

Automatic word form processing in masked priming: An ERP study

GIORDANA GROSSI AND DONNA COCH

Department of Psychology, University of Oregon, Eugene, Oregon, USA

Abstract

Five prime types (unrelated words, pronounceable nonwords, illegal strings of letters, false fonts, or neutral strings of Xs) preceded word and nonword targets in a masked priming study designed to investigate word form processing as indexed by event-related potentials (ERPs). Participants performed a lexical decision task on targets. In the 150–250-ms epoch at fronto-central, central, and temporo-parietal sites ERPs were smallest to targets preceded by words and nonwords, followed by letter strings, false fonts, and finally neutral primes. This refractory pattern sensitive to orthography supports the view that ERPs in the 150–250-ms epoch index activation of neural systems involved in word form processing and suggests that such activation may be graded, being maximal with word-like stimuli and relatively reduced with alphabet-like stimuli. Further, these results from a masked priming paradigm confirm the automatic nature of word form processing.

Descriptors: Event-related potentials, Word form, Orthography, N200, Masked priming, Refractory effects

Despite the feeling of effortlessness that fluent, expert readers experience while reading, the process of reading is extremely complex and requires multiple levels of analysis and representation (for a review, see Rayner & Pollatsek, 1989). A printed word can be analyzed at a basic visual featural level; as an orthographic unit; as a sequence of sounds; as a string with morphological, grammatical, and syntactic specification; and as a group of letters with meaning. Moreover, there are interconnections among these representational systems. Even in this vastly oversimplified and incomplete summary, the complexity of the various systems involved in reading a single word begins to be revealed. Indeed, much of the functioning of the reading system is currently under active scientific investigation. Numerous studies using event-related potentials (ERPs) have explored semantic (e.g., Holcomb & Neville, 1990; Kutas & Hillyard, 1980) and syntactic (e.g., Osterhout & Holcomb, 1992) word processing and have reported specific ERP components sensitive to these types of processing. Fewer ERP studies have investigated word processing at the orthographic level (e.g., Compton, Grossbacher, Posner, & Tucker, 1991) and none, to our knowledge, have simultaneously probed the automaticity and specificity of orthographic processing.

In alphabetic languages such as English, written words are composed of letters arranged according to specific combinatorial rules. These rules, which vary across languages, specify the orthography of a language. Orthography—the arrangement of letters into word-like forms—plays an important role in word recognition and reading. Indeed, in beginning reading, the primary task of the novice reader is to learn to connect the sounds of spoken language (phonology) to the strings of letter symbols printed on the page (orthography; Adams, 1990). In fluent reading, some “exception” words (e.g., *yacht*) may only be recognized through orthographic processing, as phonological analysis fails.

Experimental studies manipulating orthographic information and requiring participants to make lexical decisions have shown that legal nonwords (sometimes termed pseudowords), nonsense strings of letters that follow the orthographic rules of a given language but have no semantic content (e.g., *lape* in English), are rejected more slowly than illegal nonwords (sometimes termed letter strings, e.g., *glwk* in English; e.g., Forster, Mohan, & Hector, 2003). Moreover, studies have demonstrated a “word superiority effect” in which single letters are recognized more efficiently when embedded in a legal sequence of letters as compared to random combinations of letters (e.g., Reicher, 1969). This pattern of results has suggested a special status for word-like orthographic forms and prompted hypotheses about the existence of an abstract mental representation of words, termed the “visual word form” (Warrington & Shallice, 1980). According to the visual word form hypothesis, letter strings at some level of processing are specified according to their orthographic properties, regardless of whether the string is a real word.

In most visual word recognition models (for a review, see Jacobs & Grainger, 1994), the stage of word form analysis is

Giordana Grossi is now at the State University of New York at New Paltz. Donna Coch is now at Dartmouth College, Hanover, New Hampshire. Grossi was supported by an NIH/NIDCD grant to Helen Neville (DC00128) and Coch was supported by an NIH/NICHHD postdoctoral grant (HD08598).

Address reprint requests to: Giordana Grossi, Department of Psychology, State University of New York at New Paltz, New Paltz, NY 12561. E-mail: grossig@newpaltz.edu.

preceded by two earlier levels of processing. At the first level, strings of letters are analyzed in terms of visual features, such as straight and curved segments; at the second, single letters are recognized in terms of their identity, regardless of physical variability in font, case, or size. Only after the features, identities, and relative positions have been computed are the letters combined to form words. Correspondences between representations in long-term memory (i.e., lexicon) and the whole form of the word facilitate retrieval of further information about word meaning (semantics), morphological and grammatical specifications, and sound (phonology). Theoretically, it is at the level of whole word forms that orthographic regularities are implemented and that phenomena such as the word superiority effect and faster rejection of illegal than legal nonwords take place.

Despite substantial differences among models (e.g., in terms of interactionist or connectionist architecture, or in terms of the specific implementation of letter position and combination of letters; for reviews, see Jacobs & Grainger, 1994; Perea & Lupker, 2003; and Grainger & Dijkstra, 1996, respectively), experimental evidence from both normal and brain-lesioned (i.e., dyslexic and alexic) individuals supports the existence of these three levels of representation. A deficit in visual feature analysis (e.g., *apperceptive agnosia*) disrupts both letter and word identification (e.g., Grossman, Galetta, & D'Esposito, 1997). At the level of identity, Miozzo and Caramazza (1998) reported an alexic patient who could not determine whether a pair of letters had the same name despite intact visual ability to recognize the shape and orientation of letters. And in word form dyslexia, or letter-by-letter reading, patients can identify single letters, but cannot access the whole form of words (e.g., Patterson & Kay, 1982). In the present study we focused on the computational specificity of the whole word form representation in fluent readers.

Investigations of the visual word form hypothesis at the neural level have suggested that a specific region within the left fusiform gyrus, predictably referred to as the "visual word form area," is particularly tuned to the detection of orthographic regularities (Petersen, Fox, Posner, Mintun, & Raichle, 1989). In classic PET studies, the visual word form area has been shown to be more active in response to visually presented words and nonwords than to random consonant strings or strings of nonalphabetic characters (e.g., Petersen, Fox, Snyder, & Raichle, 1990). Activation of this area has also been found to be invariant to the color, font, font size, and case in which letters are presented (for recent reviews, see Cohen et al., 2002; McCandliss, Cohen, & Dehaene, 2003). This pattern of findings is consistent with the results of behavioral studies with expert readers that have suggested that the visual system becomes efficient in recognizing words even in the presence of physical variability. For example, the presentation of mixed case stimuli does not dramatically disrupt word identification (Coltheart & Freeman, 1974; Smith, Lott, & Cronnell, 1969). In addition, in repetition priming experiments in which primes and targets are presented in different cases, repetition effects are similar for words that are visually similar and dissimilar in upper- and lowercase formats (e.g., "kiss" and "read," respectively; Bowers, Vigliocco, & Haan, 1998). Overall, this pattern of results indicates that the neural word recognition system is able to extract invariant characteristics of written stimuli, such as letter identity; moreover, as word superiority effects show, this system is tuned to the combinatorial rules that characterize the reader's language.

Studies employing more temporally accurate methods have shown that processing in this area is sensitive to the orthographic

properties of stimuli within 250 ms of stimulus presentation (e.g., Nobre, Allison, & McCarthy, 1994). Recording intracranially from the inferior temporal lobe Nobre et al. reported a negative component peaking around 200 ms (N200) elicited by both words and nonwords in the posterior fusiform gyrus. Further, they reported that both pronounceable and unpronounceable nonwords elicited an N200 in this "prelexical" area reportedly postero-lateral to the visual word form region identified in PET studies. Overall, the N200 component was not influenced by the semantic context in which stimuli were presented, consistent with the contention that the N200 reflects prelexical processing. More recently, an N200 larger to strings of letters than to other types of stimuli (e.g., faces, objects) has been recorded at fusiform and other inferior, posterior sites (Allison, Puce, Spencer, & McCarthy, 1999).

Several ERP studies have also reported effects of orthography reflected in an N200 component recorded at the posterior scalp. Over a decade ago, Compton et al. (1991) described an early negativity (~ 200 ms) that was larger to consonant strings than to words across passive reading, feature detection, and letter detection tasks; interestingly, the effect was reversed in a lexical decision task. In a study investigating learning of a created miniature language with some orthographic features of English and some non-English-like orthographic patterns, a posterior component labeled N1 (peak at 170–230 ms) was more negative to consonant strings than to English words, whereas words and nonwords in the miniature language elicited a larger N1 than English words but a smaller N1 than consonant strings (McCandliss, Posner, & Givon, 1997). In a study comparing English orthography with symbols and forms, Bentin, Mouchetant-Rostaing, Girard, Echallier, and Pernier (1999) described a temporo-occipital negativity (N170) larger to orthographic (words, pronounceable nonwords, and consonant strings) than nonorthographic (symbols and forms) stimuli in a task requiring size judgments. Finally, in a divided visual field study both word and consonant string stimuli elicited a marked posterior negativity peaking at around 200 ms, irrespective of the field of presentation; regarded by the authors as the electrical signature of the visual word form area, this N200 was larger for words than consonant strings over left temporal and occipital sites (Cohen, et al., 2000).

Overall, the results of these neuroimaging studies suggest that the visual word form area processes abstract linguistic information (i.e., orthography) rather than lower level, featural visual characteristics of letter strings. Moreover, these results indicate that word form systems are activated not only by orthographically legal stimuli, such as words and pronounceable nonwords, but also by illegal strings of letters. Intracranial recording studies suggest that some neurons in the middle fusiform gyrus respond preferentially to alphabetic material (Allison et al., 1999), but activation patterns in PET and fMRI studies tend to show a linear increase with increasing word-likeness of the stimuli, with varying degrees of activation elicited by nonwords, letter strings, and false fonts (e.g., Petersen et al., 1990; Price, Wise, & Frackowiak, 1996; Rees, Russell, Frith, & Driver, 1999; Tagamets, Novick, Chalmers, & Friedman, 2000). That the purported visual word form area can be activated during tasks that do not require visual word form processing has led to some debate regarding the specificity of processing within this area and to the hypothesis that a set of regions may be involved in processing visual word form representations (e.g., Price & Devlin, 2003, p. 473; Price, Winterburn, Giraud, Moore, & Noppeney, 2003;

for further discussion, see Cohen & Dehaene, 2004; Price & Devlin, 2004).

The ERP findings are particularly interesting in regard to the specificity of processing within the visual word form area. Although there is clear evidence that ERPs recorded at posterior sites within the 150–250-ms time window (typically in the form of the N200) are modulated by orthographic information, the inconsistencies in the direction of the effect for consonant letter strings and words both within and across studies remains to be explained. In some reports, N200 is larger to consonant strings than to English words (Compton et al., 1991; McCandliss et al., 1997) whereas, in other reports, the opposite holds true (Cohen et al., 2000) or no differences are found between legal and illegal orthographic strings of letters (Bentin et al., 1999). Given the equivocal nature of these findings, the specificity of processing within word form systems has not adequately been addressed by these ERP studies.

There are a number of possible reasons for these inconsistent ERP findings. First, there is some evidence that this differential effect is sensitive to task demands and is in fact dependent on the type of processing required by the task (Compton et al., 1991; Ziegler, Besson, Jacobs, & Nazir, 1997). However, other evidence suggests no effect of task (across no task, visual, and semantic; McCandliss et al., 1997), and, indeed, no clear patterns concerning the influence of task demands seem to emerge across studies. For example, the N200 was larger for letter strings than words in a visual (feature search) task in Compton et al. (1991) whereas no differences were found in a visual (size judgment) task in Bentin et al. (1999). Second, differences in attention might play a role in the differential findings across studies. For example, participants in Compton et al.'s feature search task had to detect the presence of a thickened segment in the letters composing the targets, whereas participants in Bentin et al.'s size judgment task had to detect the presence of large-sized stimuli among standardized stimuli. Clearly, these two tasks differ in terms of the possible strategies adopted by participants: A wider focus of attention can be successfully adopted in the latter case, whereas the former requires attention to be focused on single letters and letter elements (cf. McCandliss et al., 1997). Third, a number of methodological differences make these studies difficult to compare. For example, stimuli in the Bentin et al. study included symbols and forms, whereas only alphabetic stimuli were presented in the Compton et al. and McCandliss et al. studies. These compositional differences may also have played a role in the direction of the N200 effect.

Across ERP studies, results suggest that the N200 may index processing within word form systems; however, the nature of that processing remains unclear. To further investigate the representational specificity of visual word form processing as indexed by the N200, we designed a masked priming experiment that would minimize the confounding influences of attentional or task demands on the N200. Pattern masking appears to have little effect on automatic visual processing itself, but rather is thought to affect the availability of the results of perceptual processing to consciousness (Marcel, 1983). Recent reports have indicated that the visual word form area is activated by orthographic stimuli even when those stimuli are presented subliminally and are not available for verbal report (Dehaene et al., 2001), suggesting that orthographic processing can be triggered, perhaps through a processes of automatic spreading activation (Posner & Snyder, 1975), even when participants are not aware of the presentation of a stimulus (Dehaene et al., 2004). By employing a masked

priming paradigm, we could address the issues of automaticity and specificity in word form processing while controlling for attentional and task demands.

In experiments using rapid serial visual presentation of stimuli (such as those employing priming paradigms), the response of a recently activated neural system has been shown to be reduced in comparison to the response of that same system reactivated after an extended period of time, a phenomenon indexing the refractoriness of the system and the recovery cycle of visual neurons. That is, refractory effects are hypothesized to reflect the excitability of the population of responding cortical neurons in terms of processing rates within cortical sensory areas (Gastaut, Gastaut, Roger, Carriol, & Naquet, 1951), and thus the adaptation of neural systems activated by particular stimuli. Refractoriness of visual neural systems has been described in both electrophysiological (e.g., Allison, 1962; Cigánek, 1964; Skrandies & Raile, 1989) and neuroimaging (e.g., Blamire et al., 1992; Dale & Buckner, 1997; Huettel & McCarthy, 2000, 2001) studies. Our experiment was designed to investigate the adaptation of specific neural systems involved in word form analysis, as indexed by ERPs in the 150–250-ms time window (N200)¹ evoked by targets preceded by types of primes designed to elicit various degrees of orthographic processing.

In the present masked priming experiment, targets (both words and nonwords) were preceded by primes presented briefly (67 ms) and masked to prevent their identification. To more effectively investigate the nature of the N200 word form effect, we manipulated the word-likeness of the unrelated primes by using five types of primes: words, nonwords, illegal strings of letters, false fonts, and neutral (strings of Xs, matched by length with the other primes). These different types of primes varied in word-likeness in terms of local and global features. Words and nonwords conformed to both local (letters) and global (letter combinations and word form) characteristics of English; letter strings conformed to local but not global characteristics; false fonts, created by reassembling letter elements of word and nonword primes, and therefore matching linguistic primes in terms of luminance and spatial frequency, maintained only some of the local features of words, such as high spatial frequency information; finally, neutral primes did not conform to either local or global features of word-likeness, and were chosen to minimally activate the word form system.

Assuming that ERP effects in the N200 time window reflect automatic word form processing, we hypothesized that we would observe differences in the N200s to targets preceded by the different types of primes based on the word-likeness of the primes: The more word-like the prime, the more refractory (i.e., smaller) the N200 to targets. Specifically, we made the following predictions:

- Prediction 1: Because legal nonwords are characterized by English orthography and because previous research has shown that N200 indexes word form analysis at a prelexical level (e.g., Nobre et al., 1994), the same pattern of results was predicted for word and nonword targets across types of primes.

¹Note that here, the N200 is considered an index of the activity of the neural systems involved in visual word form analysis, regardless of whether these systems are identified with a single area or with a pattern of interaction across multiple areas.

- Prediction 2: Because strings of letters do not conform to English orthography, we predicted that the N200 would be less refractory, and therefore more negative, to targets preceded by strings of letters than to targets preceded by word and nonword primes. That is, the greater word-likeness of the word and nonword primes was expected to result in a more refractory (i.e., smaller amplitude) N200 to targets than the N200 to targets preceded by letter string primes. This effect would reflect word form processing in a strict sense, because letter strings were formed by letters but arranged in a fashion that violated English orthography.
- Prediction 3: Because the nonlinguistic false font primes would not elicit extensive word form processing, we predicted that the N200 would be less refractory, and therefore more negative, to targets preceded by false font primes than to targets preceded by letter string primes. This prediction was made assuming the existence of a specific level of representation for letter identity within the word form system(s). Alternatively, if the N200 reflects pure word form processing (only at the level of the word and not the letter), no differences in amplitude would be observed to targets preceded by letter string and false font primes (as neither have regular orthography but both are alphabetic-letter-like).
- Prediction 4: Because the string of Xs as a prime was expected to minimally activate neural systems involved in word form analysis, we predicted that the N200 would be less refractory, and therefore more negative, to targets preceded by neutral primes (which do not resemble words) compared to all other primes.

Although the priming effects on the N200 to targets were the primary focus of the present experiment, we also investigated effects on the N100 for comparison and to capture earlier levels of processing such as the ones involved in visual feature analysis. Results of a number of studies have shown that posterior effects within the earlier N100 time window (90–150 ms) are sensitive to the physical characteristics of visual stimuli. For example, Allison et al. (1999) found that the N100 was not modulated by stimulus category but was sensitive to the luminance, contrast, and size of the stimuli. Similar results have been reported in MEG studies (e.g., Tarkiainen, Helenius, Hansen, Cornelissen, & Salmelin, 1999; Wydell, Vuorinen, Helenius, & Salmelin, 2003). For example, Tarkiainen et al. reported that a posterior response in the N100 time window originated in the extrastriate areas bordering V1 and was modulated by stimulus (letter strings and symbols) length.

We hypothesized that if ERPs within the N100 time window reflected physical differences between stimuli (in this specific case, the primes), we would observe less refractory and more negative ERPs to targets preceded by neutral primes than by any other type of prime, because neutral primes would activate different neural systems from all other primes. Neutral primes did not resemble alphabetic-like material, being composed of a repetitive and consistent pattern of only straight lines; they were also presented in uppercase and were therefore larger than the other types of primes, which were presented in lowercase. Moreover, we predicted no differences in N100 amplitude to targets preceded by all other types of primes, which were matched on physical characteristics (i.e., spatial frequency and luminance). Critically, different patterns of effects for the N100 and N200 would support the view that these two components reflect different stages of visual processing during reading and would

strengthen the view that any observed N200 effects would specifically reflect (by pattern, timing, and distribution) word form processing.

Methods

Participants

Twenty undergraduate students at the University of Oregon participated (12 women, mean age 21.4 years, range 18–29). All participants were right-handed (Edinburgh Handedness Inventory; Oldfield, 1971), native English speakers with normal or corrected-to-normal vision and were volunteers paid for their participation.

Stimuli

Two hundred words and 200 nonwords served as target stimuli. Target words had a mean frequency of 73.81 (*SD* 127.68) and a mean length of 4.38 (*SD* 0.89). Nonword targets were created by changing one or two letters of real words (some included in the experiment, some not) and had a mean length of 4.39 (*SD* 0.89).

Five types of primes were associated with each target (see Figure 1): words, nonwords, strings of letters, false fonts, and neutral (strings of Xs). Word primes had a mean frequency of 73.61 (*SD* 127.31) and a mean length of 4.38 (*SD* 0.89). Nonword primes were created by changing one or two letters of real words (some included in the experiment, some not) and had a mean length of 4.38 (*SD* 0.89). Letter-string primes were created by reordering the letters from word and nonword primes so as to violate English orthographic rules (e.g., fsta, lslo, ssma). False font primes were created by reassembling components of real letters with a graphics program (Adobe Photoshop) to keep physical variables, such as spatial frequency and luminance, constant. Each letter and false font was presented as a single file on the screen (i.e., the word “sun” was composed of three different files presented simultaneously). Neither the height (34 pixels in Photoshop for all letters and false fonts) nor the width (letters: range 9–25, mean 15.42, *SD* 3.64; false fonts: range 9–26, mean 15.96, *SD* 4.04) of the letter and false font files differed significantly (width: $p = .62$, two-tailed). Neutral primes were matched to targets by length.

	Mask	# # #	# # #
Primes	Neutrals	X X X	X X X
	False fonts	Ɲ 4 μ	ǧ ƚ ƚ
	Letter strings	n s u	r g a
	Nonwords	g e k	g a r
	Words	s u n	s k i
	Targets	c a t	k u n
		Word targets	Nonword targets

Figure 1. Examples of prime and target stimuli used in the present experiment.

Five lists were created from the master list. Each list was comprised of 40 pairs of each prime–target type (40 each of word–word pairs, word–nonword pairs, nonword–word pairs, nonword–nonword pairs, letter–word pairs, letter–nonword pairs, false font–word pairs, false font–nonword pairs, neutral–word pairs, neutral–nonword pairs) for a total of 400 stimulus pairs. Targets and primes in each list were matched on frequency (words) and length (words and nonwords). The five lists were counterbalanced across participants so that each subject saw a particular stimulus only once, allowing for comparison of the same target preceded by different types of primes across participants. For example, the target DOG was preceded by another word (sun) in list 1, a nonword (nus) in list 2, a string of letters (nsu) in list 3, false fonts [s l p] in list 4, or a neutral prime (XXX) in list 5. Thus, it was possible to protect against any uncontrolled target-related factors and to compare the same targets preceded by different types of primes across subjects. Order of presentation of stimuli within each list was randomly varied across participants.

Procedure

All participants were tested in a sound-attenuating and electrically shielded booth. Participants were seated 150 cm directly in front of a 23-in. monitor on which stimuli were presented, such that each stimulus subtended 0.5–3.5° of horizontal visual angle and 1° of vertical visual angle. The sequence of events (see Figure 2) was the following: A white rectangle appeared at the center of the screen and served as a warning signal that the new trial was about to begin; 1000 ms after the presentation of the rectangle, a mask created from seven consecutive pound symbols (#####) was presented for 500 ms, replaced by the prime (67 ms), and then by the target (500 ms). The white rectangle disappeared 1.5 s after the target disappeared. Participants were instructed not to blink when the white rectangle was present on the screen.

The session was self-paced; that is, participants controlled when the next trial would begin by pressing a button on a response box in their laps. Participants were further instructed to press one button (labeled “word”) if the target was a real word and another button (labeled “nonword”) if the target was not a real word, and to respond as rapidly as possible without jeopardizing the accuracy of their responses. Response hand for word and nonword responses was counterbalanced across participants. Thirty-two practice trials preceded the actual test session. None of the targets in the practice list were included in the experimental list. Neither during the practice nor during the experiment was the presence of the prime mentioned.

After completion of the experiment a debriefing questionnaire was administered to assess awareness of the primes or their identity. The questionnaire included the following questions: What did you realize about the experiment? Did you realize that there were other stimuli or words flashed before the ones you saw? If yes, could you identify them or read them?

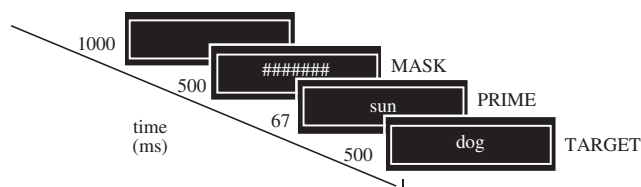


Figure 2. Sequence of events used in the experiment. Presentation time in milliseconds for each event is indicated by the number to the left of each rectangle. Interstimulus interval (ISI) between events is zero.

ERP Recording and Analysis

The electroencephalogram (EEG) was recorded from 29 electrodes mounted in an elastic cap (Electro-Cap) according to a standard extended International 10–20 configuration. In addition, electrodes were placed beneath one eye to monitor blinking and vertical eye movements and at the outer canthus of each eye to monitor horizontal eye movements. On-line recordings were referenced to the right mastoid and re-referenced to averaged mastoids in the final data averaging. Impedances were kept under 2 k Ω for the mastoids and scalp electrodes, under 5 k Ω for horizontal and vertical eye channels, and under 8 k Ω for the isoground channel.

The EEG was amplified with Grass 7P511 amplifiers (3-dB cutoff, bandpass 0.01 to 100 Hz) and digitized on-line at a sampling rate of 250 Hz. An epoch of 1000 ms poststimulus was considered for statistical analyses, using a 200-ms prestimulus baseline. Analyses were time-locked to presentation of the targets. Trials characterized by eye movements, muscular activity, and electrical noise were rejected by automatized programs and were not included in the analyses. Blinks, eye movements, and drift were detected through a “peak-to-peak amplitude” function: Trials were rejected if the amplitude value between the maximum and minimum data points in the specified time window were larger or smaller than an a priori established threshold. Amplifier blocking was detected through similar routines identifying the number of data points within the minimum and maximum values within a given search window; trials outside an experimenter-established a priori threshold were rejected. Only targets correctly identified as words or nonwords were included in analyses.

Based on visual inspection of data across single subjects, the N100 was identified as the first visible negative peak after target presentation with latency 90–150 ms; the N200 was identified as the second negative peak after target presentation with latency 150–250 ms. To calculate scalp voltage maps for the N100 and N200, a spherical spline interpolation (Perrin, Pernier, Bertrand, & Echallier, 1989) was used to interpolate the potential on the surface of an idealized, spherical head based on the voltages measured at each electrode location.

Primary analyses involved investigation of word form effects within the N200 time window. First, an omnibus ANOVA was conducted to investigate effects of prime type. Second, an ANOVA comparing word targets preceded by word and neutral primes was conducted to investigate the N200 effect and its distribution. Subsequent analyses focused on electrode sites at which the N200 effect was maximal. Similar analyses were undertaken to investigate the N100 effect. Significant interactions involving condition effects were followed up by simple effects analyses. Factors for ANOVAs were the following: target type (two possible levels; word and nonword), prime type (five possible levels; words, nonwords, letter strings, false fonts, neutral strings of Xs), hemisphere (two levels; left and right), anterior/posterior (a/p, six possible levels), lateral/medial/midline (l/m, three possible levels). Electrode sites included in the anterior/posterior factor were F7/8 and F3/4 (frontal), FT7/8 and FC5/6 (fronto-temporal), T3/4 and C5/6 (temporal), CT5/6 and C3/4 (centro-temporal), T5/6 and P3/4 (temporo-parietal), and TO1/2 and O1/2 (temporo-occipital). Sites included in the lateral/medial factor were F7/8, FT7/8, T3/4, CT5/6, T5/6, TO1/2 (lateral) and F3/4, FC5/6, C5/6, C3/4, P3/4, O1/2 (medial). Adjusted *p* and epsilon values (Greenhouse–Geisser correction) are reported for all within-subject measures with more than one de-

gree of freedom. Bonferroni correction (standard alpha value of .05 corrected by number of comparisons) was applied to simple comparisons.

Results

Behavioral Results

Reaction times. Reaction times (RTs) for correct responses and percentages of correct responses are shown in Figure 3. Reaction times were faster for word (mean 591.88 ms, SD 90.47) than nonword (mean 654.12 ms, SD 85.69) targets, $F(1,19) = 25.22$, $p < .0001$. There were no differences in RT due to the different types of primes (prime, $p = .37$). The interaction between target and prime type did not reach full significance, $F(4,76) = 2.27$, $p = .08$. Neither type of target nor type of prime affected the accuracy of responses, $p = .29$ and $p = .11$, respectively, although the interaction between target and prime approached statistical significance, $F(4,76) = 2.5$, $p < .06$. Simple comparisons revealed no significant differences between word and nonword targets for any of the prime types, all $ps > .08$.

Prime awareness. Fourteen participants realized that there were other stimuli briefly presented before the targets. Only two participants reported having identified some letters. One participant mentioned that targets were preceded by related words (in fact, only unrelated primes preceded word targets). Two participants mentioned, incorrectly, the presence of the forward mask (pound symbols) as a prime. Therefore, apart from occasional letter identification, responses to the questionnaire indicated that participants were not able to identify the different types of primes.

ERP Results

N200 (150–250 ms)

In an omnibus ANOVA, type of prime was significant as a main effect, $F(4,76) = 11.37$, $p < .0001$, $\epsilon = .63$, confirming that the N200 to targets was sensitive to the orthography of the primes. However, this N200 effect varied across the scalp (prime \times a/p, $F[20,380] = 4.00$, $p < .003$, $\epsilon = .24$; prime \times l/m, $F[4,76] = 11.87$, $p < .0001$, $\epsilon = .71$; prime \times hemisphere \times l/m, $F[4,76] = 2.92$, $p < .05$, $\epsilon = .73$; prime \times a/p \times l/m, $F[8,152]$

$= 7.90$, $p < .0001$, $\epsilon = .3$), prompting further analyses investigating the sites at which the effect was most prominent (see below). Importantly, no differences in N200 amplitude were found between word and nonword targets, $F(1,19) = 0.26$, $p = .62$, n.s. Moreover, no significant interactions between prime and target were found.

To investigate the sites at which the observed N200 effect was maximal, an ANOVA was carried out comparing word targets preceded by word and neutral primes (Figure 4). ERPs to word targets were more negative when preceded by neutral than word primes, $F(1,19) = 27.49$, $p < .0001$. This effect, although broadly distributed across the scalp, was largest at medial sites (prime \times l/m, $F[1,19] = 9.57$, $p = .006$) and medial frontal, central, and temporo-parietal sites in particular (prime \times a/p \times l/m, $F[5,95] = 7.59$, $p = .0003$, $\epsilon = .53$; frontal sites, $F[1,19] = 12.28$, $p = .002$; fronto-temporal, $F[1,19] = 21.53$, $p = .0002$; temporal, $F[1,19] = 39.49$, $p < .0001$; centro-temporal, $F[1,19] = 31.74$, $p < .0001$; temporo-parietal, $F[1,19] = 9.77$, $p = .006$; temporo-occipital, $F[1,19] = 5.70$, $p = .03$).

Further analyses of the N200 effect were conducted only at sites at which the effect was maximal: FC5/6, F3/4, C5/6, C3/4, CT5/6, P3/4, Fz, Cz, and Pz. Thus, subsequent ANOVAs included the following factors: target (two levels), prime (five levels), a/p (three levels, fronto-central, central, and temporo-parietal), and electrode (five levels, left lateral, left medial, midline, right medial, and right lateral). ERPs for the five prime conditions at the fronto-central, central, and temporo-parietal sites are shown in Figure 5.

Prediction 1. Prime was significant as a main effect, $F(4,76) = 13.21$, $p < .0001$, $\epsilon = .63$, an effect somewhat more robust at central sites (prime \times a/p, $F[8,152] = 2.43$, $p < .06$, $\epsilon = .48$). Confirming our prediction that there would be no differences between ERPs elicited by word and nonword targets within the N200 time window across prime types, no differences in N200 amplitude between word and nonword targets and no significant interactions between prime type and target type were found (target, $F[1,19] = 0.26$, $p = .62$, n.s.; target \times prime, $F[4,76] = 0.6$, $p = .62$, n.s.). Therefore, follow-up analyses were performed on mean amplitude collapsed across word and nonword targets.

Follow-up simple comparisons focused on the effects of prime type, contrasting N200 amplitude to targets in the five prime

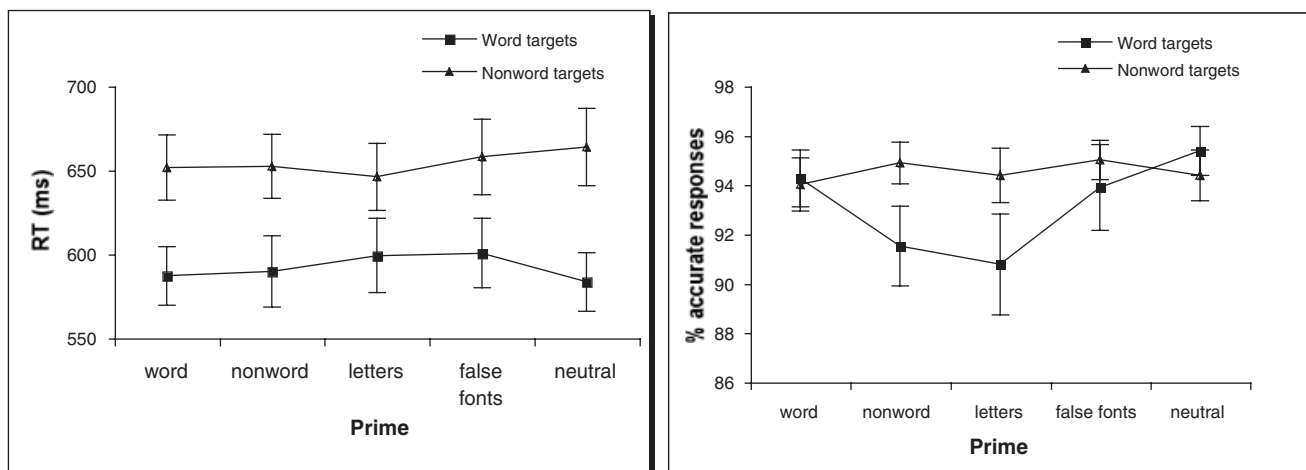


Figure 3. Reaction times (RT) for accurate responses and accuracy (percentage of correct responses). Bars indicate standard errors (throughout).

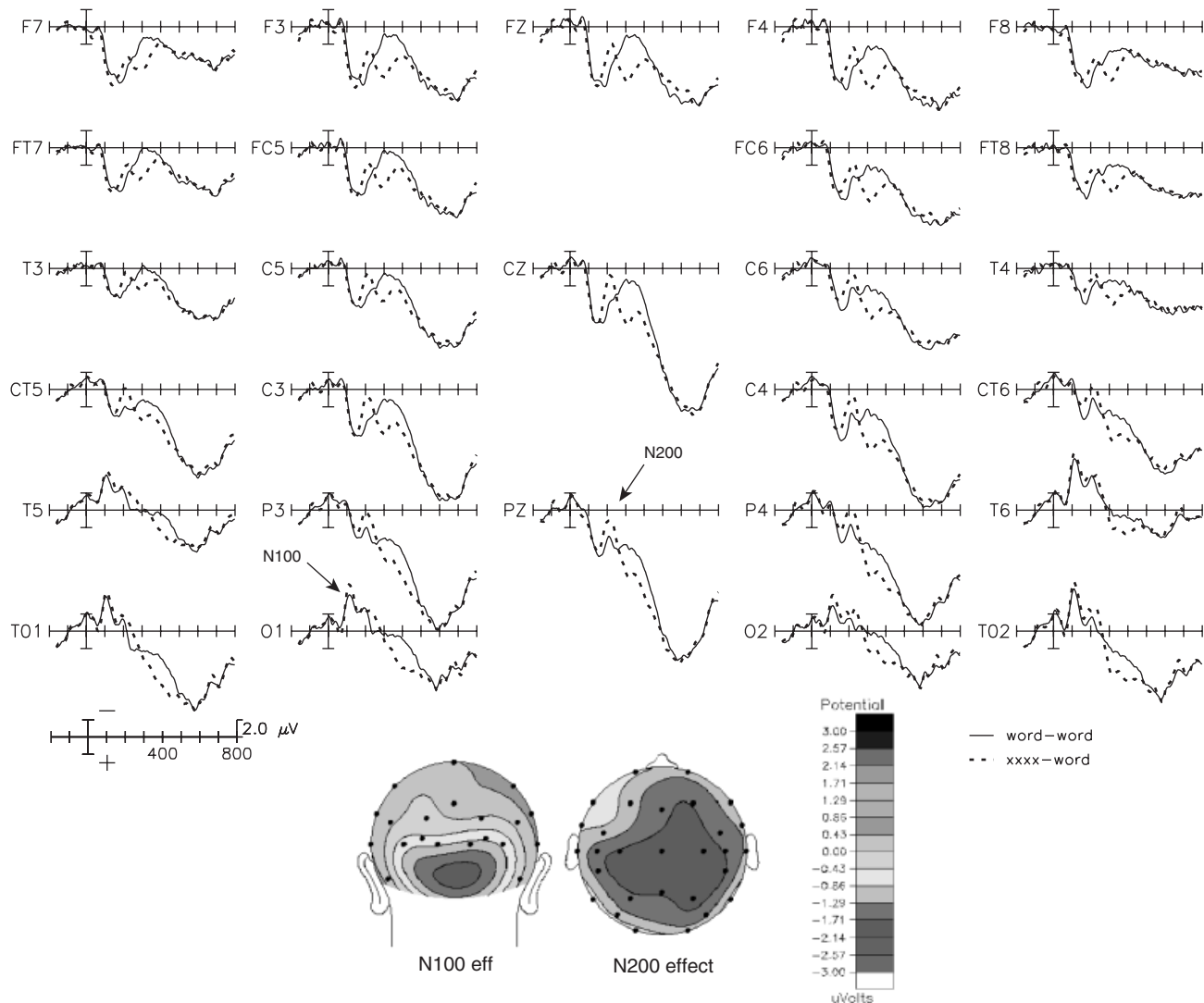


Figure 4. ERP waveforms to word targets preceded by word and neutral (XXXX) primes at all scalp recording sites (negative is plotted up). The voltage maps at the bottom of the figure show the distributions of the N100 (90–150 ms) and N200 (150–250 ms) effects (the voltage maps, reflecting ERPs to targets preceded by word primes subtracted from ERPs to targets preceded by neutral primes, clearly illustrate the different distributions of the two negative effects).

conditions; alpha level was adjusted to .0125 to correct for the four possible comparisons for each set of contrasts. Scalp voltage maps for the main contrasts are shown in Figure 6 and modulation of N200 amplitude to targets preceded by the different types of primes is shown in Figure 7.

Prediction 2. Consistent with our prediction of a more refractory N200 to targets preceded by word and nonword primes than by letter string primes, the N200 was larger to targets preceded by letter strings than by orthographic primes (word and nonword primes averaged together, $F[1,19] = 6.59, p = .02$).

Prediction 3. N200 was larger to targets preceded by false fonts than by letter strings, $F(1,19) = 9.46, p = .006$; prime \times a/p, $F(2,38) = 5.46, p < .03, \epsilon = .61$. This effect was localized over fronto-central, $F(1,19) = 13.36, p = .002$, and central, $F(1,19) = 11.38, p = .003$, sites, not at temporo-parietal sites, $F(1,19) = 1.25, p = .3$. N200 was also larger to targets preceded by false fonts than by orthographic primes (words and nonwords

averaged together, $F[1,19] = 23.55, p < .0001$). This pattern of results suggests that word form processing as indexed by the N200 may occur not only at the word level but also at the letter level.

Prediction 4. Consistent with the hypothesis that the string of Xs would minimally activate the word form system, N200 was larger to targets preceded by neutral primes than to targets preceded by all other prime types averaged together, $F(1,19) = 19.05, p = .0003$. Single comparisons contrasting each other type of prime with neutral primes showed that the N200 was significantly smaller to targets preceded by every other type of prime relative to neutral primes (words, $F[1,19] = 33.08, p < .0001$; nonwords, $F[1,19] = 18.59, p = .0004$; letter strings, $F(1,19) = 14.45, p = .001$; false fonts, $F(1,19) = 5.54, p = .03$, prime \times a/p, $F(1,19) = 8.33, p = .001$).

Finally, confirming each prediction in another way, a trend analysis showed that N200 amplitude was linearly modulated by the orthographic relationship between primes and targets in the

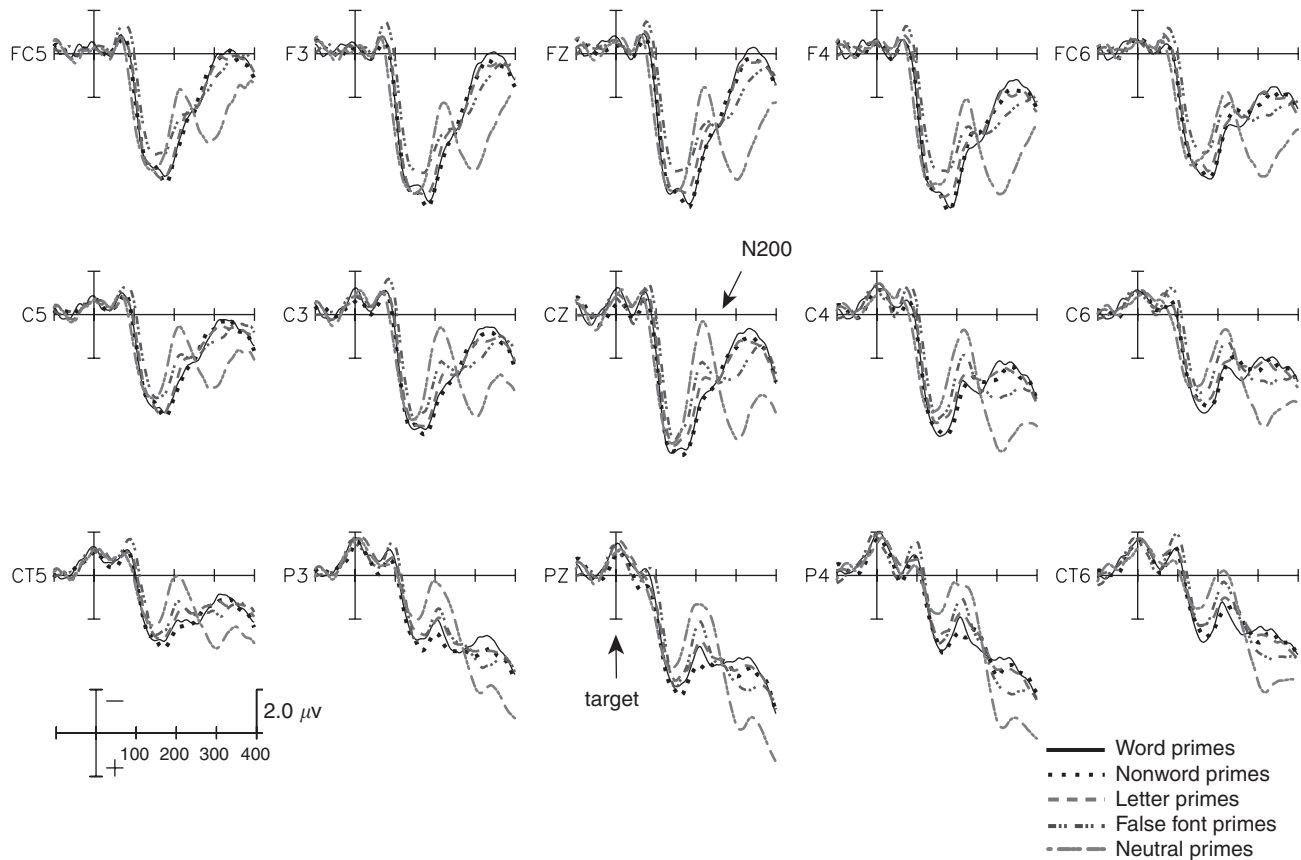


Figure 5. ERP waveforms illustrating N200 mean amplitude (150–250 ms, in microvolts) to targets (collapsed across word and nonword targets) at fronto-central, central, and temporo-parietal sites (the sites at which the N200 effect was maximal) for all five prime conditions (negative is plotted up).

expected direction, $F(1,19) = 43.44$, $p < .0001$: N200 amplitude was smaller (more refractory) when targets were preceded by word and nonword primes, followed by letter strings, false fonts, and neutral primes.

N100 analysis (90–150 ms)

An omnibus ANOVA indicated that the N100 was largest at posterior and lateral sites, specifically at temporo-occipital sites (a/p, $F[5,59] = 44.48$, $p < .0001$, $\epsilon = .24$; l/m, $F(1,19) = 35.50$, $p < .0001$; a/p \times l/m, $F(5,59) = 45.95$, $p < .0001$, $\epsilon = .35$; see Figure 4). The effect of prime type was significant, $F(4,76) = 3.91$, $p < .02$, $\epsilon = .7$, and interacted with the anterior/posterior and lateral/medial factors (prime \times a/p, $F[20,380] = 15.69$, $p < .0001$, $\epsilon = .22$; prime \times l/m, $F[4,76] = 5.74$, $p < .002$, $\epsilon = .79$; prime \times a/p \times l/m, $F[20,380] = 5.72$, $p = .0001$, $\epsilon = .27$), prompting more distributionally circumscribed analyses (see below). Once again, no differences in N100 amplitude between word and nonword targets and no significant interactions between prime type and target type were found (target, $F[1,19] = 0.00$, $p = .96$, n.s.; target \times prime, $F[4,76] = 0.52$, $p = .67$, n.s.), so follow-up analyses were performed on mean amplitude collapsed across word and nonword targets.

To investigate the sites at which the N100 effect was maximal an ANOVA was carried out comparing ERPs to word targets preceded by word and neutral primes (Figure 4). The main effect of prime type was not significant, $F(1,19) = 0.5$, $p = .49$, n.s., but the effect of prime type varied across the scalp (prime \times a/p, $F[9,95] = 10.28$, $p < .004$, $\epsilon = .29$). Separate analyses at anterior

and posterior sites revealed that ERPs to targets were more negative when preceded by neutral than word primes at posterior sites (three posterior rows: centro-temporal, temporo-parietal, and temporo-occipital), particularly at temporo-occipital sites (prime \times a/p, $F[2,38] = 11.13$, $p = .003$, $\epsilon = .56$; prime \times a/p \times l/m, $F[2,38] = 3.99$, $p = .03$, $\epsilon = .78$; see Figure 4). These results suggest a different distribution for the N100 and N200 effects.

Effects of prime type were further explored at the sites at which the N100 effect was maximal: T5/6, TO1/2, and O1/2. Type of prime was significant as a main effect, $F(4,76) = 5.75$, $p < .006$, $\epsilon = .61$. No differences in N100 amplitude between word and nonword targets and no significant interactions between prime type and target type were found (target, $F[1,19] = 0.40$, $p = .53$, n.s.; target \times prime, $F[4,76] = 0.71$, $p = .59$, n.s.).

As predicted, N100 was more negative for targets preceded by neutral primes in comparison to all other prime types combined ($p = .005$). Single comparisons (corrected alpha = .0125) revealed that the N100 was more negative to targets preceded by neutral primes as compared to word ($p = .016$, strong trend with corrected level), nonword ($p = .004$), letter string ($p = .036$, weak trend with corrected level), and false font ($p = .008$) primes. An ANOVA performed on N100 amplitude to targets preceded by word, nonword, letter string, and false font primes yielded an interaction between prime type and site, $F(2,38) = 2.76$, $p < .04$, $\epsilon = .62$; however, ANOVAs conducted at specific sites (T5/6, TO1/2, O1/2) did not reveal any statistical difference between the four types of primes, all $ps > .08$. The pattern of effects in the N100 time window is shown in Figures 8 and 9.

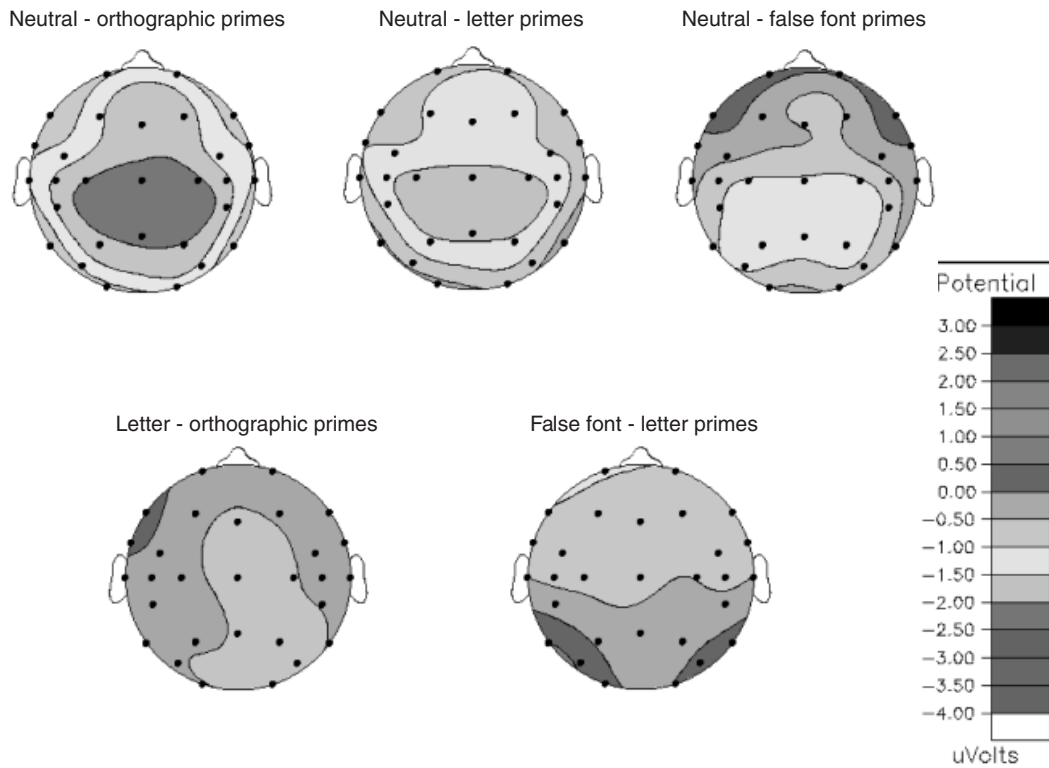


Figure 6. Voltage maps of the N200 effect for the primary contrasts (mean amplitude within the 150–250-ms time window). “Orthographic primes” were comprised of word and nonword primes averaged together. All effects were negative.

To substantiate our claim that the N200 effect specifically reflects word form processing (whereas the N100 effect does not), we assessed whether the pattern of word form effects described for the N200 was present in the N100 time window at the fronto-central, central, and temporo-parietal sites (the sites at which the N200 effect was maximal). No effect of target or significant interactions between prime type and target type were found (target, $F[1,19] = 0.17$, $p = .68$, n.s.; target \times prime, $F[4,76] = 0.71$, $p = .59$, n.s.), so analyses were performed on mean amplitudes collapsed across word and nonword targets. Prime type was significant as a main effect, $F(4,76) = 6.14$, $p = .001$, $\epsilon = .72$, but

this effect varied across the scalp (prime \times a/p, $F[8,152] = 7.32$, $p = .0001$, $\epsilon = .44$ and prime \times ap \times site, $F[32,608] = 2.20$, $p < .04$, $\epsilon = .22$). Separate analyses at fronto-central, central, and temporo-parietal sites revealed that the effect of prime type was significant only over fronto-central and central sites (fronto-central, $F[4,76] = 9.43$, $p < .0001$, $\epsilon = .77$; central sites, $F[4,76] = 6.73$, $p = .0006$, $\epsilon = .72$; temporo-parietal, $F[4,76] = 1.89$, $p = .12$, n.s.). These results show once again that the N100 and N200 effects did not have the same distribution.

The results of this comparative analysis were consistent with the N200 effect findings in that no differences were observed

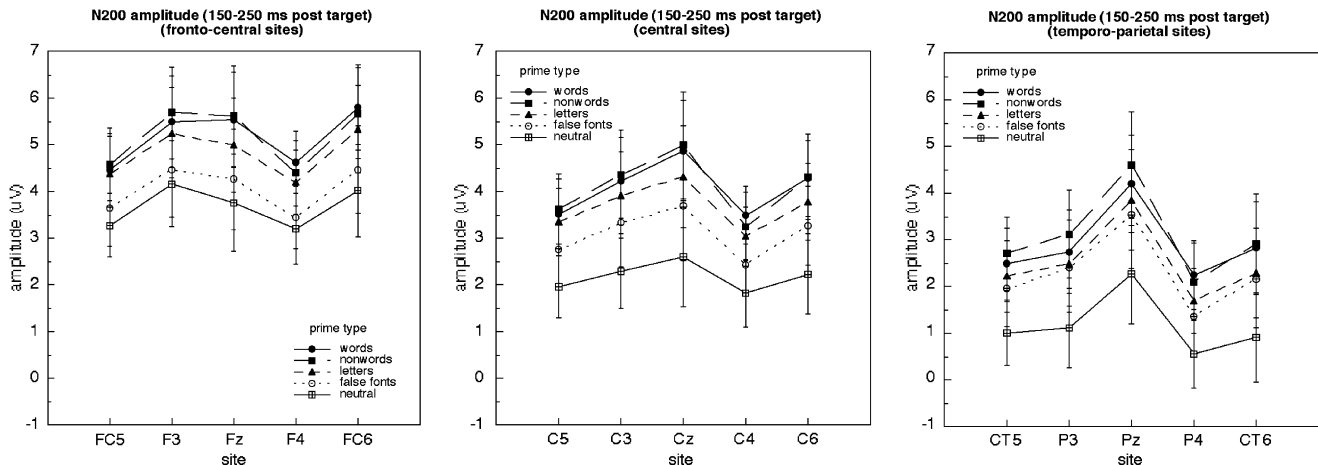


Figure 7. N200 mean amplitude (150–250 ms, in microvolts) to targets (collapsed across word and nonword targets) for all five prime conditions at fronto-central, central, and temporo-parietal sites.

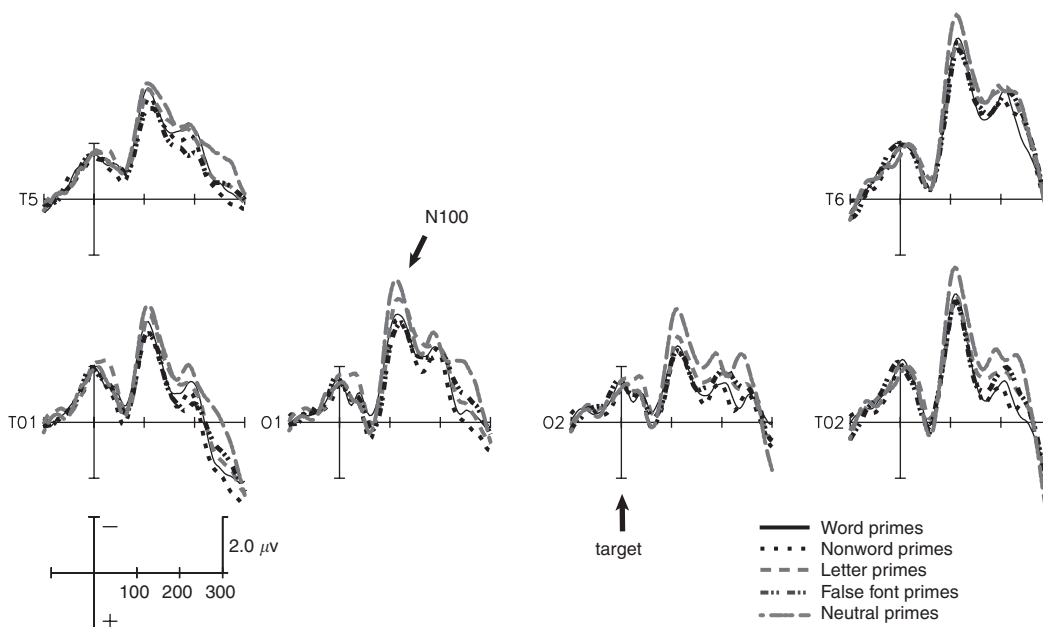


Figure 8. ERP waveforms illustrating N100 mean amplitude (90–150 ms, in microvolts) to targets (collapsed across word and nonword targets) at temporo-occipital sites (the sites at which the N100 effect was maximal) for all five prime conditions (negative is plotted up).

between word and nonword primes, $F(1,19) = 0.0, p = .98, n.s.$, and ERPs were more negative to targets preceded by false font as compared to letter string primes, $F(1,19) = 11.98, p = .003$. Inconsistent with the N200 results, N100 amplitude to targets was more *positive* when preceded by neutral than word primes (prime \times a/p, $F[2,38] = 4.89, p < .04, \epsilon = .53$), nonword primes (prime \times a/p, $F[2,38] = 9.59, p < .006, \epsilon = .55$), letter string primes (prime \times a/p, $F[2,38] = 10.67, p < .004, \epsilon = .55$), and false font

primes, $F(1,19) = 18.38, p = .0004$, a reversal in effect likely due to an earlier fronto-central P200 to neutral primes (see Figure 4). Moreover, no differences were observed for targets preceded by orthographic (word and nonword) and letter string primes, $F(1,19) = 2.26, p = .15, n.s.$ Finally, there was no significant linear trend for prime type in the N100 time window, $F(1,19) = 0.48, p = .5, n.s.$

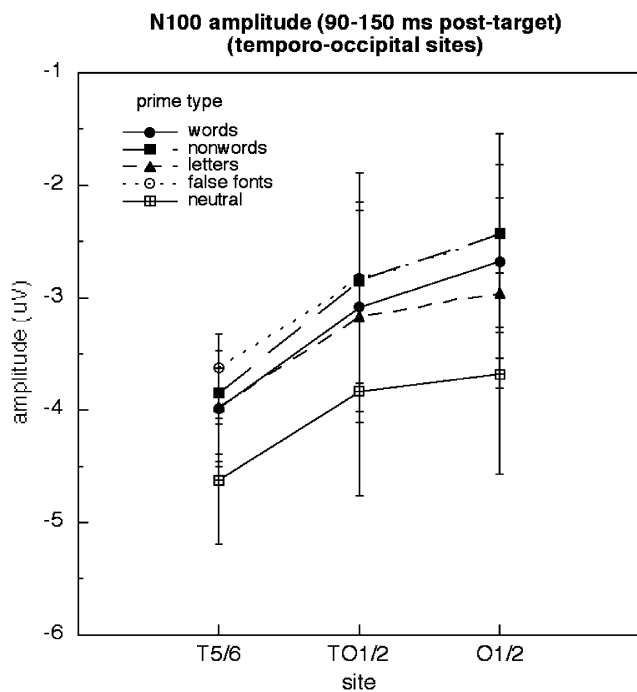


Figure 9. N100 mean amplitude (90–150 ms, in microvolts) to targets (collapsed across word and nonword targets) at temporo-occipital sites, collapsed across hemisphere.

Discussion

The nature of the representational specificity of word form systems was investigated in a masked priming experiment with a lexical decision task in which word and nonword targets were preceded by five types of masked primes: words, nonwords, illegal strings of letters, false fonts, and neutral strings of Xs. It was hypothesized that the amplitude of the N200 (150–250 ms) to targets would be more refractory and therefore smaller when the orthographically legal targets were preceded by similarly orthographically legal word and nonword primes, but would become less refractory with increasingly dissimilar and orthographically illegal primes, from legal alphabetic letter strings through illegal alphabetic-like false fonts to nonlinguistic neutral strings of Xs. Indeed, we report an N200 effect such that ERPs within the 150–250-ms time window were linearly modulated by the orthographic relationship between prime and target, being less negative to targets preceded by word and nonword primes, followed by letter strings, false fonts, and neutral primes. This pattern indicates that neural systems involved in automatic orthographic analysis of visually presented stimuli are not only maximally activated by legal strings of letters, but also are moderately activated by illegal strings of letters and alphabetic-like information as contained in our false font stimuli.

The linear, rather than binary, modulation of the N200 masked priming effect is perhaps the most interesting finding of the present study. PET and fMRI studies have similarly found

that regions involved in visual word analysis are maximally activated by words, but are also activated by nonwords, letter strings, and false fonts to varying degrees (Price et al., 1996; Rees et al., 1999; Tagamets et al., 2000). Previous ERP studies not using a masked priming paradigm have also reported an N200-like component elicited by both orthographic and nonorthographic stimuli (Bentin et al., 1999; Cohen et al., 2000; Compton et al., 1991; McCandliss et al., 1997) but have been equivocal with regard to the direction of the N200 effect for words as compared to letter strings: As discussed in the Introduction, in some reports, N200 is larger to consonant strings than to English words (Compton et al., 1991; McCandliss et al., 1997) whereas in other reports, the opposite holds true (Bentin et al., 1999; Cohen et al., 2000). A coherent picture of the computational specificity of word form systems is difficult to obtain given the differences in stimuli, task, and attentional demands across these past ERP studies.

The present study, which investigated automatic word form analysis as revealed by refractoriness of the neural systems involved, is critical to resolving this issue of the pattern of activation of word form processing systems. Because participants were unaware of the presence or identity of the primes, it is highly unlikely that the observed N200 effects were influenced by task and attentional demands; rather, by using a masked priming paradigm, we were able to provide a more pure measure of the structural properties of visual word form systems uncontaminated by “higher level” processes. Indeed, our results across prime type do form a coherent and consistent picture of the computational specificity of word form systems indexed by ERPs 150–250 ms after stimulus presentation.

As predicted, no differences were found in N200 amplitude when targets were preceded by equally orthographically legal word and nonword primes (similarly, no differences in activation in the mid-fusiform gyrus between words and nonwords were found by Tagamets et al., 2000, in an fMRI study). Because word and nonword primes differed in terms of familiarity and meaning, this result is consistent with the hypothesis that word form systems analyze visual linguistic stimuli at a prelexical level while information concerning lexical status and meaning is processed within additional neural systems (Bentin et al., 1999).

Perhaps the most clear indication of the specificity of word form processing comes from the comparison of word and letter string stimuli, the very comparison for which previous ERP studies using unmasked stimuli have produced equivocal results. This comparison reflects the tuning of word form systems to orthographic regularities, in terms of letter combinations in the participant’s language. We found a significantly less refractory (larger amplitude) N200 to targets preceded by letter string primes than to targets preceded by word and nonword primes. Remarkably, we were able to observe this decreased refractoriness in N200 target amplitude in a comparison between the orthographic primes and letter string prime stimuli composed of the *same letters* as the orthographic primes rearranged to violate the orthographic rules of English. Because the component letters were exactly the same across these prime stimulus types, these results corroborate the existence of neural systems sensitive to orthographic regularities, consistent with previous PET and fMRI (e.g., Büchel, Price, & Friston, 1998; Cohen et al., 2002; Polk & Farah, 2002; Rees et al., 1999) as well as ERP (Bentin et al., 1999; Compton et al., 1991; McCandliss et al., 1997; Ziegler et al., 1997) findings.

Further delineating the specificity of word form processing systems, we found evidence for tuning to alphabetic information:

N200 amplitude showed less refractoriness to targets preceded by false font than letter string primes. Because false fonts were created by rearranging segments of letters used in the other prime types (within letter), this effect cannot be attributed to differences in terms of visual features between the primes. It seems that word form systems as indexed by the N200 are modulated by the alphabetic nature of the stimuli. A similar result has been observed in PET studies comparing activation in the left fusiform gyrus to strings of consonants and strings of false font characters (Price et al., 1996).

Tagamets et al. (2000) have reported different peaks of activation in the ventral visual processing pathway for orthographic (words and nonwords) and nonorthographic (letter strings and false fonts) stimuli in an fMRI study: The former maximally activated mid-fusiform gyrus whereas the latter maximally activated more posterior inferior occipital cortex. Dehaene et al. (2004) have more recently reported specialization within the medial fusiform gyrus, with more posterior areas sensitive to letter position and activation within more anterior areas invariant to letter position. These findings suggest a hierarchical organization of systems involved in processing visual linguistic information from more specific to more abstract units (Dehaene et al., 2004). Although our data clearly do not have the spatial resolution necessary to speak to such issues, they may provide some support for such a distinction. In our study, the N200 effect due to the presence of legal combinations of letters (letter string primes vs. orthographic primes contrast) had a fronto-central and temporo-parietal distribution, whereas the effect due to the presence of alphabetic material (false font vs. letter string primes contrast) was not significant at temporo-parietal sites.

Although our results mostly confirm and add to the literature on word form processing, we did not replicate an effect of hemisphere in the present study, although a number of authors have reported slight left lateralization of an N200 (Bentin et al., 1999; Cohen et al., 2000; Compton et al., 1991; but cf. Allison et al., 1999). It is possible that the lateralization of the N200 varies with task or with attentional demands required by the task. It is also possible that the inconsistent findings may be due to different recording procedures, such as the choice of reference used during data collection or during data averaging procedures. At present, it is unclear what the contributing factors might be and whether the N200 is indeed lateralized.

For comparison to the modulation of the target N200 by prime orthographic information, we measured an earlier temporo-occipital N100 (90–150 ms post target onset). Data from intracranial recording (Allison et al., 1999) and MEG (Tarkiainen et al., 1999; Wydell et al., 2003) studies have shown that neural systems indexed by the posterior N100 are sensitive to physical characteristic of stimuli such as luminance and size, so we did not expect the N100 to be modulated by orthography. Instead we predicted that the N100 to targets preceded by all prime types except neutral primes would be similar in amplitude, because these prime types were matched in terms of physical features. However, neutral primes (strings of Xs) were larger, brighter, and different, both in terms of constituent elements such as curves and straight lines and in terms of language-likeness, from the other types of primes. These unique stimulus characteristics yielded the prediction that the N100 to targets preceded by neutral primes would be less refractory and therefore larger in comparison to all other prime types. Our data confirmed our predictions: The N100 was larger to targets preceded by neutral primes than by any other type of prime; moreover, in contrast to

the N200 results, ERPs to targets preceded by all other types of primes displayed similar amplitude N100s. Thus, the visual processing systems indexed by the N100 do not appear to discriminate among different types of stimuli in terms of their identity, as seen with the N200. These results, along with the different scalp distributions of the N100 (temporo-occipital) and N200 (maximal at fronto-central, central, and temporo-parietal sites) effects, provide support for the hypothesis that these effects reflect different aspects of the reading process. Specifically, the results are consistent with our assumptions that the N100 effect reflects processing of lower level physical characteristics of the stimuli while the N200 effect reflects word form processing.²

Our purpose was to isolate word form processing while minimizing the role of confounding factors such as phonology and semantics, which are typically present in repetition priming experiments (although word form analysis was not sufficient to perform the lexical decision task; e.g., see Dehaene et al., 2001, for repetition suppression effects in the word form area). Although one advantage of the present masked priming paradigm is in providing a relatively uncontaminated index of automatic processing, it could be argued that the short stimulus onset asynchrony (67 ms) between primes and targets resulted in ERPs to targets reflecting not only the response to targets influenced by the primes but also processing of the primes. Thus, the early N100 and N200 effects might be claimed to reflect superimposed activity of two distinct processes (prime and target processing) with partial temporal overlap. Although it is possible that prime processing affected N100 amplitude to targets (larger when targets were preceded by bigger primes), the appearance and timing of the 150–250-ms effect (word form analysis) are completely consistent with previous reports from studies not using masked priming, arguing against this interpretation. The N100 effect could be explained in terms of different prime size, as the neutral primes were larger and brighter than the other primes; it is possible that the N100 to targets in part reflected prime, instead of target alone, processing. This explanation does not argue against an interpretation of the N100 effect as a reflection of processing in terms of physical features, but offers an alternative account. These alternative explanations might be tested by using primes that differ in terms of size but not constituent elements

(e.g., larger false fonts). Thus, the possibility of prime–target processing overlap remains an empirical question for future research.

Another possible disadvantage of the masked priming paradigm is that visual thresholds do vary across individuals; thus, titrating duration of the prime by individual participant is ideal to ensure nonawareness of the prime stimuli. There is some debate about whether subjective or objective measures of awareness are more effective in assuring that performance reflects unconscious perception of stimuli (e.g., Merickle, Smilek, & Eastwood, 2001). Here, we depended on participants' verbal reports regarding awareness of the primes. Although follow-up studies should include more rigorous measures to ensure that participants are indeed unaware of the presence of the primes, the masked priming paradigm was used here to limit the impact of strategic and attention-related factors on target processing. Both the self-report and behavioral results suggest that the role of such factors was indeed minimized. No participant accurately reported any prime and the average reaction time for word responses was faster than 600 ms; it is unlikely that such speed, accompanied by high accuracy, would have been observed if participants' attention had been captured by the primes. Moreover, because the critical effects reported are refractory effects and not typical priming effects, the efficacy of the masking is not as crucial as it might be in other studies.³

In conclusion, the N200 as measured in the current paradigm appears to be a remarkably sensitive index of automatic word form processing. Our data show that neural systems involved in word form processing are maximally activated by orthographic stimuli (both words and legal nonwords). Further, our data show that these systems are also activated, but to a lesser degree, by illegal strings of letters and false fonts that resemble alphabetic material. These results from a masked priming paradigm reveal a graded functional organization within word form systems uncontaminated by task or attentional demands. The process of reading—and the neural instantiation of that process—is extremely complex; the findings of the present investigation augment our understanding of one aspect of that process, confirming the automaticity and specificity of orthographic word form processing.

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²The differential effect of prime type was clearly observed for the N200 (150–250 ms) and N100 (90–150 ms) measured at sites at which each of the effects was maximal. In a more direct comparison of the N100 and N200 effects at fronto-central, central, and temporo-occipital sites (reflecting the distribution of the N200 effect), ERPs to targets preceded by false fonts were more negative than ERPs to targets preceded by letter strings in the N100 (90–150 ms) time window at fronto-central sites only. Although this pattern is similar to that observed for the N200, this more anterior N100 effect does not appear to be the posterior N100 effect to which we refer throughout and likely reflects activation of other neural systems involved in the process reading, of which there are many, as reviewed in the Introduction.

³We thank an anonymous reviewer for noting this point.

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