On-line Orthographic Influences on Spoken Language in a Semantic Task

Chotiga Pattamadilok[1,2], Laetitia Perre[3,4], Stéphane Dufau[3,4], and Johannes C. Ziegler[3,4]

Abstract

■ Literacy changes the way the brain processes spoken language. Most psycholinguists believe that orthographic effects on spoken language are either strategic or restricted to meta-phonological tasks. We used event-related brain potentials (ERPs) to investigate the locus and the time course of orthographic effects on spoken word recognition in a semantic task. Participants were asked to decide whether a given word belonged to a semantic category (body parts). On *no-go trials*, words were presented that were either orthographically consistent or inconsistent. Orthographic inconsistency (i.e., multiple spellings of the same phonology) could occur either in the first or the second syllable. The ERP data showed a clear orthographic consistency effect that preceded lexical access and semantic effects. Moreover, the onset of the orthographic consistency effect was time-locked to the arrival of the inconsistency in a spoken word, which suggests that orthography influences spoken language in a time-dependent manner. The present data join recent evidence from brain imaging showing orthographic activation in spoken language tasks. Our results extend those findings by showing that orthographic activation occurs early and affects spoken word recognition in a semantic task that does not require the explicit processing of orthographic or phonological structure. ■

INTRODUCTION

Learning to read and write alters the way people process spoken words (Frith, 1998). This idea has been confirmed in several studies showing that performance in spoken language tasks was influenced by orthographic consistency (i.e., the fact that a phonological unit in a given language can have several spellings). For example, the rhyme /ʌk/ is consistent in English because it has only one possible spelling (''uck''), whereas the rhyme /aɪt/ is inconsistent because it has several possible spellings (''ight,'' ''ite,'' or ''yte'').

Much of the evidence for literacy effects in spoken language comes from meta-phonological tasks. For instance, participants were faster in deciding whether two words rhymed when they had the same spellings, such as *toast* and *roast*, than when they had different spellings, such as *toast* and *ghost* (e.g., McPherson, Ackerman, & Dykman, 1997; Zecker, 1991; Zecker, Tanenhaus, Alderman, & Siqueland, 1986; Rack, 1985; Donnenwerth-Nolan, Tanenhaus, & Seidenberg, 1981; Seidenberg & Tanenhaus, 1979). In agreement with this finding, a functional magnetic resonance imaging (fMRI) study by Booth et al. (2004) found that rhyme decisions produced activation in the left fusiform gyrus, an area that is typically involved in processing orthographic information (Dehaene et al., 2001, 2004).

More recently, Bolger, Hornickel, Cone, Burman, and Booth (2007) studied the effects of orthographic and phonological inconsistency in the visual modality, with fMRI using a rhyming (does *jazz* rhyme with *has*) and a spelling task. They found greater activation for inconsistent compared with consistent words in several brain regions including the left inferior temporal gyrus, the left superior temporal cortex, the left fusiform gyrus, and the bilateral medial frontal gyrus/anterior cingulate cortex. Higher-skill readers were more sensitive to the consistency manipulation than lower-skill readers in the fusiform gyrus and the precuneus/posterior cingulate cortex. Together, these data suggest that visual word recognition is best described as a coupling between orthographic and phonological information in a widely distributed cortical network.

Finally, literacy clearly changes the way the brain processes spoken language. For example, Castro-Caldas, Petersson, Reis, Stone-Elander, and Ingvar (1998) found that illiterates who have never learned a written language do not activate the same brain areas as do literate people when processing spoken language (see also Petersson, Reis, Askelöf, Castro-Caldas, & Ingvar, 2000). Interestingly, the differences were restricted to the processing of pseudowords. The processing of pseudowords requires a fine-grained (sublexical) analysis of the speech signal. Thus, it

[1]Université Libre de Bruxelles (ULB), Belgium, [2]Fonds de la Recherche Scientifique (F.N.R.S.), Belgium, [3]Aix-Marseille Université, France, [4]CNRS, Laboratoire de Psychologie Cognitive, France

is possible that learning to read is crucially involved in developing fine-grained phonological representations.

Although earlier research suggested that literacy effects on spoken language processing were restricted to meta-phonological tasks (e.g., rhyme judgments), more recent studies found orthographic effects in on-line spoken word recognition tasks that do not require any explicit analysis of the phonological representations. Using a lexical decision task, Ziegler and Ferrand (1998) showed that spoken word recognition was affected by orthographic consistency: Words that ended with a consistent rhyme led to faster decision times and lower error rates than those that ended with an inconsistent rhyme. Perre and Ziegler (2007) have recently shown that this effect can be seen in event-related brain potentials (ERPs) as early as 350 msec after the onset of a spoken word.

The existence of an orthographic consistency effect in spoken word recognition has been replicated in different languages (English: Miller & Swick, 2003; Portuguese: Ventura, Morais, Pattamadilok, & Kolinsky, 2004; French: Pattamadilok, Morais, Ventura, & Kolinsky, 2007) and with different orthographic manipulations (e.g., Ziegler, Muneaux, & Grainger, 2003). Furthermore, it has been shown that the effect is not due to phonetic confounds between consistent and inconsistent items (Ziegler, Ferrand, & Montant, 2004). Finally, studies with illiterates, dyslexics, and beginning readers have clearly shown that the effect is directly linked to a persons' reading ability (Ventura, Morais, & Kolinsky, 2007; Ziegler & Muneaux, 2007; Miller & Swick, 2003; Morais, Cary, Alegria, & Bertelson, 1979).

One major outstanding question is whether orthographic consistency effects would occur in a semantic task when people listen to speech in order to extract meaning. Indeed, all previous studies have used either meta-phonological or lexical decision tasks. It could be argued that orthographic information is used strategically in both of these tasks (e.g., Cutler, Treiman, & Van Ooijen, 1998). In meta-phonological tasks, participants might create an orthographic image of the word to facilitate abstract phonological judgments. In the lexical decision task, participants might "consult" the orthographic lexicon to help decide upon the lexical status of a spoken word. To put the strategy hypothesis to rest, what is needed is a demonstration of an orthographic effect in a semantic task that does not require the explicit analysis of phonological structure or lexical status.

A second issue that needs to be addressed is whether the orthographic consistency effect occurs before or after lexical access. Perre and Ziegler (2008) have shown that the orthographic consistency effect occurs early but they did not compare the emergence of this effect to a marker of lexical access (e.g., the frequency effect). If the orthographic consistency effect occurs before lexico-semantic processes, then it is likely to reflect the automatic mapping between orthography and phonology (e.g., Van Orden & Goldinger, 1994). In contrast, if the orthographic consistency effect occurs after lexico-semantic processes, then it is likely to reflect decisional or postlexical processes (e.g., Ventura et al., 2004).

The present study addressed both issues. First, we used a go/no-go version of a semantic categorization task to address the question of whether orthographic consistency effects could be found in a semantic task. In this task, participants listened to spoken words in order to decide whether a given word was a part of the human body (see Holcomb & Grainger, 2006). Participants were asked to press a button if the spoken words corresponded to parts of the human body (go response) and withhold from responding if this was not the case (no-go response). The critical items (i.e., orthographically consistent and inconsistent words) were presented on no-go trials, which allowed us to use a large variety of items and to record ERPs that are uncontaminated by motor responses. The presence of the orthographic consistency effect in this situation would provide unequivocal evidence for the nonstrategic nature of orthographic activation in spoken word recognition.

Second, to address the question of whether the orthographic consistency effect occurs before or after lexical access, we used ERPs to track the on-line time course and the locus of the orthographic consistency effect. A number of studies have used ERPs to study the time course of word recognition (O'Rourke & Holcomb, 2002; Sereno & Rayner, 2000; Bentin, Mouchetant-Rostaing, Giard, Echallier, & Pernier, 1999). The main idea was to compare the onset of the orthographic consistency effect with the onsets of the word frequency and the go/no-go effects. The word frequency effect is a classic marker of lexical access, whereas the go/no-go effect reflects the time necessary for making the semantic decision.

Finally, to investigate whether the orthographic representations were activated in an "on-line" fashion (as claimed by interactive models of word recognition, e.g., Grainger & Ziegler, 2007; Van Orden & Goldinger, 1994), we also manipulated the arrival of the orthographic inconsistency within a spoken word, that is, orthographic inconsistency could either be on the first or the second syllable. If the orthographic representations are activated in a time-dependent manner, the onset of the orthographic ERP effect should be time-locked to the "arrival" of the orthographic inconsistency (for a similar idea, see Perre & Ziegler, 2008; O'Rourke & Holcomb, 2002).

METHODS

Participants

Seventeen students from the Aix-Marseille University (mean age = 22.4 years; age range = 19–40 years; 15 women) took part in the experiment. All participants reported being right-handed native speakers of French with normal hearing. All reported being free of neurological disorders.

Materials

Stimuli were recorded by a female native speaker of French in a soundproof room on a digital audiotape recorder (Teac DA-P20) using a Sennheiser MD43 microphone. They were digitized at a sampling rate of 48 kHz with 16-bit analog-to-digital conversion using a wave editor.

The critical stimuli (i.e., no-go trials) consisted of 180 disyllabic French words that were equitably separated into six experimental conditions (30 items per condition), which resulted from a manipulation of word frequency and orthographic consistency of either the first or the second syllable (see Appendix 1). The six conditions were as follows: high- and low-frequency words that contained only consistent syllables (*HCC* and *LCC*, respectively; e.g., ''montagne'' (mountain): the syllables ''mon'' and ''tagne'' have only one possible spelling in French); high- and low-frequency words in which the first syllable was inconsistent but the second was consistent (*HIC* and *LIC*, respectively, e.g., ''champagne'' (champagne): the syllable ''cham'' has more than one possible spelling, whereas the syllable ''pagne'' has only one possible spelling); high- and low-frequency words in which the first syllable was consistent and the second inconsistent (*HCI* and *LCI*, respectively, e.g., ''printemps'' (spring): the syllable ''prin'' has only one possible spelling in French, whereas the syllable ''temps'' has more than one possible spelling).

The syllable consistency ratio[1] was computed from the disyllabic words in the BRULEX database (Content, Mousty, & Radeau, 1990). The critical stimuli from the different conditions were matched on the following variables (see Appendix 2): number of phonemes, phonological uniqueness point, number of phonological neighbors, phonological enemies (i.e., spelling-to-sound consistency ratios), and mean durations (all ps $\geq .20$). Within each frequency class, the stimuli were matched on two frequency counts: LEXIQUE (New, Pallier, Ferrand, & Matos, 2001) and BRULEX (Content et al., 1990).

In addition to the critical stimuli described above, the material also included 45 disyllabic French words representing parts of the body. These stimuli represented the go trials which corresponded to 16.7% of all trials.

Procedure

A go/no-go paradigm was used (Holcomb & Grainger, 2006). Participants were asked to respond as quickly as possible by pushing a response button placed in their right hand when they detected the name of a body part (go) and to withhold from responding when this was not the case (no-go). Participants were tested individually in a soundproof room. Stimuli were presented binaurally at a comfortable listening level through headphones. The session started with 13 practice trials to familiarize participants to the task. The 225 stimuli (45 go trials and 180 no-go trials) were divided into five blocks. Each block consisted of 9 go trails and 36 no-go trials (6 trials per condition) randomly presented. A trial consisted of the following sequence of events: A fixation point (+) was presented for 500 msec in the center of the screen, then the spoken stimulus was presented while the fixation cross remained on the screen for 2000 msec. Participants were told not to blink or move while the fixation point was present. Intertrial interval was 1500 msec (blank screen). No feedback was provided during the experiment.

EEG Recording Procedure

Continuous electroencephalogram (EEG) was recorded from 64 Ag/AgCl active electrodes held in place on the scalp by an elastic cap (Electro-Cap International, Eaton, OH). The electrode montage included 10 midline sites and 27 sites over each hemisphere (American Clinical Neurophysiology Society, 2006; see Figure 1). Two additional electrodes (CMS/DRL nearby Pz) were used as an on-line reference (for a complete description, see www.biosemi.com; Schutter, Leitner, Kenemans, & van Honk, 2006). Six other electrodes were attached over the right and left mastoids, below the right and left eyes (for monitoring vertical eye movements and blinks), and lateral to the left and right external canthi (for monitoring horizontal eye movements). Bioelectrical signals were amplified using an ActiveTwo Biosemi amplifier (DC-67 Hz bandpass, 3 dB/octave) and were continuously sampled (24 bit sampling) at a rate of 256 Hz throughout the experiment. EEG was filtered off-line (20 Hz low-pass,

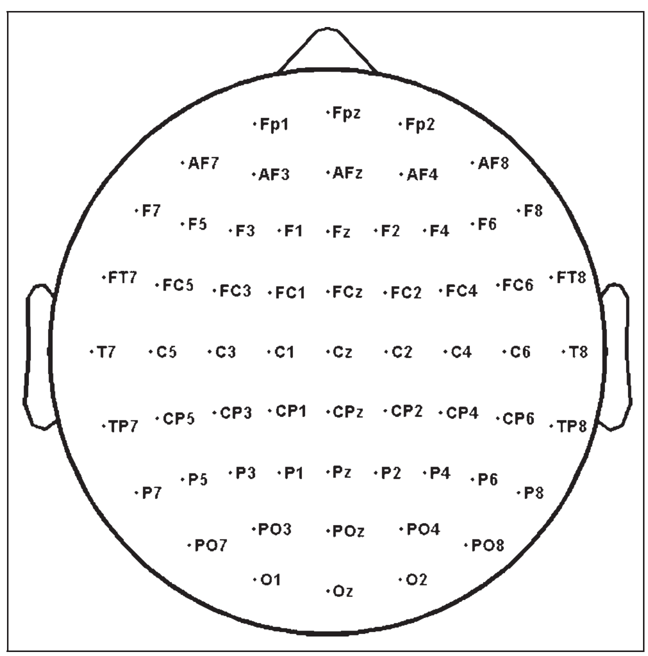

Figure 1. Electrode montage schematic (standard 10–10 system) used in the ERP analysis.

24 dB/octave) using EEGLAB software (Delorme & Makeig, 2004). The signal from the left mastoid electrode was used off-line to re-reference the scalp recordings.

RESULTS

Behavioral Data

The accuracy data showed that participants performed the task perfectly well. On average, 96.1% (SD = 2.95) of body part stimuli were detected within a window of 200–2000 msec poststimulus onset. Mean reaction time for go decisions was 1002 msec (SD = 79.2). False alarm rate was 1.2%.

Electrophysiological Data

Averaged ERPs were formed off-line from correct trials free of ocular and muscular artifact (less than 10% of trials were excluded from the analyses). ERPs were calculated by averaging the EEG time-locked to a point 100-msec prestimulus onset and lasting 1000 msec poststimulus onset. The 100-msec prestimulus period was used as the baseline. Separate ERPs were formed for the six experimental conditions and the go trials.

In order to localize the electrodes showing the consistency effect and to select appropriate time windows for the ERP analyses, we first performed for each electrode a preliminary stepwise analysis (t tests) comparing the mean amplitude obtained in the consistent condition with that of the inconsistent conditions. This mean amplitude was measured in short and successive epochs (i.e., 20 epochs of 25 msec each, from 250 to 750 msec poststimulus onset). This procedure allowed us to identify the precise moments at which the consistency effect appeared.

The data obtained from the stepwise analyses were then combined with the visual inspection of the grand-average difference waveforms of the consistent (CC) and each of the two inconsistent conditions (IC and CI). Together, the analyses showed that the consistency effect

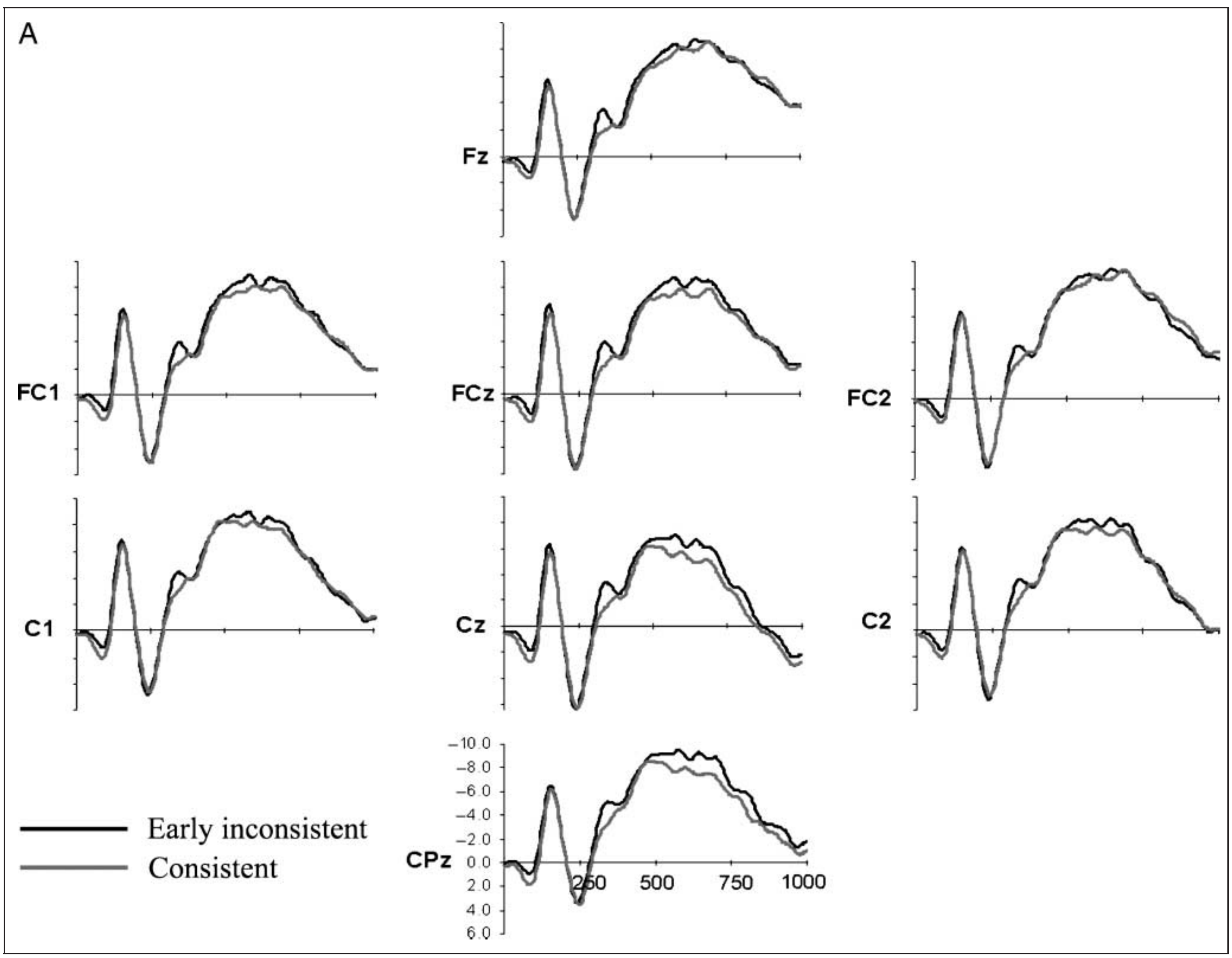

Figure 2. (A) ERPs (mean amplitude in μV) to early inconsistent and consistent words. (B) ERPs (mean amplitude in μV) to late inconsistent and consistent words.

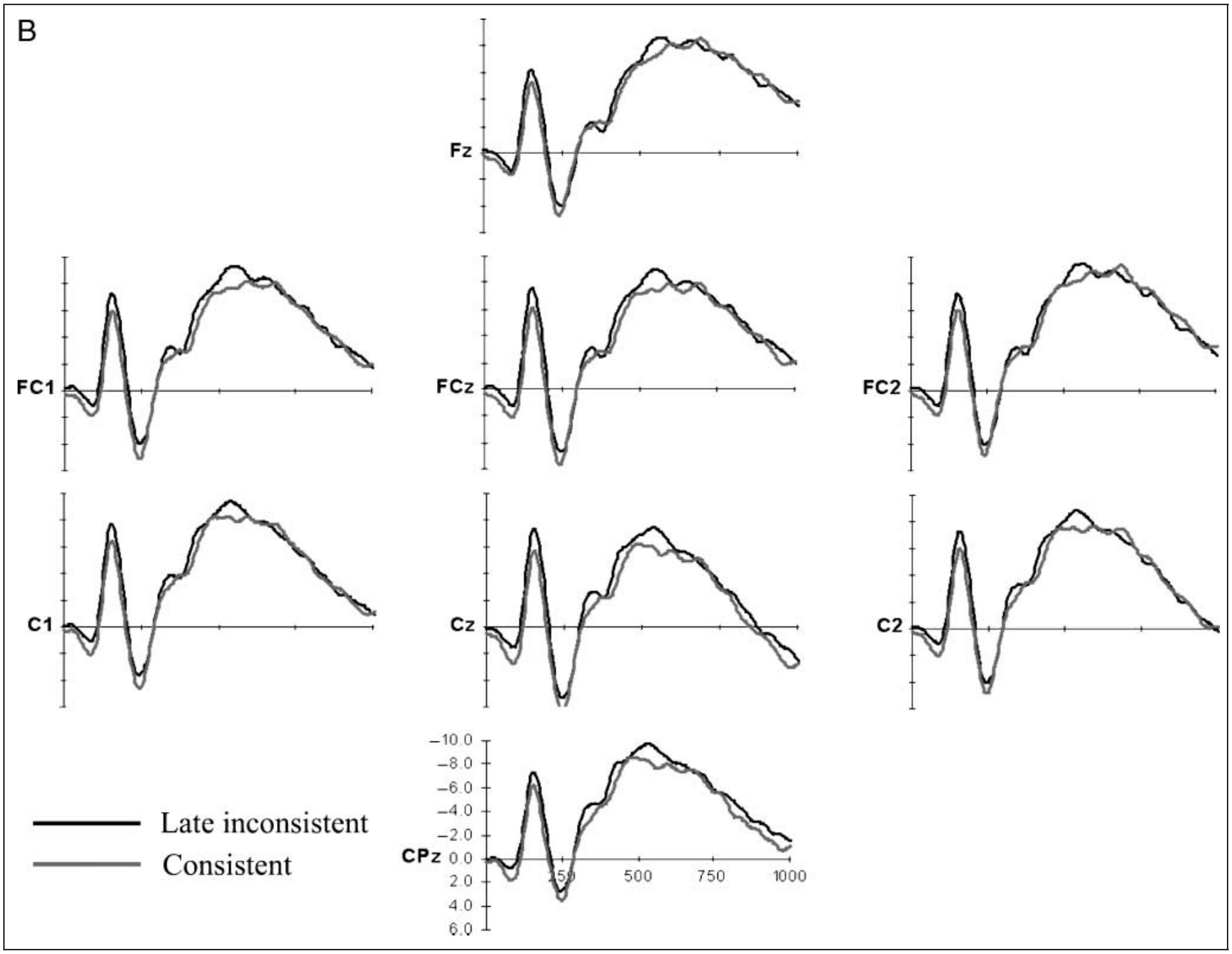

Figure 2. (*continued*)

tended to appear in three time windows (300–350 msec, 400–425 msec, and 525–575 msec), although the size of the effect within each time window varied with the type of comparison (CC vs. IC and CC vs. CI) (see analyses below). However, for both comparisons, the effect seemed to be located over central electrode sites. As shown in Figure 2A and B, this procedure allowed us to select eight adjacent electrodes for which the consistency effect was maximal: Fz, FCz, FC1/FC2, Cz, C1/C2, and CPz. This electrode cluster was used for the following analyses.

Early Inconsistency Effect

Differences in mean amplitudes were assessed by repeated measures analysis of variance (ANOVA), using the Geisser and Greenhouse (1959) correction where appropriate. Consistency (consistent vs. early inconsistent), frequency (low vs. high), and electrodes (8) were treated as within-subject factors. Because ERP waveforms generally vary from one electrode to another, the main effect of this factor which was significant in nearly all analyses is not reported here. As summarized in the top part of Table 1, the main effect of consistency showing a larger negativity to inconsistent than to consistent words was significant only in the 300–350 msec epoch [$F(1, 16) = 6.6, p < .025$], but not in the 400–425 msec ($F < 1$) and the 525–575 msec epochs [$F(1, 16) = 1.38, p > .25$]. Neither the frequency effect nor the Consistency × Frequency interaction was observed in any of the windows (all Fs $\leq$ 1). None of the main factors interacted significantly with electrodes (all Fs $\leq$ 1).

Late Inconsistency Effect

The same analyses as above were performed for the late inconsistency effect. The effect was significant in the last two epochs [400–425 msec: $F(1, 16) = 5.3, p < .05$; 525–575 msec: $F(1, 16) = 7.05, p < .025$] (see bottom of Table 1). As was the case for the early inconsistency effect, the interaction between consistency and frequency was not significant in either epoch [400–425 msec: $F(1, 16) = 1.55, p > .10$; 525–575 msec: $F(1, 16) = 1.10,$

Table 1. Time Course of the Consistency Effect as a Function of the Arrival of the Orthographic Inconsistency at FCz and Eight Electrode Sites

	Epochs (msec)		
	300–350	*400–425*	*525–575*
Early Inconsistent			
Eight electrodes	*	*ns*	*ns*
FCz	*	*ns*	*ns*
Late Inconsistent			
Eight electrodes	*ns*	*	*
FCz	*ns*	*	*

ns: $p > .10$.

*$p \leq .05$.

$p > .25$]. The effect of frequency was significant only in the last epoch [$F(1, 16) = 7.42$, $p < .025$]. None of these factors interacted significantly with electrodes (all Fs ≤ 1).

As concerns the 300–350 msec epoch, the late inconsistency effect was not significant [$F(1, 16) = 2.66$, $p > .10$] but it interacted with electrodes [$F(7, 112) = 3.41$, $p = .025$] and with electrodes and frequency [$F(7, 112) = 2.51$, $p = .056$]. These interactions reflected the fact that the late inconsistency effect in this early time window was only obtained for a single electrode when high-frequency words were presented [CPz: $F(1, 16) = 9.13$, $p < .01$]. The most plausible explanation is that for some of our high-frequency words, orthography could be fully activated long before the end of the word by anticipation.

Taken together, the results obtained for both early and late inconsistency effects clearly suggested that the onset of the effect was time-locked to the arrival of the orthographic inconsistency in a spoken word. This crucial observation was indeed confirmed by a significant interaction between effect type (early vs. late inconsistency[2]) and time window (300–350 vs. 400–425) [$F(1, 16) = 6.37$, $p < .025$]. This interaction is shown in Figure 3.

Analyses of Go/No-go and Frequency Effects

The time course of the orthographic consistency effect can be compared to that of the go/no-go and the frequency effects.[3] If the consistency effect occurs before the frequency effect, this could be taken as evidence that the consistency effect occurs before lexical access is complete. Similarly, if the consistency effect occurs before the go/no-go effect, this would suggest that the consistency effect occurs before the semantic decision about body parts has taken place.

To identify the precise moment at which the frequency and the go/no-go effects emerged, we performed comparisons between high- and low-frequency words and between go and no-go responses in short and successive epochs (i.e., 20 epochs of 25 msec each, from 250 to 750 msec poststimulus onset). For each epoch, two ANOVAs were performed on the mean amplitude of 29 centro-anterior electrodes (CPz, CP1/CP2, CP3/CP4, Cz, C1/C2, C3/C4, C5/C6, FCz, FC1/FC2, FC3/FC4, FC5/FC6, Fz, F1/F2, F3/F4, F5/F6, AFz, AF3/AF4), one with frequency and electrodes as factors and one with trial type (go vs. no-go) and electrodes. The frequency effect corresponded to a broad negativity which was significantly larger for low- than high-frequency words. As shown in the top part of Table 2, the frequency effect emerged around 450 msec poststimulus onset and continued beyond the end of the stimuli ($p \leq .05$ for all epochs).

As concerns the go/no-go effect, we observed a larger negativity to the no-go than to go stimuli. This negativity had similar characteristics as the one observed for the frequency effect. As can be seen in the bottom part of Table 2, the difference on mean amplitude became statistically significant around 450 msec poststimulus onset and continued beyond the end of the stimuli ($p \leq .05$ for all epochs, except in the 475–500 msec epoch where the effect was not significant).

Interestingly, as depicted in Figure 4, the onset of the orthographic consistency effect for both the CC versus IC and CC versus CI comparisons preceded the onset of the frequency and go/no-go effects. We therefore performed a direct comparison between the onset of the consistency effects (early and late inconsistency, separately) and the onset of the frequency and go/no-go effects using ANOVAs that took into account effect type, time window, and electrodes (those used in the analyses of the consistency effect presented above). As

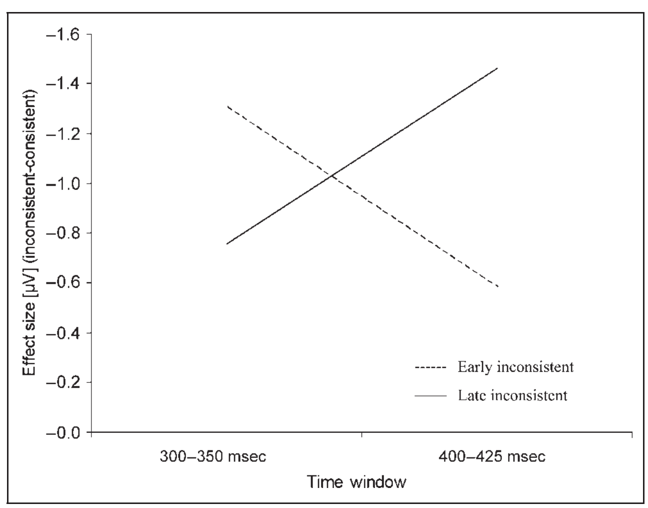

Figure 3. Interaction between effect type (early vs. late inconsistency) and time window (300–350 vs. 400–425).

Table 2. Time Course of the Frequency and the Go/No-go Effects at FCz and 29 Electrode Sites

	Epochs (msec)								
	250–375	*375–400*	*400–425*	*425–450*	*450–475*	*475–500*	*500–525*	*525–550*	*550–750*
Low frequency/High frequency									
29 Electrodes	*ns*	+	*ns*	*ns*	*	*	*	*	***
FCz	*ns*	+	*ns*	*ns*	*	*	*	*	***
No-go/Go									
29 Electrodes	*ns*	*ns*	*ns*	+	*	*ns*	**	**	***
FCz	*ns*	*ns*	+	*	*	*	***	***	***

ns: $p > .10$.

+$p \leq .10$.

*$p \leq .05$.

**$p \leq .01$.

***$p \leq .005$.

summarized in Table 3, there were clear interactions between effect type and time window (except for the first comparison where the interaction just failed to reach significance).

The decomposition of these interactions showed that the frequency and the go/no-go effects were significant only in the 450–750 msec epoch [frequency effect: $F(1, 16) = 15.61$, $p = .001$; go/no-go effect: $F(1, 16) = 22.07$, $p < .0001$], but not in the 300–350 msec [frequency effect: $F(1, 16) = 1.98$, $p > .10$; go/no-go effect: $F < 1$] or the 400–425 msec epoch [frequency effect: $F(1, 16) = 1.07$, $p > .25$; go/no-go effect: $F(1, 16) = 3.25$, $p > .05$]. Together, these results clearly show that the consistency effect occurred before the frequency or go/no-go effects.

DISCUSSION

Although the idea that orthographic information can influence spoken language processing is now widely accepted (e.g., Castro-Caldas et al., 1998; Frith, 1998), researchers still disagree on the locus of the orthographic effects. The main debate is between those who believe that the orthographic information is activated in the course of lexical access and those who believe that orthographic effects are postlexical and/or exclusively strategic (e.g., Cutler et al., 1998). Previous behavioral studies were unable to tease apart these two interpretations because latency and accuracy measures reflect the final outcome of word recognition. Instead, ERPs can be used to track the time course of the orthographic effect, thus allowing us to identify the locus of the effect.

Using ERPs, the present study provides the first demonstration of the existence of an orthographic consistency effect in a rather natural spoken language task, that is, while participants listened to a series of words making semantic decisions. In this situation, orthographic information is clearly not necessary to decide whether a spoken word refers to the human body, and yet inconsistency in the mapping between phonology and orthography seems to affect lexical access and the retrieval of semantic information. This finding provides the strongest evidence available thus far for the claim that orthography influences spoken language processing in a nonstrategic way.

The increased difficulty in lexical access to inconsistent words is reflected in larger negativities to inconsistent than to consistent words. A similar pattern has been found for ERPs to low-frequency words or to words with many neighbors. In both cases, increased difficulty in lexical access resulted in increased N400 amplitudes

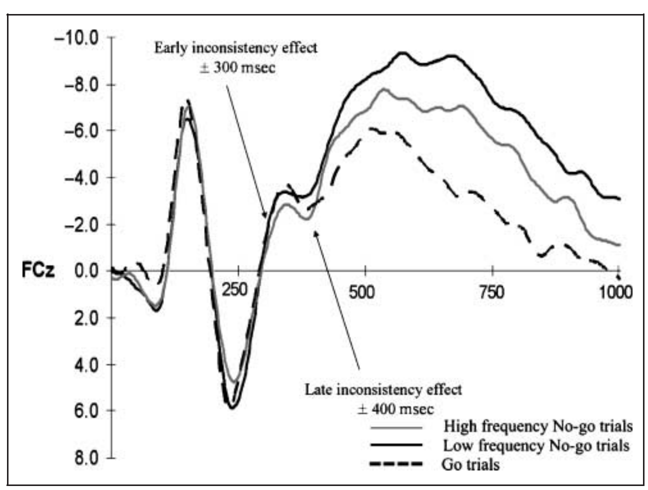

Figure 4. ERPs (mean amplitude in μV) to the go trials as well as low- and high-frequency no-go trials at FCz.

Table 3. Summary of the ANOVAs Showing the Interactions between the Onset of the Consistency Effects and the Onset of the Frequency and Go/No-go Effects

Effect Type	*Time Window (msec)*	*Effect Type × Time Window*
Early inconsistency vs. Frequency	300–350 vs. 450–750	$F(1, 16) = 3.09, p = .098$
Early inconsistency vs. Go/No-go	300–350 vs. 450–750	$F(1, 16) = 29.75, p < .0001$
Late inconsistency vs. Frequency	400–425 vs. 450–750	$F(1, 16) = 9.45, p < .01$
Late inconsistency vs. Go/No-go	400–425 vs. 450–750	$F(1, 16) = 15.81, p = .001$

(Holcomb, Grainger, & O'Rourke, 2002; Rugg, 1990). Note also that Bolger et al. (2007) reported increased activation in fMRI in several brain regions in response to inconsistent compared with consistent words.

An important finding of the present study is the observation that the onset of the orthographic consistency effect was time-locked to the arrival of the inconsistency in a spoken word (see also Perre & Ziegler, 2008). That is, first-syllable inconsistency produced an ERP difference around 300 msec poststimulus onset, whereas second-syllable inconsistency produced an ERP difference later around 400 msec. Most importantly, the onset of the consistency effect occurred before the onset of the frequency or the go/no-go effects, suggesting that the orthography effect is not due to postlexical processes. Instead, these results clearly show that orthographic information is activated early enough to affect the core processes of lexical access.

Our results are consistent with the accumulating data from brain imaging studies (e.g., Bolger et al., 2007; Bitan et al., 2006; Booth et al., 2004; Petersson et al., 2000; Castro-Caldas et al., 1998) showing spelling–sound interactions in written or spoken language processing. Indeed, in phonological tasks (meta-phonological or not), one typically seems to observe activation in brain regions that are involved in orthographic processing. For example, in an auditory lexical decision task, Orfanidou, Marslen-Wilson, and Davis (2006) found an activation of the left posterior fusiform gyrus, which is very close to the fusiform region that has been identified as the *visual word form area* (McCandliss, Cohen, & Dehaene, 2003). Similarly, in phonological rhyme judgment, Booth et al. (2004) found activation both in the fusiform gyrus and in the angular gyrus (see also Bolger et al., 2007).

In sum, the present data, together with the brain imaging results cited above, highlight the important link between reading development and spoken language processing. Because reading development is fundamentally based on setting up connections between orthography and phonology (Ziegler & Goswami, 2006), once reading is acquired, orthographic and phonological representations are intricately linked in a functional network that involves the left fusiform gyrus, the angular gyrus and more anterior language areas. As suggested by Pulvermüller (1999), such a functional network is best described as a Hebbian cell assembly. Partial activation of the cell assembly, such as when a spoken word is presented, will activate the entire network (i.e., ignition of a cell assembly). With reading acquisition, orthographic information becomes part of the cell assembly that links phonology to meaning. As a consequence, orthographic effects are obtained not only in phonological but also in semantic tasks.

APPENDIX 1: CRITICAL STIMULI (NO-GO TRIALS)

Consistent/Consistent		*Consistent/Inconsistent*		*Inconsistent/Consistent*	
High Frequency	*Low Frequency*	*High Frequency*	*Low Frequency*	*High Frequency*	*Low Frequency*
besoin	blocus	bouteille	astuce	aiguille	anchois
bidon	bouilloire	client	bronzage	ambiance	ancrage
brigade	boutade	climat	cachemire	angoisse	anguille
corbeille	chenille	diamant	constat	champagne	autruche
cortège	chevron	dortoir	corsaire	champion	baignade
dialogue	clivage	drapeau	cuistot	chrétien	cerise
dispute	doublage	espèce	diadème	citron	céruse
esclave	escrime	esprit	diarrhée	compagne	châtaigne

APPENDIX 1 (*continued*)

Consistent/Consistent		*Consistent/Inconsistent*		*Inconsistent/Consistent*	
High Frequency	*Low Frequency*	*High Frequency*	*Low Frequency*	*High Frequency*	*Low Frequency*
espoir	esquive	guitare	dragée	comtesse	chômeuse
estime	exode	instinct	escroc	empereur	compresse
fortune	feutrage	journée	fiasco	emploi	cyanure
gardien	givrage	justice	gadget	empreinte	emblème
lumière	granule	lointain	judas	faiblesse	emprise
montagne	gravure	lundi	lutteur	fauteuil	feignante
oubli	junior	marchand	mosquée	janvier	framboise
pelouse	lardon	matelas	muscat	maintien	gâchette
principe	levier	médecin	nectar	maîtresse	hybride
refuge	levure	navire	oursin	maîtrise	impact
remarque	mouchard	outil	ourson	mensonge	osmose
reprise	perdreau	piano	porto	passerelle	paupiette
royaume	retouche	princesse	pruneau	physique	pêcheuse
sagesse	rougeole	printemps	pulsion	rêverie	perruche
salive	rudesse	public	rebond	rêveur	phonème
saveur	sacoche	regret	rugby	sandwich	rôdeuse
savon	savane	tuyau	symptôme	sanglot	sanguine
triomphe	solfège	vestiaire	tartare	sauvage	sauveur
vedette	tornade	vêtement	torsion	seigneur	syncope
victime	vidange	victoire	transfert	serviette	teigneux
vigueur	vigile	vilain	truand	signal	tondeuse
vitesse	vignette	village	slogan	tendresse	voyelle

APPENDIX 2: CHARACTERISTICS OF THE CRITICAL STIMULI (*SD* IN BRACKETS)

	Consistent/Consistent		*Consistent/Inconsistent*		*Inconsistent/Consistent*	
Variables	*High Frequency*	*Low Frequency*	*High Frequency*	*Low Frequency*	*High Frequency*	*Low Frequency*
Consistency ratio first syllable	1 [0]	1 [0]	1 [0]	1 [0]	0.23 [0.1]	0.19 [0.09]
Consistency ratio second syllable	1 [0]	1 [0]	0.18 [0.1]	0.15 [0.06]	1 [0]	1 [0]
Frequency (LEXIQUE)	39.3 [58.5]	1.7 [1.4]	44.7 [43.6]	1.8 [1.2]	25.5 [19.1]	1.5 [1.2]
Frequency (BRULEX)	2224.6 [1362.4]	318.5 [142.9]	7001.2 [1362.4]	103.0 [82.5]	3663.2 [1243.7]	294.3 [76.4]
Nb phonemes	5.5 [0.7]	5.5 [0.5]	5.1 [0.9]	5.3 [0.8]	5.5 [0.6]	5.2 [0.7]
Nb phonological neighbors	1.9 [2.6]	1.9 [2.5]	2.1 [2.0]	2.0 [2.2]	1.5 [1.8]	1.8 [2.1]
Phonological enemies (ratio)	.98 [.06]	.97 [.09]	.94 [.12]	.92 [.13]	.92 [.13]	.93 [.14]
Uniqueness point	5.1 [0.9]	4.8 [0.7]	4.7 [0.9]	5.0 [0.7]	4.8 [1.1]	4.6 [0.6]
Duration (msec)	649.8 [82.7]	648.4 [63.3]	645.9 [109.1]	645.7 [115.2]	650.3 [74.3]	650.2 [75.3]

Acknowledgments

This research was supported by grants from the Belgian *Fonds de la Recherche Scientifique* to C. P. (2007/V3/5/133-A4/5-IB/CAV-6491) and from the *Agence Nationale de la Recherche* (no. JC05_44765) to J. C. Z. We thank two anonymous reviewers for their insightful comments.

Reprint requests should be sent to Johannes C. Ziegler, Laboratoire de Psychologie Cognitive, Pôle 3C, Case D, CNRS and Université de Provence, 3 place Victor Hugo, 13331 Marseille Cedex 3, or via e-mail: Johannes.Ziegler@univ-provence.fr.

Notes

1. The consistency ratio was calculated by dividing the number of disyllabic words sharing both the phonological and orthographic forms of a given syllable at a given position (friends) by the number of all disyllabic words that contain that syllable at the same position (friends and enemies; see Ziegler, Jacobs, & Stone, 1996). The consistency ratio varies between 0 (*totally inconsistent*) and 1 (*totally consistent*), and thus, reflects the degree of orthographic consistency.
2. The early inconsistency effect corresponds to the difference in mean amplitude between the IC and the CC conditions. The late inconsistency effect corresponds to the difference between the CI and the CC conditions.
3. The frequency effect corresponds to the difference in mean amplitude between low-frequency and high-frequency words. The go/no-go effect corresponds to the difference in mean amplitude between no-go and go trials.

REFERENCES

American Clinical Neurophysiology Society. (2006). Guideline 5: Guidelines for standard electrode position nomenclature. *Journal of Clinical Neurophysiology, 23,* 107–110.

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

Bitan, T., Burman, D. D., Lu, D., Cone, N. E., Gitelman, D. R., Mesulam, M. M., et al. (2006). Weaker top–down modulation from the left inferior frontal gyrus in children. *Neuroimage, 33,* 991–998.

Bolger, D. J., Hornickel, J., Cone, N. E., Burman, D. D., & Booth, J. R. (2007). Neural correlates of orthographic and phonological consistency effects in children. *Human Brain Mapping*.

Booth, J. R., Burman, D. D., Meyer, J. R., Gitelman, D. R., Parrish, T. B., & Mesulam, M. M. (2004). Development of brain mechanisms for processing orthographic and phonologic representations. *Journal of Cognitive Neuroscience, 16,* 1234–1249.

Castro-Caldas, A., Petersson, K. M., Reis, A., Stone-Elander, S., & Ingvar, M. (1998). The illiterate brain. Learning to read and write during childhood influences the functional organization of the adult brain. *Brain, 121,* 1053–1063.

Content, A., Mousty, P., & Radeau, M. (1990). Une base de donnees lexicales informatisee pour le francais ecrit et parle [BRULEX: A computerized lexical data base for the French language/BRULEX]. *Annee Psychologique, 90,* 551–566.

Cutler, A., Treiman, R., & Van Ooijen, B. (1998). Orthografik inkoncistensy ephekts in foneme detektion? In *Proceedings of the Fifth International Conference on Spoken Language Processing* (pp. 2783–2786). Sydney, Australia.

Dehaene, S., Jobert, A., Naccache, L., Ciuciu, P., Poline, J. B., Le Bihan, D., et al. (2004). Letter binding and invariant recognition of masked words: Behavioral and neuroimaging evidence. *Psychological Science, 15,* 307–313.

Dehaene, S., Naccache, L., Cohen, L., Bihan, D. L., Mangin, J. F., Poline, J. B., et al. (2001). Cerebral mechanisms of word masking and unconscious repetition priming. *Nature Neuroscience, 4,* 752–758.

Delorme, A., & Makeig, S. (2004). EEGLAB: An open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods, 134,* 9–21.

Donnenwerth-Nolan, S., Tanenhaus, M. K., & Seidenberg, M. S. (1981). Multiple code activation in word recognition: Evidence from rhyme monitoring. *Journal of Experimental Psychology: Human Learning and Memory, 7,* 170–180.

Frith, U. (1998). Literally changing the brain. *Brain, 121,* 1011–1012.

Geisser, S., & Greenhouse, S. (1959). On methods in the analysis of profile data. *Psychometrika, 24,* 95–112.

Grainger, J., & Ziegler, J. C. (2007). Cross-code consistency effects in visual word recognition. In E. L. Grigorenko & A. Naples (Eds.), *Single-word reading: Biological and behavioral perspectives* (pp. 129–157). Mahwah, NJ: Erlbaum.

Holcomb, P. J., & Grainger, J. (2006). On the time course of visual word recognition: An event-related potential investigation using masked repetition priming. *Journal of Cognitive Neuroscience, 18,* 1631–1643.

Holcomb, P. J., Grainger, J., & O'Rourke, T. (2002). An electrophysiological study of the effects of orthographic neighborhood size on printed word perception. *Journal of Cognitive Neuroscience, 14,* 938–950.

McCandliss, B. D., Cohen, L., & Dehaene, S. (2003). The visual word form area: Expertise for reading in the fusiform gyrus. *Trends in Cognitive Sciences, 7,* 293–299.

McPherson, W. B., Ackerman, P. T., & Dykman, R. A. (1997). Auditory and visual rhyme judgements reveal differences and similarities between normal and disabled adolescent readers. *Dyslexia, 3,* 63–77.

Miller, K. M., & Swick, D. (2003). Orthography influences the perception of speech in alexic patients. *Journal of Cognitive Neuroscience, 15,* 981–990.

Morais, J., Cary, L., Alegria, J., & Bertelson, P. (1979). Does awareness of speech as a sequence of phones arise spontaneously? *Cognition, 7,* 323–331.

New, B., Pallier, C., Ferrand, L., & Matos, R. (2001). Une base de données lexicales du français contemporain sur internet: LEXIQUE. *L'Année Psychologique, 101,* 447–462.

Orfanidou, E., Marslen-Wilson, W. D., & Davis, M. H. (2006). Neural response suppression predicts repetition priming of spoken words and pseudowords. *Journal of Cognitive Neuroscience, 18,* 1237–1252.

O'Rourke, T. B., & Holcomb, P. J. (2002). Electrophysiological evidence for the efficiency of spoken word processing. *Biological Psychology, 60,* 121–150.

Pattamadilok, C., Morais, J., Ventura, P., & Kolinsky, R. (2007). The locus of the orthographic consistency effect in auditory word recognition: Further evidence from French. *Language and Cognitive Processes, 22,* 1–27.

Perre, L., & Ziegler, J. C. (2008). On-line activation of orthography in spoken word recognition. *Brain Research, 1188,* 132–138.

Petersson, K. M., Reis, A., Askelöf, S., Castro-Caldas, A., & Ingvar, M. (2000). Language processing modulated by literacy: A network analysis of verbal repetition in literate

and illiterate subjects. *Journal of Cognitive Neuroscience, 12,* 364–382.
Pulvermüller, F. (1999). Words in the brain's language. *Behavioral and Brain Sciences, 22,* 253–336.
Rack, J. P. (1985). Orthographic and phonetic coding in developmental dyslexia. *British Journal of Psychology, 76,* 325–340.
Rugg, M. D. (1990). Event-related brain potentials dissociate repetition effects of high- and low-frequency words. *Memory & Cognition, 18,* 367–379.
Schutter, D. J. L. G., Leitner, C., Kenemans, J. L., & van Honk, J. (2006). Electrophysiological correlates of cortico-subcortical interaction: A cross-frequency spectral EEG analysis. *Clinical Neurophysiology, 117,* 381–387.
Seidenberg, M. S., & Tanenhaus, M. K. (1979). Orthographic effects on rhyme monitoring. *Journal of Experimental Psychology: Human Learning and Memory, 5,* 546–554.
Sereno, S. C., & Rayner, K. (2000). The when and where of reading in the brain [Special Issue: Millennium issue]. *Brain & Cognition, 42,* 78–81.
Van Orden, G. C., & Goldinger, S. D. (1994). Interdependence of form and function in cognitive systems explains perception of printed words. *Journal of Experimental Psychology: Human Perception and Performance, 20,* 1269–1291.
Ventura, P., Morais, J., & Kolinsky, R. (2007). The development of the orthographic consistency effect in speech recognition: From sublexical to lexical involvement. *Cognition, 105,* 547–576.
Ventura, P., Morais, J., Pattamadilok, C., & Kolinsky, R. (2004). The locus of the orthographic consistency effect in auditory word recognition. *Language and Cognitive Processes, 19,* 57–95.
Zecker, S. G. (1991). The orthographic code: Developmental trends in reading-disabled and normally-achieving children. *Annals of Dyslexia, 41,* 178–192.
Zecker, S. G., Tanenhaus, M. K., Alderman, L., & Siqueland, L. (1986). Lateralization of lexical codes in auditory word recognition. *Brain and Language, 29,* 372–389.
Ziegler, J. C., & Ferrand, L. (1998). Orthography shapes the perception of speech: The consistency effect in auditory word recognition. *Psychonomic Bulletin & Review, 5,* 683–689.
Ziegler, J. C., Ferrand, L., & Montant, M. (2004). Visual phonology: The effects of orthographic consistency on different auditory word recognition tasks. *Memory & Cognition, 32,* 732–741.
Ziegler, J. C., & Goswami, U. (2006). Becoming literate in different languages: Similar problems, different solutions. *Developmental Science, 9,* 429–436.
Ziegler, J. C., Jacobs, A., & Stone, G. (1996). Statistical analysis of the bidirectional inconsistency of spelling and sound in French. *Behavior Research Methods, Instruments, & Computers, 28,* 504–515.
Ziegler, J. C., & Muneaux, M. (2007). Orthographic facilitation and phonological inhibition in spoken word recognition: A developmental study. *Psychonomic Bulletin & Review, 14,* 75–80.
Ziegler, J. C., Muneaux, M., & Grainger, J. (2003). Neighborhood effects in auditory word recognition: Phonological competition and orthographic facilitation. *Journal of Memory and Language, 48,* 779–793.