for each exposure duration in the word and nonword contexts. Stars indicate significant differences between word (upper row) and nonword (lower row) contexts in terms of mean amplitude. (b) ERPs measured over left and right parietal occipital (PO) regions (linear derivation of electrodes O1, PO3, PO7, P5 and O2, PO4, PO8, P6), for word and nonword contexts and each of the stimulus exposure durations. First differences between lexical contexts were found in the N1 amplitudes at 200 ms poststimulus onset. Grey bars indicate the interval of paired t significant differences between word and nonword contexts at left and right linear derivations.

Finally, in the [200–300] ms time window, ERPs elicited in the word and nonword contexts differed significantly in mean amplitude ($F[1,9] = 9.3$; $P < 0.01$), with a significant hemispheric effect ($F[1,9] = 5.14$; $P < 0.05$) and a significant interaction between lexicality and hemisphere ($F[1,9] = 21.58$; $P < 0.001$). A sustained negativity was found over left temporal parietal electrodes in the word context in both the 50 and 66 ms exposure duration conditions (see Fig. 3a). Comparisons of left and right temporal parietal electrodes in the word context using paired t tests revealed significant differences from 242 to 298 ms.

3. Discussion

We found that letter identification was significantly faster and more accurate in words than nonwords. Lexicality dependent ERP differences appeared as early as 200 ms.

The amplitude of the corresponding N1 wave was affected by lexicality over both hemispheres in the 66 ms stimulus exposure duration condition, but not when stimulus exposure was only 50 ms. In the [200–300] ms time window following the N1, a sustained lexicality effect was found for both stimulus exposure durations over the left temporal parietal electrodes.

The greater performance for letter identification in words as compared to nonwords replicates the Word Superiority Effect (Proverbio et al., 2004; Reicher, 1969). The rates of errors observed here (0.14 and 0.31 for letter detection in words and nonwords, respectively) are similar to those reported by McClelland, 1976 (mean error rates for letter detection in words = 0.15 and nonwords = 0.30) and Grainger (2003; mean error rates for letter detection in words = 0.14 and nonwords = 0.31) who used the same conditions as those used in the Reicher paradigm. The replication of these effects in the present experiment lends

support to the involvement of top-down mechanisms in our task.

3.1. Early electrophysiological events (P1)

The P1 component identified in this study was independent of stimulus lexicality and comparable to the P1 observed by others (Cornelissen et al., 2003; Rossion et al., 2003; Sereno and Rayner, 2003). The absence of any effects of lexicality at the P1 stage is congruent with the fact that discrimination between words and nonwords (Simon et al., 2004) or linguistic and nonlinguistic material (Rossion et al., 2003) does not affect ERPs before 150 ms poststimulus onset. Furthermore, we observed that P1 was not different between the two stimulus exposure conditions, which suggests independence of P1 from stimulus duration at least in the case of stimulus durations of 50 and 66 ms.

3.2. N1 and top-down lexical effects

As mentioned in the Introduction, the better performance for letter identification in words relative to nonwords can be explained by the intervention of top-down processes in the sense that lexical information increases the level of activation of all letter representations associated with it. ERP differences between word and nonword contexts indicate that word representations in the mental lexicon influence performance approximately 200 ms after stimulus onset since the primary significant differences were found in the N1 range over occipital regions of the scalp, bilaterally. We speculate that the N1 peak latency might have been slightly delayed due to the presence of the mask associated with a P1' event (see Fig. 3b). The N1 event found here is comparable to the N170 component (Bentin et al., 1999; Rossion et al., 2003); see also the M170 observed in MEG (Stockall et al., 2004; Tarkiainen et al., 1999). If the N170 indexes prelexical processing specific to letter-strings as suggested by some authors (Bentin et al., 1999; Cornelissen et al., 2003), our results support the hypothesis that lexical representations can influence the recognition of letters prelexically. Sauseng et al. (2004) identified effects of visual-orthographic word representations on letter string processing as early as 160 ms after stimulus onset, which is also compatible with the earliest differences identified using ms-by-ms *t* tests in our study (~156 ms). The 40 ms difference between the two studies could be explained by the use of masking with short stimulus exposure in our experiment, which may have delayed the onset of processing differences between words and nonwords.

Our assumption that the activation of visual-orthographic word memories facilitate letter string processing via top-down mechanisms between 160 and 200 ms after stimulus onset is supported by ERP findings from Sauseng et al. (2004), but also Hauk and Pulvermüller (2004), Assadollahi and Pulvermüller (2001) and Sereno et al. (1998) who found an effect of word frequency between 120 and 190 ms. Some authors, however, found the earliest lexical effects only 350 ms after stimulus onset (Braun et al., 2006; Holcomb et al., 2002). The relative timing inconsistency between studies can be due to various methodological parameters, such as word length, word class, repetition rate, word frequency, display duration, mask type

and duration, task type, etc. (Binder et al., 2003; Hauk and Pulvermüller, 2004). Stimulus variability, in particular, is likely to greatly attenuate early short-lived focal activity while leaving late, long-lasting spread-out potentials relatively intact (Pulvermüller, 1999). Variations in task requirements can also alter the temporal onset of differences, as shown by Holcomb et al. (2002): neighborhood size has a significant influence in the [150–350] ms time window during a semantic categorization task, whereas no such effect is seen before 350 ms in a lexical decision task. Finally, neighborhood density and lexical frequency of orthographic neighbors also affect the speed and accuracy with which a given word form is accessed or nonword item dismissed (Grainger and Jacobs, 1996).

In prominent models of visual word recognition, words and nonwords can be differentiated on the basis of a high-threshold lexical identification mechanism or global lexical activity generated by the stimulus (Coltheart et al., 2001; Grainger and Jacobs, 1996). ERP evidence for the latter global lexical activity effect has been obtained by Braun et al. (2006) and Holcomb et al. (2002). Whether this effect reflects a re-processing mechanism or is fully part of the lexical evaluation stream is still a matter of debate (see for instance, Hauk et al., 2006, for considerations on timing).

3.3. Left temporal parietal negativity and lexical processing

The left temporal parietal negativity found in the [200–300] ms time window in the word context was affected by lexicality. This could correspond to a lexical phase in which words and nonwords are distinguished. Such left–right differences have been found by other authors comparing letter strings making up words or nonwords (Cohen et al., 2000; Pammer et al., 2004). Cohen et al. (2000) in particular attributed these differences to the preferential involvement of the left mid-fusiform gyrus in the recognition of visual word form (Cohen et al., 2003; McCandliss et al., 2003).

3.4. Exposure duration effects

The P1 was unaffected by stimulus exposure duration but the N1 was significantly delayed by approximately 26 ms when exposure duration increased from 50 to 66 ms. Moreover, the N1 was modulated in amplitude by the lexical context in the 66 ms condition only. A tentative explanation for this observation derives from the Grainger and Jacobs model (Grainger and Jacobs, 1994). In this model, top-down lexical effects can influence letter identification at the letter-level or at the word-level. We hypothesize that only the latter level was involved when stimulus exposure duration was 50 ms whereas longer exposure duration allowed feedback to act at the letter level. In the 66 ms stimulus duration condition, top-down effects would intervene down to the level of letter processing, inducing bilateral ERP differences in the N1 peak. In the 50 ms condition, stimulus exposure would be too short to allow significant feedback effects on processing at the letter level. Differences between word and nonword processing would therefore be based on the word level only, inducing differences between lexical contexts only in the

[200–300] ms time window over the left temporal parietal region. This would also account for the difference in accuracy between the two exposure conditions (0.76 for the 50 ms exposure duration condition and 0.79 for the 66 ms condition).

4. Conclusion

The present study was based on the ‘Interactive Activation Model’ (McClelland and Rumelhart, 1981; Rumelhart and McClelland, 1982). Our results are compatible with a first level of information processing (low-level feature analysis) reflected in the P1 event peaking approximately 100 ms after stimulus onset. We hypothesize that the second level, related to prelexical treatment, is reflected by a bilateral parietal occipital N1 event indexing the extraction of letter-shape information. Then, the lexical stage would correspond to the left-sided temporal parietal negativity observed in the [200–300] ms time window. In light of our results, we propose that visual word form representations can constrain letter identification at a prelexical stage—i.e., during the extraction of letter-shape information, within the first 200 ms poststimulus. This facilitatory top-down effect appears to require a minimum exposure duration in order to become evident in the ERPs.

5. Experimental procedures

5.1. Participants

Ten fluent readers of French (5 females and 5 males; mean age 24.8 ± 1.6 years, all right-handed) gave their informed consent to participate in the experiment that was approved by a local ethic committee. All subjects had normal or corrected-to-normal vision.

5.2. Stimuli

Stimuli were 40 French nouns of high lexical frequency (mean \log_{10} (frequency) = 4.35, range 3.14–5.08; e.g., ‘LIGNE’-LINE) selected from the Brulex database (Content and Radeau, 1990) and 40 unpronounceable consonant strings (e.g., ‘PGSRF’). Both words and nonwords were 5 letters long. Word selection was constrained as proposed in the original WSE paradigm (Reicher, 1969): the nouns were selected on the basis of existing orthographic neighbors of matched lexical frequency differing only by one letter (e.g., ‘VIGNE’-VINE and ‘LIGNE’-LINE). Five matched lists of 8 nouns were generated that corresponded to each letter position shared by the orthographic neighbors. Consonant strings were orthographically illegal and had very low digraph frequencies (mean \log_{10} (frequency) = 1).

5.3. Task and procedure

At the beginning of each trial, a fixation cross was displayed at the center of a computer screen for 2.5 s. The fixation then disappeared for 50 ms before a second fixation appeared for

200 ms. After a second pause of 50 ms, a stimulus (word or nonword) was displayed for either 50 or 66 ms in “Times New Roman” lower case, font size 28. Stimuli were centered on a different letter (the target letter) each time: this was achieved by varying the stimulus position laterally on the screen (Fig. 4a). Stimuli subtended 6.65° of visual angle, at a distance of 60 cm. After 50 or 66 ms, the stimulus was replaced by a string made of 7 upper case Xs masking the entire stimulus string (mask) and two probe letters, one above and one below the mask. Subjects had to indicate which of the two probe letters was the target letter previously presented at fixation, by pressing the top or bottom button of a response-pad. The mask and the two probe letters remained on the screen until the response (Fig. 4b). To increase statistical power, each of the 40 words and nonwords was presented 6 times in the 50 ms condition and 6 times in the 66 ms condition. Overall, the 960 trials were pseudo-randomly distributed in 12 blocks of 80, with each item displayed only once per block, to avoid habituation effects. Exposure durations (50 and 66 ms) and stimulus categories (words and nonwords) were randomized within each block. Blocks order and response side were fully counterbalanced across participants.

5.4. ERP acquisition and processing

Participants were comfortably seated in a quiet room and asked to refrain from moving and blinking. Electrophysiological data were recorded from 64 Ag/AgCl electrodes (placed according to the extended International 10–20-system) at a sampling rate of 500 Hz, using SynAmps™ amplifiers (Neuroscan™, El Paso, TX, USA). The electrooculogram was recorded using supraorbital and infraorbital electrodes connected to a bipolar channel. Signals were filtered on-line between 0.1 and 100 Hz. Impedances were kept below 20 k Ω . Continuous recordings were digitally band-pass filtered off-line in the interval [1–40] Hz. Eye-blink artifacts were mathematically corrected and remaining artifacts manually dismissed. Epochs ranged from –100 to 1700 ms after the onset of the five letter string (word or nonword). Signal variations exceeding $\pm 75 \mu V$ anywhere in the analysis window and on any of the channels except the vertical electrooculogram (veog) were automatically

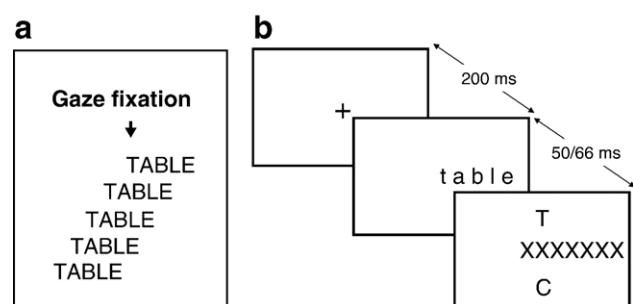


Fig. 4 – (a) Locations of the stimulus on the screen vis-à-vis fixation. The stimulus was centered on the first, second, third, fourth or fifth letter relative to the fixation cross. (b) Experimental design of the forced two-choice task.

dismissed. After baseline correction relative to prestimulus activity and rejection of errors, there were at least 48 epochs per condition in all participants. Individual difference waveforms and grand-average waveforms were then derived from individual ERPs.

5.5. Statistical analysis

Behavioral data (error rates and reaction times) were compared using a repeated measures analysis of variance (ANOVA), in order to estimate main effects (lexicity and stimulus exposure duration) and possible interactions between these factors. Potential violation of sphericity was addressed using a *Greenhouse-Geisser* adjustment.

Peak search was confined to specific intervals on the basis of the main components identified on the Mean Global Field Power of all 64 electrodes (Picton et al., 2000). Search intervals were 70 to 130 ms for the P1, 150 to 240 ms for the N1. Peak mean amplitudes and latencies at the electrodes of maximal sensitivity (i.e., where peak amplitude is maximal) were analyzed for each component using a repeated measures ANOVA. ANOVA factors were lexicity (word vs. nonword), stimulus exposure duration (50 vs. 66 ms) and hemisphere (left vs. right). The 'Hemispheric' effect was introduced in the ANOVA to define the laterality of the main factors. In addition, the onset of differences between conditions was estimated using ms-by-ms paired *t* tests for the contrasts of interest (e.g., Word vs. Nonword in each hemisphere). Unstable differences (remaining below $P = 0.05$ for less than 30 ms) were discarded (Rugg et al., 1993).

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