ERROR-RELATED NEGATIVITIES DURING SPELLING JUDGMENTS EXPOSE ORTHOGRAPHIC KNOWLEDGE

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Understanding the role of phonological awareness in reading has been the focus of much psycholinguistic research, but less attention has been paid to understanding knowledge of the spellings that activate phonology. We carried out two experiments using ERPs to expose linguistic processes related to orthographic knowledge during judgments about the spellings of English words. In the first experiment, we confirmed that the error-related negativity (ERN) can be elicited during spelling decisions, and that its magnitude was correlated with behavioral measures of spelling knowledge. In the second experiment, we manipulated the phonology of misspelled stimuli and observed that ERN magnitudes were larger when misspelled words altered the phonology of their correctly spelled counterparts than when they preserved it. This finding has implications for the influence of internal phonological and orthographic representations on error monitoring during reading. In both experiments, ERN effect sizes were correlated with performance on a number of reading-related assessments, including offline spelling ability and vocabulary knowledge, affirming the interdependent nature of reading processes and suggesting the usefulness of ERNs for indexing knowledge of a wide range of reading-related skills.

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PREFACE

I wish to thank Eric Benau for help with stimulus creation and running pilot subjects, Ben Rickles for help in collecting and preprocessing the event-related potential data, and Laura Halderman for guidance on statistical analysis and programming E-Prime software. I thank my academic advisor, Charles Perfetti, for comments on previous versions of this manuscript. Finally, I'd like to thank the members of my master's committee for their insightful comments.

1.0 INTRODUCTION

Over the past three decades of cognitive research on reading processes, the view that phonological activation is essential and automatic for reading in any language or writing system has evolved from a minority opinion to a near-universally accepted conclusion (Perfetti, 2011). "No reading without phonology" has finally been established[1]. "No reading without orthography," meanwhile, is such an obvious statement that cognitive researchers have largely neglected the role of adult orthographic activation in word identification. This oversight should be addressed, given the evidence that orthographic knowledge contributes uniquely to reading ability (Barker, Torgesen, and Wagner, 1992; Cunningham and Stanovich, 1990; Stanovich and West, 1989), and the growing number of studies identifying reading difficulties in individuals with no phonological deficits (Nation, 2005).

The importance of orthographic knowledge for fluent reading ability is consistent with the lexical quality hypothesis, which posits that skilled reading emerges from quality representations of individual words, and that high-quality lexical representations are built on substantial specifications of the three lexical constituents: phonology, orthography, and semantics (Perfetti and Hart, 2001; Perfetti, 2007). An individual who comprehends the spoken /ˈkɜrnl/, for instance, and is acquainted with individuals in the U.S. Army with the rank below that of brigadier general, who nonetheless fails to connect the pronunciation or concept with the orthographic form *colonel* on a page has a low-quality representation of that word, and will be at a disadvantage in comprehending the text it appears in. In alphabetic writing systems, spelling knowledge and orthographic knowledge are closely tied (although not indistinguishable—most of us can read words we cannot spell), and spelling knowledge, as a proxy for orthographic specification, can be used as an indicator of lexical quality, just as vocabulary or decoding skill can indicate lexical quality by acting as windows onto pure semantic and phonological representations. In Experiment 1, we attempt to obtain a measure of lexical quality by using a speeded spelling judgment task to shed light on the complexity of participants' orthographic representations.

Perhaps one reason spelling has been largely overlooked by cognitive psychologists is its entanglement with phonology in alphabetic systems[2]. In a logographic writing system such as Chinese, in which the orthographic form of a word is not decomposable into individual phonemes, phonology and orthography are more obviously independent lexical constituents. In a language such as English, the picture is more complicated. There is no access to the phonology of a word during reading without some knowledge of its spelling, and spelling ability in turn depends to some degree on phonological skills: poor decoding will over time prevent the formation of quality orthographic representations. The link between spelling and phonological knowledge may not be equally strong for all readers, however. Perfetti and Hart (2002) provided quantitative evidence of more robust integration of phonology and orthography in better readers, through a factor analysis of reading data that found orthographic and phonological knowledge loading onto the same factor in skilled readers and onto separate factors in less-skilled readers. Experiment 2 attempts to tease apart the individual contributions of phonological and spelling skills to lexical knowledge by manipulating the phonology of the misspelled words participants are asked to judge.

1.1 THE ERROR-RELATED NEGATIVITY

In both experiments, we record event-related potentials (ERPs) while subjects perform the assigned task. Our focus is on a waveform known as the error-related negativity (ERN), a response-locked, negative-going component generally peaking within 100 ms of a key press that has been associated with error detection in decision-making (Falkenstein, Hohnsbein et al., 1991; Gehring, Goss et al., 1993). Its scalp distribution is frontocentral, and evidence from dipole modeling (Dehaene, Posner, and Tucker, 1994), as well as convergent evidence with nonhuman-primate (Gemba, Sasaki, and Brooks, 1986) and fMRI studies (e.g., Carter et al., 1998) of error-related activity place the source of the ERN in anterior cingulate cortex. Researchers initially suspected that the ERN signaled a mismatch between a given response and the internal representation of an intended response, thus directly reflecting an error-monitoring process in the brain (Falkenstein et al., 1991; Coles, Scheffers, and Holroyd, 2001). More recent evidence suggests the ERN arises from a conflict-monitoring process, which indirectly accomplishes error detection by identifying ongoing conflict between two or more competing responses after one response has been selected (Yeung, Botvinick, and Cohen, 2004; Carter et al., 1998).

The exact mechanism of error detection, be it a mismatch of representations or an accumulation of conflicting information, is of secondary interest in the present study (although we consider both hypotheses in the General Discussion, where we speculate on the unfolding of events leading to our findings). Our aim is simply to use the ERN to expose individuals' levels of certainty or perceived accuracy surrounding a decision about the spelling of a word, and thereby also reveal orthographic knowledge that underpins reading. The amplitude of the ERN has been correlated with offline reports of a subject's perceived inaccuracy in a flanker task (Scheffers and Coles, 2000) and, on correct trials, with the subject's level of certainty in his or her choice in letter and tone discriminations tasks (Pailing and Segalowitz, 2004). (An ERN on correct trials is often termed a correct-related negativity, or CRN, but for simplicity we will refer to both components as an ERN.) We therefore use the amplitude of the ERN, and what we term the "ERN effect"—the difference between the average ERN amplitude on correct and error trials—as an implicit indicator of how certain a participant was about the accuracy of his or her response throughout the experiments.

The majority of studies that have investigated the ERN have used basic perceptual tasks to elicit errors. For example, studies employing Stroop or flanker paradigms are common (e.g., Gehring, Goss et al., 1993; Yeung et al., 2004; Pailing and Segalowitz, 2004; Scheffers and Coles, 2000; Hajcak and Simons, 2002). These tasks are simple enough that errors are few and, when committed, easily recognized by participants. Until recently it was not known if errors committed during the performance of more complex linguistic tasks were subject to the same error-detection mechanism as errors in perception (but see Dehaene et al. (1994) for an early study using a semantic categorization task to produce ERNs). A handful of recent studies using linguistic tasks to elicit the ERN suggest that they are. Two such studies involved the exploration of error monitoring in bilingual populations, and several have used tasks requiring attention to sublexical phonological details to elicit errors.

Masaki et al. (2001) introduced a linguistic element to the Stroop task by asking subjects to name aloud the color of the stimulus being presented, and confirmed that slips of vocalization lead to an ERN. Sebastián-Gallés et al. (2006) demonstrated that even very early Spanish-Catalan bilinguals had high error rates when asked to discriminate between correctly pronounced Catalan words and Catalan words in which the proper vowel was replaced with a similar vowel that does not exist in Spanish; furthermore, the Spanish-dominant bilinguals did not produce an

ERN on error trials, suggesting restrictions on second-language phonological acquisition are established early in life. Ganushchak and Schiller (2006, 2008, 2009) published a series of studies using verbal self-monitoring to produce ERNs. They initially found the typical decrease in ERN amplitude under time pressure in a phoneme-monitoring task that required participants, native Dutch speakers, to determine if a target phoneme was present in the name of the object pictured in a line drawing (Ganushchak and Schiller, 2006). A follow-up study using German-Dutch bilingual participants, however, found that ERN amplitudes actually increased under time pressure in this sample, leading the authors to conclude that native-language interference can increase response conflict (Ganushchak and Schiller, 2009). A third verbal self-monitoring study showed an increase in ERN amplitude when a distractor image that was semantically related to the stimulus preceded the error, suggesting that semantic incongruency can increase conflict during error detection (Ganushchak and Schiller, 2008).

The first researchers to use visually presented lexical stimuli in eliciting the ERN were Horowitz-Kraus and Breznitz (2008), who reported reduced ERN amplitudes for dyslexic readers compared with non-dyslexics after error commission during lexical decisions. They took this finding to suggest that the error-detection process is somehow impaired in individuals with reading difficulties, which could prevent disabled readers from learning from their mistakes. Subsequent studies replicated these results, and showed that ERN amplitudes increased, especially in dyslexic subjects, after working-memory training (Horowitz-Kraus and Breznitz, 2009) and when subjects were asked to read lists of words as compared to sentences (Horowitz-Kraus and Breznitz, 2011).

Spelling judgments are somewhat more complex than lexical decisions, requiring retrieval of a more fine-tuned orthographic representation than is generally necessary to establish whether or not a letter string corresponds to a real word. Put another way, making a spelling decision as opposed to a lexical decision causes an exact spelling to be activated, and introduces a spelling-verification step to the decision-making process that is unnecessary in lexical decisions. (In Experiment 2, we provide a more detailed model that illustrates how the stages of a spelling decision might develop.) Horowitz-Kraus and Breznitz (2008) proposed that the instability of a dyslexic's mental lexicon may interfere with error detection during lexical decisions; it is conceivable that the instability of orthographic representations, even in normal readers, could impair error detection during speeded spelling decisions if the level of orthographic specification necessary to judge a spelling accurately cannot be activated in the allotted time, or simply does not exist. The likelihood of such instability increases as the difficulty of the words being judged increases; a given adult, for example, is more likely to have a complete orthographic specification of *Afro* than he or she is of *aphrodisiac*. Hence, our first goal in the present study is to determine if spelling knowledge is stable enough and sufficiently well specified in adult normal readers to produce an ERN for words that are orthographically somewhat complex.

1.2 INDIVIDUAL DIFFERENCES IN SPELLNIG AND READING

Bearing in mind that ERN amplitudes likely index certainty in one's choice and/or awareness of its accuracy, in the present study we are on the lookout for associations between ERN amplitude and online spelling performance, with the goal of establishing the ERN during reading-related tasks as an implicit indicator of lexical knowledge. We examine also the relationship between ERN amplitudes during spelling decisions and performance on a broader range of reading-related measures. If spelling knowledge is indeed better integrated with other components of lexical knowledge in skilled than less-skilled comprehenders, we expect to see correlations between ERN magnitude and measures of, for example, offline spelling ability, vocabulary knowledge, and reading comprehension skill. Andrews and colleagues (Andrews and Lo, 2011; Andrews and Hersch, 2010) have used masked priming paradigms to demonstrate that, contrary to the "uniformity assumption" underlying much of the psycholinguistic research on reading skill, individual differences in reading-related skills, including vocabulary, spelling, and reading speed, exist amongst samples of skilled readers. Inconsistent findings regarding the inhibitory or facilitatory effects of backwards-masked primes on target word reading are elucidated when spelling ability is controlled for: within a sample of skilled readers, target identification is facilitated by priming in poorer spellers and inhibited by priming in better spellers (Andrews and Lo, 2011; Andrews and Hersch, 2010). This pattern of results is consistent with the lexical quality hypothesis, which contends that fully specified orthographic representations that overlap perfectly with input stimuli are activated rapidly, with minimal activation of orthographic neighbors. In poorer spellers, the quality of the orthographic representation for a given word is likely to be lower than that in a better speller, and a prime likely to activate more orthographic neighbors, including the target.

2.0 PRELIMINARY NORMING STUDY

We planned to carry out two experiments in which stimuli consisted of a list of correctly spelled English words, or targets, and a list of misspelled counterparts, or foils. To efficiently and cost-effectively evaluate our experimental stimuli we employed the Amazon Mechanical Turk system (AMT; www.mturk.com), an online crowdsourcing tool in which individuals agree to perform simple tasks for small amounts of money. AMT has been shown in numerous studies to be a useful tool for collecting natural language data (e.g., Snow, O'Connor, Jurafsky, &, Ng, 2008; Munro, Bethard, Kuperman, Lai, Melnick, Potts, et al., 2010; Nikolova, Boyd-Graber, Fellbaum, & Cook, 2009; Parent & Eskenazi, 2010).

In advance of the first of the experiments we posted two tasks on AMT as "requesters". The first task was intended to ensure that participants could recognize foil stimuli as the misspellings they were intended to be. Each foil on our list of potential stimuli was presented to five AMT "workers". Each worker was paid $0.01 to produce the correctly spelled target of the given foil. For example, all five workers who evaluated the foil *vacotion* provided the intended target, *vacation*. Had we not subjected our stimuli to this norming process, we might have presumed that *vacotion*, to use the previous example, was interpreted as a misspelling of *vocation* a certain percentage of the time. New foils were normed in this manner in preparation for Experiment 2 to replace stimuli we chose to eliminate after completing Experiment 1. The second task was designed to prepare an independent variable, phonology preservation, which was eventually included in Experiment 2. For this task, each potential foil (e.g., *vacotion*) was presented to 10 AMT workers, who were paid $0.01 each to judge the degree to which the foil and its intended target were pronounced the same. They were given three options: *about the same*, *not the same*, or *can't pronounce*. In the case of *vacotion*, one worker chose *about the same*, one worker chose *can't pronounce*, and the remaining eight workers judged its pronunciation to be *not the same* as that of its target. Workers were urged to concentrate on the word's pronunciation and not its appearance when making their decisions, and to select the third option, *can't pronounce*, only "if you really have no idea whether the two words sound the same."

In neither task did we place a limit on the number of foils each individual worker could evaluate. How we used the data obtained during this process is described in the Methods sections of the respective experiments, below.

3.0 EXPERIMENT 1

The purpose of Experiment 1 was to determine whether the ERN could be elicited in a spelling judgment task and, if so, to compare electrophysiological and behavioral data to understand what ERNs reveal about the quality of orthographic representations. We were also interested in establishing correlations of ERN amplitudes with offline measures of individual differences in reading and spelling skill.

3.1 METHODS

3.1.1 Participants.

Fifteen (12 female) University of Pittsburgh undergraduates who had previously completed a variety of reading-related tasks were selected to participate in the study. To ensure that participants would be reasonably good spellers, only students who had achieved a hit rate of 85 percent or higher on a task which involved identifying the correctly spelled words on a 140-item checklist were invited to participate. All were right-handed, native speakers of English with normal or corrected-to-normal vision who had never received a diagnosis of a reading disorder. Participants received financial compensation for their participation.

3.1.1.1 Reading Assessment Measures. Although all participants had achieved a hit rate of 85 percent or higher on a previous spelling assessment, their performance in other areas of the reading skills assessment battery varied widely. Table 1 contains the means, standard deviations, and ranges of relevant reading skills outcomes for our sample. Spelling skills and phonological awareness were assessed using the Lexical Knowledge Battery developed by Perfetti and Hart (2001), adapted from Olson et al. (1989). Reading comprehension and vocabulary knowledge were assessed using the Nelson-Denny Reading Test (Brown, Bennett, and Hanna, 1981), and nonverbal intelligence was assessed using Raven's Standard Progressive Matrices (Raven, 1960). The composite scores reported for the Nelson-Denny tests and Raven's matrices were computed using the following formula for each subject: (number correct) – [(number incorrect and unanswered)/(number choices)]. Composite scores are informative because accuracy scores for those tests represent the percentage of attempted items that an individual answered correctly, and do not take into account that the number of items attempted by different individuals varies greatly.

Table 1. Descriptive Statistics for Selected Individual-Differences Variables in Experiment 1

Table 1

Descriptive Statistics for Selected Individual-Differences Variables in Experiment 1

Reading-Related Skill	Measure	Min	Max	Mean	Std. Dev.
Spelling ability	d′	1.86	3.02	2.41	0.31
	% Accuracy	86.00	100.00	95.59	3.72
Reading comprehension	Composite score	7.20	30.00	20.88	6.88
	% Accuracy	62.00	94.00	82.93	9.69
Vocabulary knowledge	Composite score	7.60	94.00	53.28	21.14
	% Accuracy	50.00	100.00	85.00	12.05
Nonverbal intelligence	Composite score	-1.13	14.63	6.98	4.95
	% Accuracy	1.00	88.00	47.20	26.12
Phonological awareness	% Accuracy	42.00	100.00	80.64	19.64

N = 15 for all variables.

3.1.2 Materials.

Stimuli lists included English target words of between five and ten letters. A foil (e.g., *hurricene*) was created for each target (e.g., *hurricane*), according to the following rules: (1) The foil must represent a plausible misspelling or typographical error of the target, and contain no letter strings illegal in English; (2) The foil must not be a homophone of another English word; (3) Letter changes must be restricted to a single syllable; (4) The foil must contain the same number of syllables as the target; (5) The foil must be no more than one letter longer or shorter than the target; (6) The foil must be recognized as a misspelling of its intended target by a predetermined number of AMT workers during the preliminary norming process. If more than one out of five workers, when presented with a foil and asked to produce the word of which it was a misspelling, provided the wrong target, the foil was removed from the list of stimuli. Moreover, if more than two out of five workers provided the intended target but did not spell it correctly, the foil was removed. Eight hundred thirty-three stimulus pairs remained after this process. No particular type of word or misspelling was targeted, because we had no *a priori* hypotheses about the relationship between the error detection mechanism and specific orthographic patterns or strings. The extent to which foils shared phonological properties with their target spellings was not systematically controlled in Experiment 1.

The 833 targets and corresponding 833 foils were organized into two lists: List A contained 414 targets and 419 foils; List B contained 419 targets and 414 foils. (The number of targets and foils in the respective lists became slightly uneven during programming of the presentation software.) A target never appeared on the same list as its foil. Statistics were retrieved from the orthographic wordform database of the Medical College of Wisconsin (Medler and Binder, 2005) to balance the two lists on word length, word frequency, orthographic neighborhood frequency, and constrained bigram frequency. Half of the participants performed the experiment using List A and half using List B, so that the correctly spelled and misspelled versions of the words were viewed an equal number of times across participants. The complete list of Experiment 1 stimuli is in Appendix A.

3.1.3 Procedure.

Participants were seated in front of a Lenova computer monitor with their chin resting in a restraint to minimize head movements. Stimuli were presented at the center of the screen in a random order, using E-Prime (Psychological Software Tools, Pittsburgh, PA) software. Subjects were instructed to hit the key corresponding to *Yes* on the keyboard in front of them if the word they saw was spelled correctly and the key corresponding to *No* if it was spelled incorrectly, and were informed that half of the words would be misspelled. Each trial began with a white fixation cross appearing in the center of a black screen, which was replaced after 500 ms by the stimulus, also in white. The stimulus remained onscreen for up to 350 ms and was followed by an empty black screen for 1150 ms; participants could make their selection (*Yes* or *No*) at any time during this 1500-ms interval, at which point a randomized (150 ms to 400 ms) inter-stimulus interval was initiated. If subjects failed to hit a key within 1500 ms, a “Too late!” message appeared in red.

A 20-trial practice block was administered to familiarize participants with the procedure. Subsequently, participants received feedback (black text on a white screen) after every 20 trials; this feedback alternated between providing accuracy information for the round immediately prior to the feedback, and providing accuracy information for the prior round as well as the current overall accuracy percentage. Subjects were offered a monetary incentive to perform both quickly and accurately: In addition to a guaranteed $12.00, subjects could earn a $5.00 bonus for responding within 1500 ms over 98 percent of the time (i.e., in 830 out of 840 trials). All 15 participants earned this bonus. Another ten cents was awarded for every accuracy percentage point of 60 or above. In the end, all participants were paid between $23.00 and $27.00. The incentive to respond quickly was meant to ensure that subjects occasionally committed errors; the incentive for accuracy was meant to ensure subjects were invested in the outcome of their performance, so that ERNs would be attributable to the quality of internal orthographic representations and not to levels of motivation.

3.1.4 ERP Data Acquisition and Preprocessing.

Participants were fitted with a Geodesic Sensor Net with a 128 Ag/AgCl electrode array and data were recorded and preprocessed using associated NetStation acquisition software (Electrical Geodesics, Inc., Eugene, OR). Scalp potentials were recorded with a sampling rate of 250 Hz and a hardware bandpass filter of 0.1 to 200 Hz, with impedences generally kept below a threshold of 40 kΩ.

Offline, trials were segmented into 700-ms epochs, starting 200 ms before response onset. Segmented data were digitally filtered with a 30-Hz lowpass filter. After bad channels were removed from the recordings and replaced via interpolation of data from surrounding channels, the data were re-referenced to the average of the recording sites. Finally, the ERP segments were corrected relative to a 125-ms baseline ending 75 ms before the response. Electrodes used in statistical analyses correspond to the international 10-20 system electrode FCz (electrode 6) and a cluster of six electrodes surrounding FCz (Figure 1). Data from this cluster was averaged as one electrode for analyses.

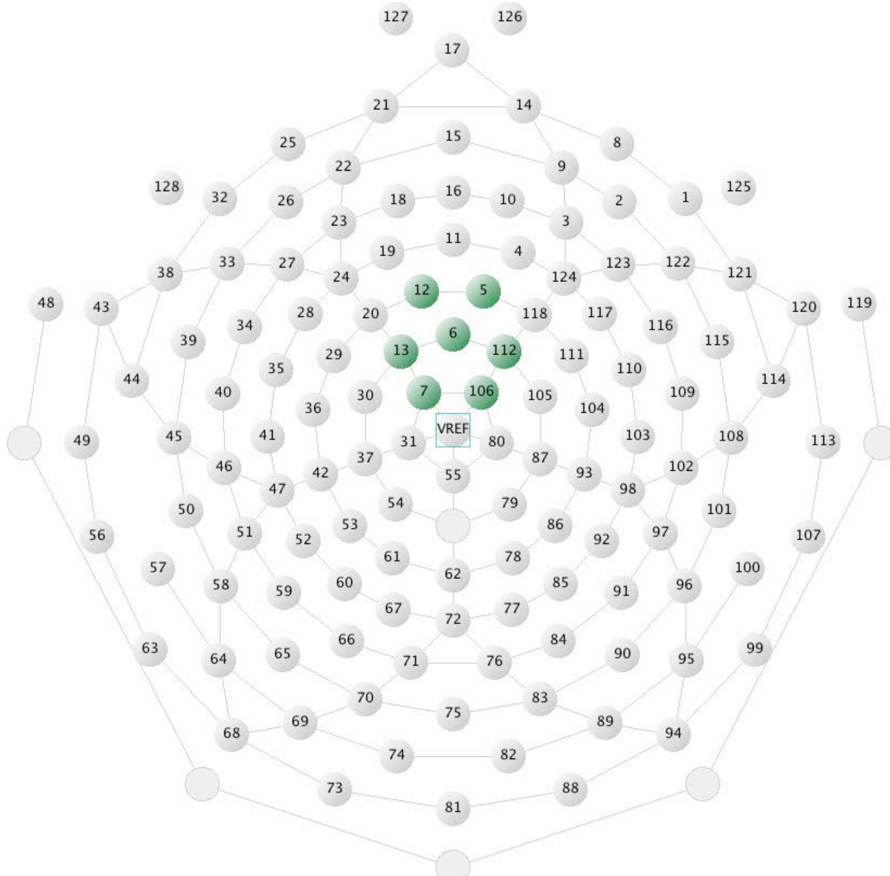

Figure 1. The arrangement of electrodes on a 128-channel Geodesic Sensor Net. The cluster of electrodes used in analyses is highlighted.

3.2 RESULTS

The four possible trial outcomes in this experiment are given in Table 2. For the purposes of this study, we were interested in participants' behavioral performance and ERP record for trials leading to each outcome.

Table 2. Possible Trial Outcomes in Experiment 1

Table 2
Possible Trial Outcomes in Experiment 1

		Response	
		Yes	No
Stimulus Type	Target	*hurricane* HIT	*hurricane* MISS
	Foil	*hurricene* FALSE ALARM	*hurricene* CORRECT REJECTION

3.2.1 Behavioral Data.

3.2.1.1 Accuracy. Table 3 contains the means, standard deviations, and ranges of the behavioral outcomes for Experiment 1. The average d′ of 2.05, as well as a d′ range that does not extend below 1.15, indicate that overall accuracy on the task was high. In an analysis of participants' accuracy data, a paired-samples *t*-test indicated a significant accuracy difference for targets and foils. Participants were more accurate on target trials (M = 88.95) than on foil trials (M = 77.10), $t(14) = 5.86$, $p < .001$.

Table 3. Descriptive Statistics for the Behavioral Outcome Measures in Experiment 1

Table 3
Descriptive Statistics for the Behavioral Outcome Measures in Experiment 1

Behavioral measure	Min	Max	Mean	Std. Dev.
Reaction Time (ms)	516.93	981.88	726.17	127.32
Overall Accuracy (%)	71.55	92.56	83.02	6.07
d′	1.15	2.91	2.05	0.50

N=15. Note that only correct trials were considered in reaction time analyses.

3.2.1.2 Reaction Times. We performed two *t*-tests on mean reaction time (RT) data to address two specific questions: first, whether, on trials when subjects responded *Yes*, RTs differed depending on the trial outcome (i.e., hits versus false alarms [FAs]), and second, whether, on correct trials, RTs differed depending on the correctness of the stimulus spelling (i.e., hits versus correct rejections [CRs]). In our analysis of the class of *Yes* responses, a paired-samples *t*-test indicated a significant difference between the decision times for hits (M = 697.82 ms) versus FAs, (M = 748.52 ms), $t(14) = -4.75$, $p < .001$. In our analysis of the class of correct responses, a second *t*-test indicated a significant difference between the decision times for hits (M = 697.82 ms) versus correct rejections (CRs), (M = 759.32 ms), $t(14) = -8.74$, $p < .001$. In both cases, participants were faster to respond to correctly spelled targets than to incorrectly spelled foils (Table 3).

3.2.2 ERP Data.

The grand average of the Experiment 1 data reveals a sharp negative deflection at electrode 6 and the surrounding cluster peaking about 25 ms after the response for all trial types (Figure 2), with the magnitude of the negativity for error trials observably greater than that of the negativity for correct trials. An adaptive mean amplitude (50 ms before and after the peak negativity for each participant in a window beginning 25 ms pre-response and ending 75 ms post-response) for the electrode cluster shown in Figure 1 was used for statistical extraction.

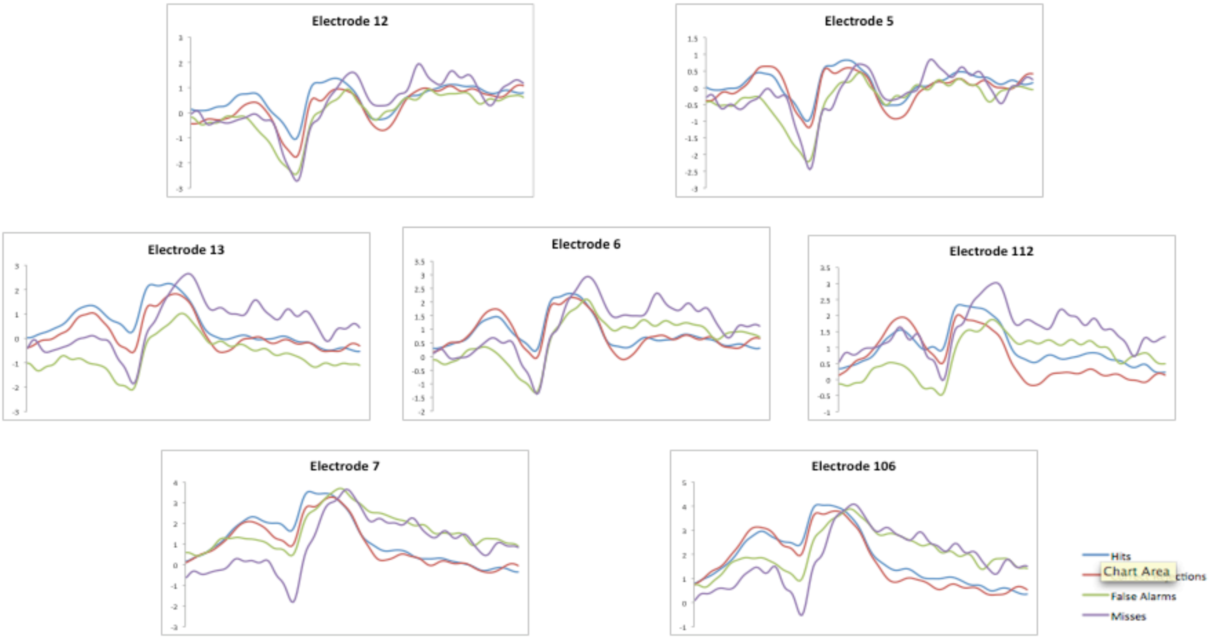

Figure 2. The grand average of EEG activity surrounding the response for each electrode in our cluster of interest for Experiment 1. Note that positive voltages are plotted upwards and negative voltages are plotted downwards throughout the present study.

A 2 x 2 ANOVA of correctness (correct, incorrect) by stimulus type (target, foil) indicated a main effect of correctness, $F(1, 14) = 5.65$, $p < .05$, in which correct trials were more positive than incorrect trials (Figure 3). Neither the main effect of stimulus type, $F(1, 14) < 1$, nor the correctness-by-stimulus type interaction, $F(1, 14) < 1$, was significant. In fact, the mean amplitudes of target and foil stimuli for incorrect trials are coincidentally identical at -0.58 μv when the values are rounded to two decimal places, although the range of the standard error for incorrect foils was narrower than that for incorrect targets.

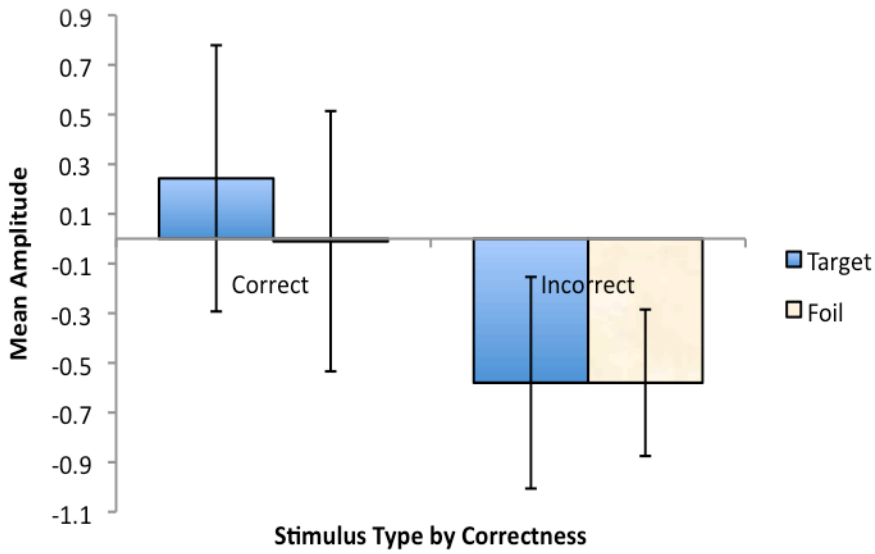

Figure 3. Mean amplitude of correct and incorrect target and foil trials for Experiment 1.

3.2.3 Individual Differences.

To measure the magnitude of the ERN (i.e., the ERN effect), the mean amplitude for error trials (misses and FAs) was subtracted from the mean amplitude for correct trials (hits and CRs) for each participant. D-prime (d′) was used as a measure of accuracy, i.e., discrimination between targets and foils. A correlational analysis of the ERN effect and d′ values indicated an $r = 0.56$, $p < .05$, indicating that the participants who were best able to discriminate targets from foils also showed the greatest difference in the amplitude of the ERN between trials on which they were correct and trials on which they were incorrect. Moreover, the ERN effect correlated significantly with individual difference measures including d′ in the offline spelling assessment ($r = 0.88$, $p < .001$), accuracy in the reading comprehension assessment ($r = 0.55$, $p < .05$) and the vocabulary composite score ($r = 0.62$, $p < .05$).

3.3 DISCUSSION

The objective of Experiment 1 was to determine whether ERNs could be elicited from a spelling judgment task using stimuli of moderate orthographic complexity. The results indicate that, in our sample comprising competent adult spellers with incentives to be correct, they are. The correlations between in-task d′ and ERN magnitude shows that ERNs are an implicit indicator of word knowledge: ERN effect sizes index the orthographic knowledge that is used in the task. Furthermore, the correlations of ERN effect size with spelling ability, reading comprehension and vocabulary knowledge suggest that an ERN elicited during spelling decisions is reflective of skill differences in a broader range of reading-related measures, and serve as a reminder of the interdependence of lexical and comprehension skills in adult populations in general. The remarkably high correlation—0.88—of ERN magnitude with offline spelling performance suggests that the ERN obtained during spelling decisions is particularly reflective of an individual's spelling-specific lexical knowledge.

In summary, Experiment 1 extends the range of understanding of interpretations of the ERN in the linguistic domain. We have shown that the ERN can be elicited during a spelling task and is strongly associated with measures of offline spelling knowledge. Experiment 2 builds on these outcomes to address the components of lexical knowledge that are exposed in spelling error detection.

4.0 EXPERIMENT 2

The purpose of Experiment 2 was to examine the lexical sources of the error signal or signals produced during a spelling decision that are reflected in the ERN. Two sources of such signals in word reading are the word's orthography and the phonological representation the orthography activates. Participants in a spelling judgment task receive information from both of these sources in the process of making a decision. Figure 4 illustrates how orthographic and phonological information from the stimulus is predicted to interact with a participant's selected response in creating an ERN. If both the orthography and the phonology activated by it are aligned perfectly with an individual's high-quality representation of a given word, then there are two input sources in support of a *Yes* decision. This is the case when, for example, *hurricane* is what is presented and *hurricane* is what is represented (Figure 4a). Alternatively, if neither orthography nor phonology is an exact match with its respective internal representation—e.g., *hurricene* is what is presented and *hurricane* is what is represented—then there are two separate sources in support of a *No* decision. Presumably, the error signal issued should an individual select *Yes*, indicating that *hurricene* is spelled correctly, on such a trial would be very strong, and create an equally strong ERN. Conversely, a *No* response in this case would result in a reduced error signal and a reduced ERN (Figure 4c). But what of a case in which one input source (orthography) is at odds with an individual's internal representation, while a second source (phonology) coincides with it? Presented with *hurricain*, the brain will have conflicting evidence for the correct *No* decision, and an error on this trial will create a weakened ERN compared with the ERN produced on an error trial in which both orthography and phonology supported a *No* decision (Figure 4b). (Note that *hurricain* is used here as an example only: because each target had only one foil, either phonology-preserving or phonology-altering, there were not two misspellings of "hurricane" included in our stimuli).

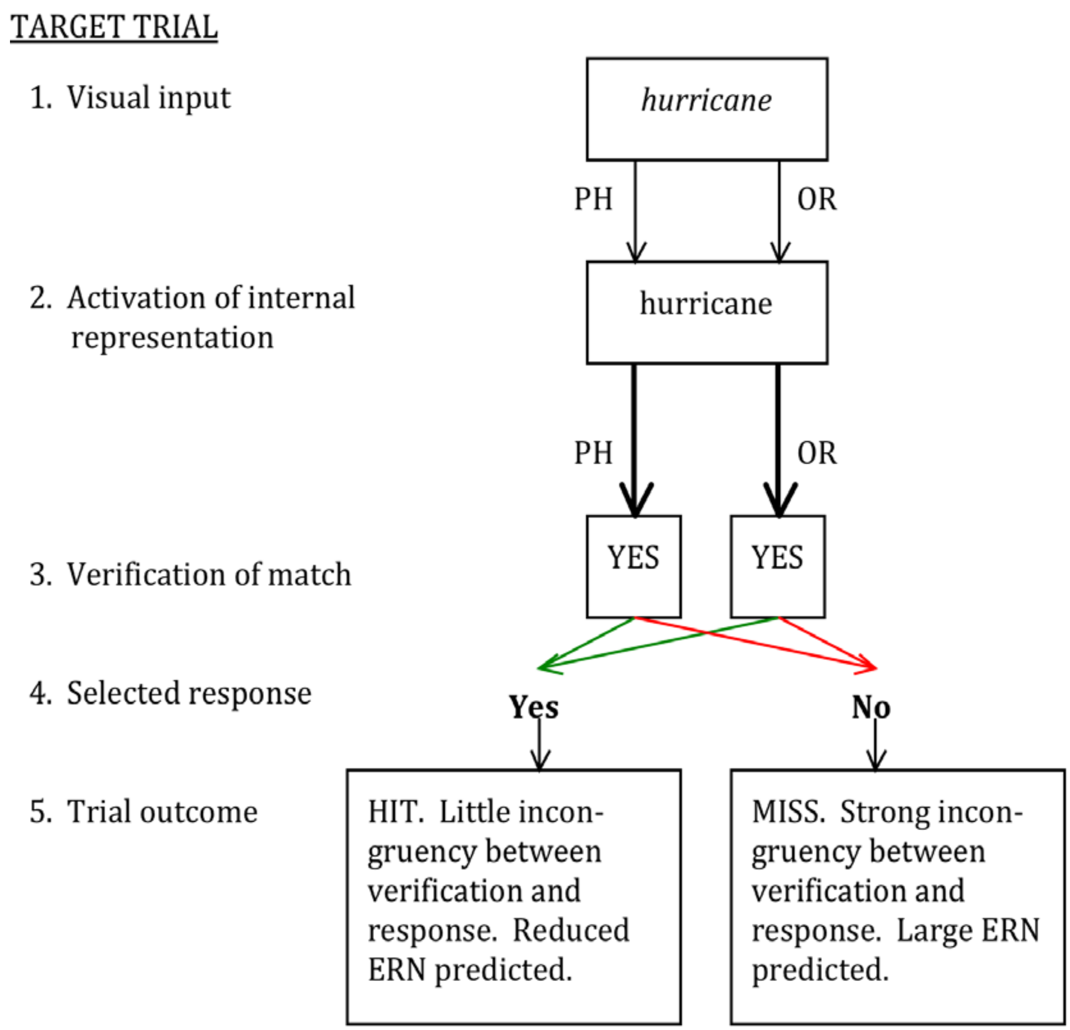

Figure 4a. Two-signal verification model of spelling decisions. When the input stimulus is correctly spelled, both phonology and orthography overlap with the representation and a match is verified. A *Yes* response will create a reduced ERN and a *No* response will create a large ERN. PH = phonological signal; OR = orthographic signal;

FApp = False Alarm, phonology preserving; FApa = False Alarm, phonology altering; CRpp = Correct Rejection, phonology preserving; CRpa = Correct Rejection, phonology altering.

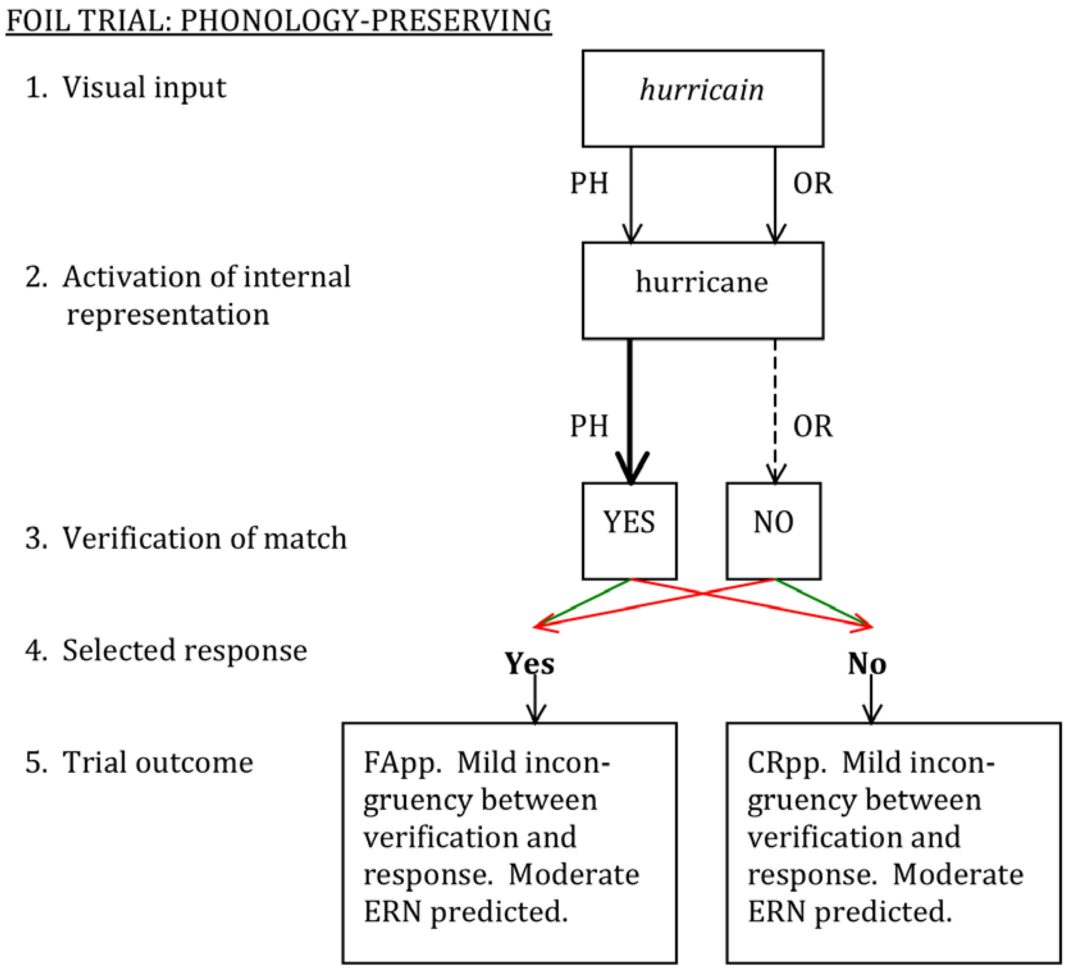

Figure 4b. When the input stimulus is incorrectly spelled but preserves the phonology of the correct spelling, the representation will overlap with the phonology but not with the orthography of the stimulus. These mixed signals will lead to a moderate ERN in the case of either a *Yes* or *No* response.

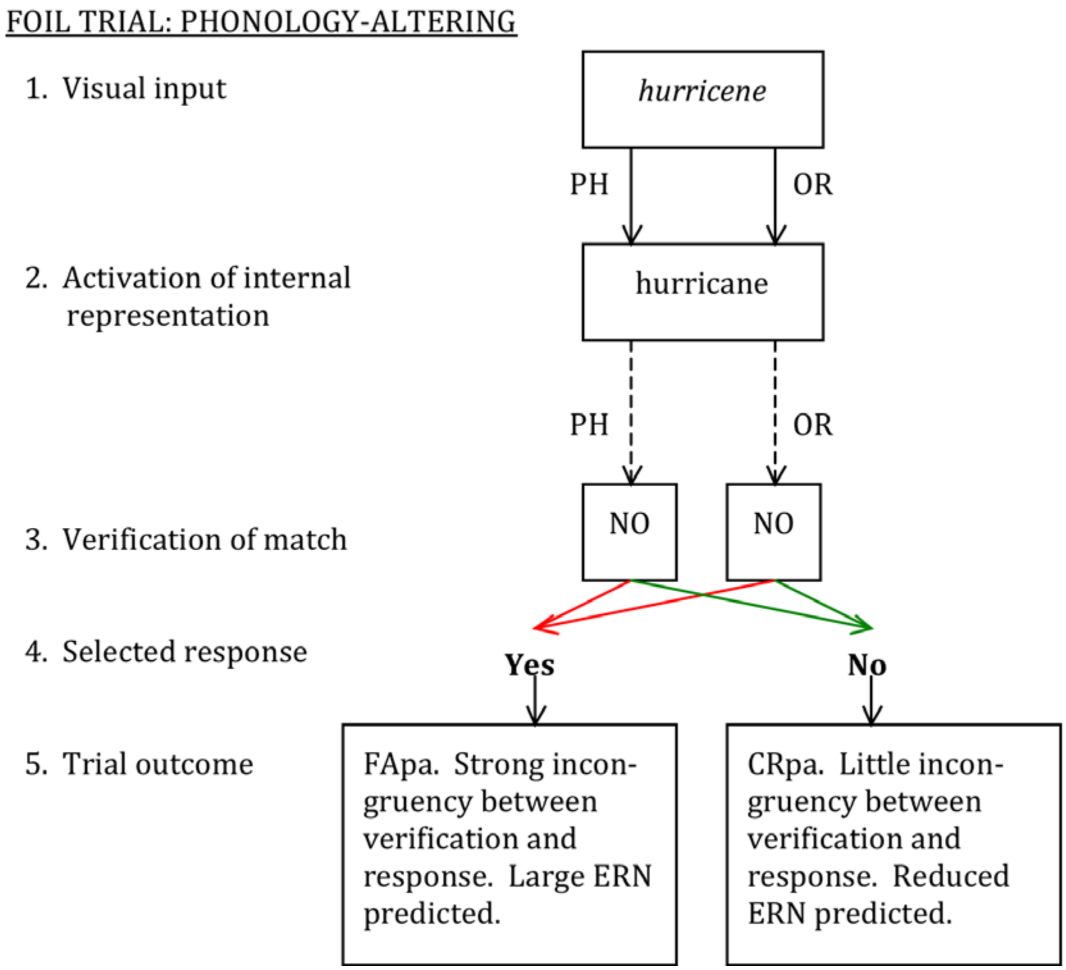

Figure 4c. When the input stimulus is incorrectly spelled and does not preserve the phonology of the correct spelling, neither phonology nor phonology overlap with the representation and a match is not verified. A *Yes* response will create a strong ERN and a *No* response will create a reduced ERN.

Figure 4. Two-signal verification model of spelling decisions.

This model of spelling decisions is not unlike Van Orden's (1987) proposed verification process for semantic categorization tasks, in which a letter string is presumed to activate a phonological representation, which in turn activates the meaning or meanings associated with that phonology. In the subsequent verification stage, the spelling associated with each activated meaning is accessed and compared with the presented stimulus. Because false candidates can be activated if their phonological form overlaps with that of the target, this process can lead to the miscategorization of homophones, e.g., *rows* being tagged as a flower. In both our model and Van Orden's, individuals must verify that a stored orthographic representation matches the orthography of an input stimulus—i.e., a spelling check is required to prevent an error. The trigger for the activation of the stored representation in a semantic categorization task versus a spelling judgment task differs, however: in semantic categorization, an associated meaning activates the orthographic representation, whereas in a spelling decision, the internal representation is activated by the input orthography itself. It is the degree of overlap between the internal and external representations in a spelling decision that determines the strength of ERN.

In Experiment 2, the phonology of our misspellings was manipulated in order to evaluate this model, bearing in mind that our predictions depend on the assumption that phonology is activated before a spelling decision is reached. Previous research has shown that phonology is activated during word reading even when it is entirely superfluous for word identification (e.g., Perfetti et al., 2005). Less clear is whether it is activated early enough during word reading when the focus is on spelling verification to affect the decision process. Whether or not the magnitude of the ERN is affected by phonological manipulations provides information on the speed and order in which the factors leading to word identification come online.

4.1 METHODS

4.1.1 Participants.

A new sample of 27 (17 female) participants who had not participated in Experiment 1 was selected to take part in the experiment. This group was restricted to individuals who had achieved a hit rate of 90 percent or higher on the earlier spelling assessment, but otherwise met the same criteria established for Experiment 1. Data from two female participants were excluded from analysis because of excessive EEG artifact in their recordings. Data from one male participant were excluded from analysis because of equipment malfunction during recording. Table 4 contains the means, standard deviations, and ranges of relevant reading skills outcomes for our sample.

Table 4. Descriptive Statistics for Selected Individual-Differences Variables in Experiment 2

Table 4

Descriptive Statistics for Selected Individual-Differences Variables in Experiment 2

Reading-Related Skill	Measure	Min	Max	Mean	Std. Dev.
Spelling ability	d′	1.72	3.26	2.22	0.37
	% Accuracy	90.00	99.00	92.47	2.24
Reading comprehension	Composite score	0.00	33.60	21.40	7.42
	% Accuracy	68.00	94.00	81.35	7.24
Vocabulary knowledge	Composite score	6.40	95.20	49.09	19.42
	% Accuracy	58.00	96.00	83.33	10.61
Nonverbal intelligence	Composite score	-2.25	12.38	5.86	4.55
	% Accuracy	00.00	85.00	43.79	26.37
Phonological awareness	% Accuracy	27.00	98.00	80.03	16.86

N=24 for all variables except phonological awareness. In that case, N=23 because phonological awareness data were not available for one participant. The tests used to assess reading-related skills are the same as in Experiment 1.

4.1.2 Materials.

The following modifications were made to the Experiment 1 stimuli for Experiment 2: (1) Targets and foils of 10 letters were replaced with stimuli of between five and nine letters to better ensure that participants would be able to perceive the full string without an eye movement in the allotted presentation time; (2) Stimuli that led to a disproportionate number of errors in Experiment 1 were replaced with targets and foils the experimenters deemed less difficult; (3) The foils were manipulated (in accordance with the previously delineated rules) so that half suggested the pronunciation of the target (i.e., preserved phonology) and half suggested a different pronunciation (i.e., altered phonology). Phonology preservation was determined during preliminary norming by AMT workers, who were presented with a foil and asked whether its pronunciation and that of its correctly spelled counterpart were *about the same* or *not the same*; they were given a third option, *can't pronounce*, for foils which they either could not pronounce or whose target they could not identify. Foils for which more than one out of ten workers chose the *can't pronounce* option were eliminated. Foils for which more than five out of ten workers chose *about the same* were tagged as "phonology-preserving". Examples of phonology-preserving foils include *floride* (target *fluoride*), *orenge* (target *orange*), and *usualy* (target *usually*). Foils for which more than five out of ten workers chose *not the same* were tagged as "phonology-altering". Examples of phonology-altering foils include *hurricene* (target *hurricane*), *juingle* (target *jungle*), and *vacotion* (target *vacation*). The 36 foils for which no option received a majority of votes were tagged as "even splits" and were excluded from later analyses in which phonology preservation was included as a variable.

Eight hundred thirty-seven stimulus pairs remained after this process, with 741 of the Experiment 1 stimuli ultimately retained. As in Experiment 1, the targets and foils were organized into two lists: List A contained 418 targets and 419 foils (203 phonology-preserving, 198 phonology-altering, and 18 even splits); List B contained 419 targets and 418 foils (202 phonology-preserving, 198 phonology-altering, and 18 even splits). (There are five more phonology-preserving than phonology-altering foils because AMT workers were slightly biased toward the *about the same* response, and many stimuli we had expected to be tagged phonology-altering were not.) A target never appeared on the same list as its foil, and there was only one foil, either phonology-altering or phonology-preserving, for each target. The two lists were again balanced to control for word length, word frequency, orthographic neighborhood frequency, and constrained bigram frequency. Half of the participants performed the experiment using List A and half using List B, so that the correctly spelled and misspelled versions of the words were viewed an equal number of times across participants. The complete list of Experiment 2 stimuli is listed in Appendix B.

4.1.3 Procedure.

The procedure for Experiment 2 was identical to that used for Experiment 1.

4.1.4 ERP Data Acquisition and Preprocessing.

Data were collected in a manner identical to that of Experiment 1. Preprocessing differed in two respects: (1) Trials were segmented into 1200-ms epochs instead of into 700-ms epochs, so that more of the EEG surrounding each response could be examined, and (2) The ERP segments were corrected relative to a 200-ms baseline ending 200 ms before the response to create a more stable baseline. The 200 ms immediately preceding the response was not included in the baseline because the electroencephalograph likely begins its deflection to the ERN as soon as a key has been *chosen*, not after it is *pressed*, and a typical motor program takes 150-200 ms to execute (Schmidt, 1975).

4.2 RESULTS

The six possible trial outcomes in this experiment are given in Table 5. For the purposes of this study, we were interested in participants' behavioral performance and ERP record for trials leading to each outcome. We first replicated the analyses from Experiment 1 so that the results of the two experiments could be compared, then performed additional analyses on foil trials to understand the effect of phonology preservation in Experiment 2.

Table 5. Possible Trial Outcomes in Experiment 2

Table 5
Possible Trial Outcomes in Experiment 2

		Response	
		Yes	No
Stimulus Type	Target	*hurricane* HIT	*hurricane* MISS
	Foil	*hurricain* * FALSE ALARM phonology preserving	*hurricain* * CORRECT REJECTION phonology preserving
		hurricene FALSE ALARM phonology altering	*hurricene* CORRECT REJECTION phonology altering

* Note that *hurricain* was not an actual stimulus in this experiment.

4.2.1 Behavioral Data.

4.2.1.1 Accuracy. Table 6 contains the means, standard deviations, and ranges of the behavioral outcomes for Experiment 2. The relatively high average d′ of 1.96 and minimum d′ of 1.06 again indicate that accuracy on the task was high for this sample. In an analysis of participants' accuracy data, a paired-samples *t*-test indicated a significant accuracy difference for targets and foils. Participants were more accurate on target trials (M = 87.49%) than on foil trials (M = 76.69%), $t(23) = 6.11$, $p < .001$. In an examination of the effect of phonology preservation on accuracy, a paired-samples *t*-test revealed a significant difference between accuracy rates for phonology-preserving (M = 69.56%) and phonology-altering (M = 84.24%) foils, $t(23) = -13.44$, $p < .001$. Participants were on average more accurate by nearly 15 percentage points when phonology was altered versus when it was preserved.

Table 6. Descriptive Statistics for the Behavioral Outcome Measures in Experiment 2

Table 6
Descriptive Statistics for the Behavioral Outcome Measures in Experiment 2

Behavioral measure	Min	Max	Mean	Std. Dev.
Reaction Time (ms)	540.62	864.14	715.70	91.09
Overall Accuracy (%)	67.03	92.83	82.10	6.50
d′	1.06	2.93	1.96	0.48

N=24. Note that only correct trials were considered in reaction time analyses.

4.2.1.2 Reaction Times. As in Experiment 1, we were specifically interested in two comparisons of RT data: whether, when subjects responded *Yes* there was a difference in RTs for hits and FAs and, when subjects responded correctly, there was a difference in RTs for hits and CRs. As to the first comparison, a *t*-test indicated a significant difference between the decision times for hits (M = 684.22 ms) versus FAs (M = 724.87 ms), $t(23) = -5.25$, $p < .001$. As to the second comparison, a *t*-test indicated a significant difference between the decision times for hits (M =

684.22 ms) versus CRs (M = 753.01 ms), $t(23) = -10.23$, $p < .001$. In both cases, participants were faster to respond to correctly spelled targets than to incorrectly spelled foils (Table 6).

We then performed a paired-samples *t*-test to investigate the effect of phonology preservation on RTs for correct foil (CR) trials. We found a significant difference between the mean RT for trials in which phonology was preserved (M = 763.96) and trials in which phonology was altered (M = 742.85), $t(23) = 4.49$, $p < .001$. Subjects were faster to respond when the phonology of the foil presented to them was altered from that of its target.

4.2.2 ERP Data.

As in Experiment 1, the grand average of the Experiment 2 data reveals a clear ERN at our cluster of interest peaking about 25 ms after the response for all six trial types (Figure 5). The adaptive mean amplitude chosen for statistical extraction and the measure of the ERN effect (i.e., correct - error) were identical to those used in Experiment 1.

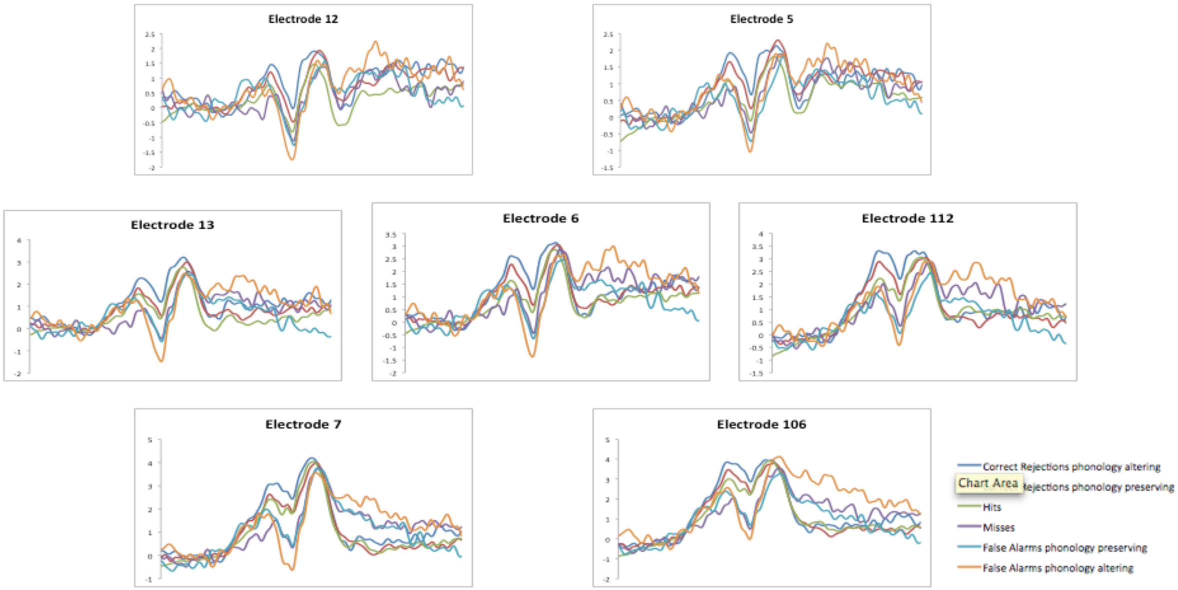

Figure 5. The grand average of EEG activity surrounding the response for each electrode in our cluster of interest for Experiment 2.

A 2 x 2 ANOVA of correctness (correct, incorrect) by stimulus type (target, foil) indicated a main effect of correctness, $F(1, 23) = 24.97$, $p < .001$, in which correct trials were more positive than incorrect trials; this finding replicates the correctness main effect reported in Experiment 1. The ANOVA also revealed a correctness-by-stimulus type interaction, $F(1, 23) = 7.71$, $p < .05$, in which target trials were more negative in amplitude than foil trials when responses were correct and less negative in amplitude than foil trials when responses were incorrect (Figure 6). A main effect of stimulus type was not significant, $F(1, 23) < 1$.

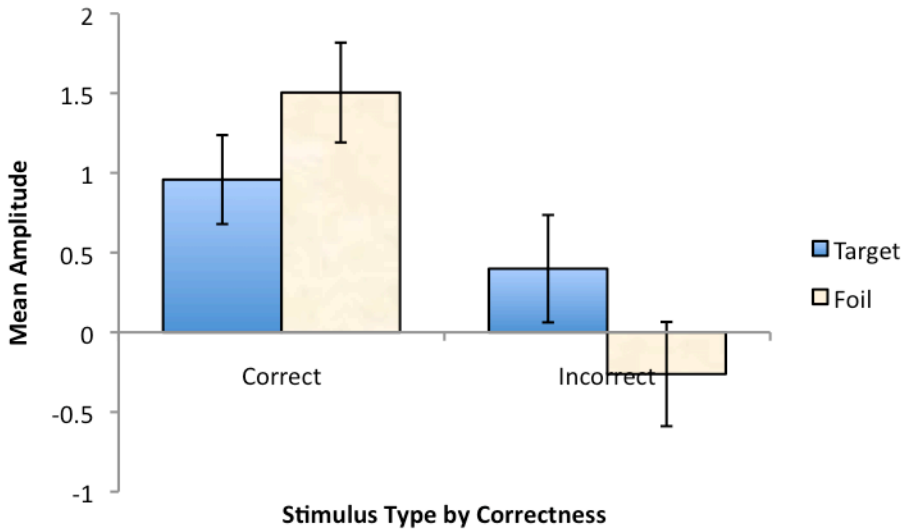

Figure 6. Mean amplitude of correct and incorrect target and foil trials for Experiment 2.

4.2.3 Individual Differences.

A correlational analysis of the ERN effect and d′ values indicated an $r = 0.46$, $p < .05$, again signaling a relationship between participants' ability to discriminate between targets and foils and their ERN amplitude difference on correct and incorrect trials. The ERN effect was also found to correlate significantly with individual difference measures including offline spelling d′ ($r = 0.66$, $p < .001$), offline spelling accuracy ($r = 0.56$, $p < .01$), vocabulary accuracy ($r = 0.45$, $p < .05$), and phonological awareness ($r = 0.49$, $p < .05$). The 0.66 correlation of offline spelling d′ with the ERN effect is lower than was found in Experiment 1 (0.88) but still relatively large; the correlation with reading comprehension observed in Experiment 1 was not replicated here, but a new correlation, between the ERN effect and phonological awareness, was obtained.

4.2.4 Phonology Preservation.

To investigate the relationship between phonology preservation in foil stimuli and ERN patterns, a 2 x 2 ANOVA of correctness (correct, incorrect) by phonology preservation (preserving, altering) was performed. The ANOVA indicated a main effect of correctness, $F(1, 23) = 26.55$, $p < .001$, in which correct trials were more positive than incorrect trials, as well as a correctness-by-preservation interaction, $F(1, 23) = 7.50$, $p < .05$, in which correct trials were more positive and incorrect trials were more negative when the foil did not preserve the phonology of its target (Figure 7).

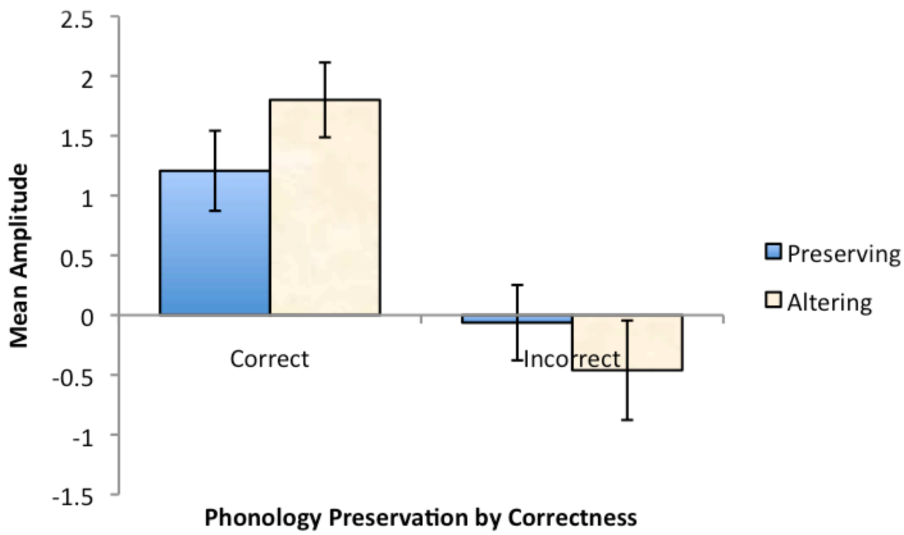

Figure 7. Mean amplitude of correct and incorrect phonology-preserving and phonology-altering foil trials for Experiment 2.

This pattern is observable in the grand average of foil trials for our cluster of interest (Figure 8). CRs are more positive than FAs overall, with phonology-altering CR (CRpa) trials being more positive on average than phonology-preserving CR (CRpp) trials, and phonology-altering FA (FApa) trials being more negative on average than phonology-preserving FA (FApp) trials.

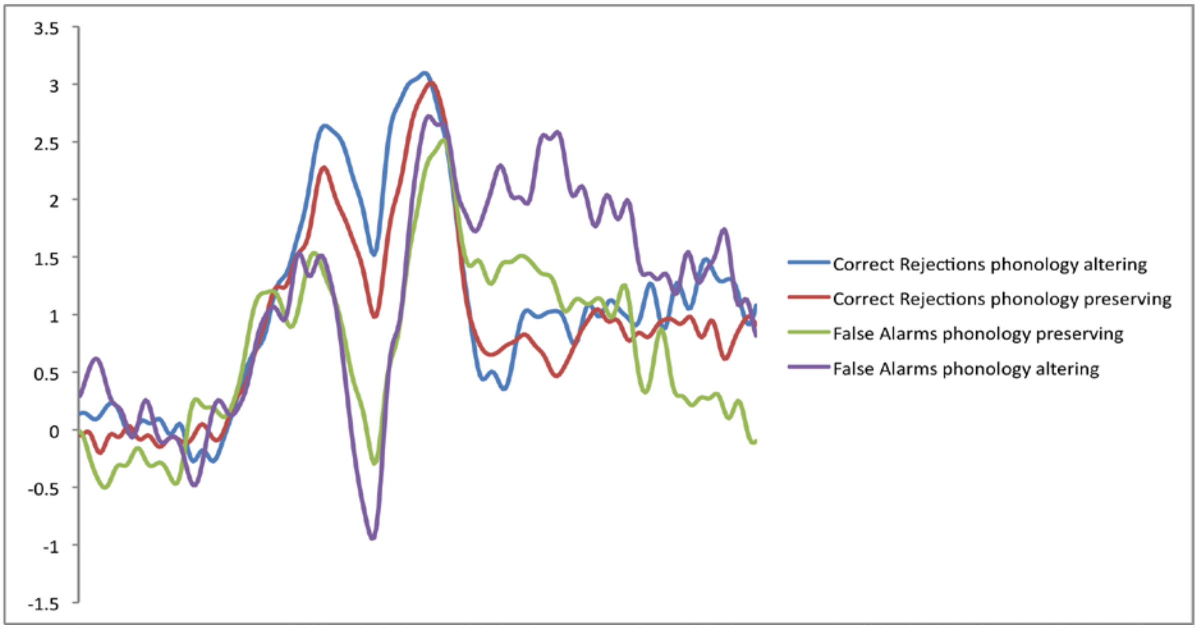

Figure 8. The grand average of EEG activity surrounding the response, averaged across our cluster of interest for Experiment 2. Only foil trials are displayed.

4.3 DISCUSSION

The objective of Experiment 2 was to examine what sources of information contained in a visually presented wordform produce the error signals that create an ERN when a mistake is made during spelling evaluation. We hypothesized that both phonology and orthography contribute to the error signal, and that the ERN would be greater when a correct *No* decision was supported by incongruencies of both phonology and orthography than when the correct *No* decision was supported only by incongruent orthography. Our finding that the ERN is least negative for correct phonology-altering trials and most negative for incorrect phonology-altering trials confirms our hypothesis. When a participant identifies as misspelled a string whose orthography and phonology both support that decision, the participant is certain of his or her decision and little to no error signal is produced—hence the very positive average ERN on CRpa trials. When, on the other hand, a participant identifies as correctly spelled a string for which there is neither phonological nor orthographic evidence for that choice, he or she receives error signals from two sources and the very negative average ERN seen for FApa trials occurs. The ERN for FApp trials, in which the participant's choice was supported by one of the two sources, is less negative than that for FApa trials, in which two lexical sources signal that an incorrect choice has been made.

In addition to our finding that ERN magnitudes are larger for phonology-altering than phonology-preserving trials, they were once again correlated with spelling ability as demonstrated by performance on offline and online tasks. Better spellers experienced greater ERN magnitudes because the verification stage of the decision-making process (Figure 4) was more accurate in these participants, who tend to have a more completely specified orthographic representation of a given word than a less skilled speller.

As in Experiment 1, we found correlations of the ERN effect size with other reading-related measures, again supporting the notion that the ERN obtained on a spelling task may index reading and linguistic abilities beyond the scope of our experiment, and offering evidence of the range of individual differences that exists within the class of skilled readers. The somewhat lower correlation of the ERN effect with spelling ability in Experiment 2 compared with Experiment 1 is likely due to the relative difficulty of Experiment 1 stimuli: because stimuli of over nine letters and those otherwise determined to be especially difficult were replaced with shorter, simpler stimuli in Experiment 2, the level of spelling ability necessary to perform well and to be aware of errors on the hardest trials was effectively lowered.

Experiment 2 also extends the range of observations of phonological activation in reading. Although we cannot say definitively from this experiment exactly when during the word identification process phonology comes online, we have shown that it is available early enough in word reading to be considered in a decision about spelling accuracy. In fact, phonology seems to be not only available but instrumental in determining whether and how quickly the correctness of the stimulus will be verified: foils that altered phonology were responded to 21.11 ms faster and 14.68 percent more accurately than phonology-preserving foils.

5.0 GENERAL DISCUSSION

The present study demonstrates that, in normal adult readers of English, orthographic representations are sufficiently specified to elicit an ERN during a speeded spelling decision. The magnitude of the ERN is related to the quality of an individual's orthographic representation of a word, and average ERN magnitudes, aside from predicting spelling ability to a considerable degree, are correlated with non-orthographic linguistic skills that are critical for fluent reading. We have provided further evidence that individual differences in lexical knowledge exist in adult populations of skilled readers, and that variations in orthographic knowledge can contribute to variability in reading outcomes. We have also shown that phonological information is activated early enough in the word-reading process to be considered in a decision about spelling, and that both phonological and orthographic information contained in an input stimulus contribute uniquely to the activation of a representation and its verification.

One could imagine a non-cognitive explanation for the correlation between ERN magnitude and spelling ability, however. The best spellers in our sample may have demonstrated the largest ERN effects because they perceived themselves as having more at stake in the task than poorer spellers, who had no reputation for spelling aptitude to defend. In other words, motivation could be the driving force behind ERN amplitude in our study, with better spellers producing ERNs of greater magnitude because of a tendency to be more self-critical after errors. We find this explanation unlikely, however, for two reasons. First, we restricted our sample to individuals who had already performed well on a spelling assessment, and they were informed of this fact upon being invited to participate in the study (so even people who don't normally consider themselves skilled spellers should have done so in the context of the experiment). Second, we did our best to equalize levels of motivation across our sample by offering monetary incentives for good performance. This way, even individuals who typically might not feel their pride is at stake in a computerized spelling assessment had reason to give the task their all on day they visited our lab. We therefore feel confident that it was the processing related to orthographic knowledge, and not the attitude of subjects toward the task, that was the primary driving force behind the ERN in this study.

Our findings are ultimately compatible with both the mismatch hypothesis (e.g., Falkenstein et al., 1991) and the conflict-monitoring hypothesis (e.g., Yeung, Botvinick, and Cohen, 2004) of the biological mechanism behind the ERN. To make an accurate judgment about the spelling of a word, one must have some internal representation of its orthographic form, however underspecified. The more fully specified one's internal orthographic representation, the more efficiently the error-detection process will work, leading to a larger ERN effect in individuals with higher-quality orthographic representations, i.e., good spellers. Under either the representational mismatch or conflict-monitoring scenario, the degree of orthographic overlap between the stimulus being encoded and the internal representation corresponds to the degree the representation is activated. If the mismatch hypothesis is correct, the ERN arises directly from the incongruency of either a *Yes* response on a trial where the degree of overlap was low or a *No* response on a trial where the degree of overlap was high. Better spellers, who experience more rapid and targeted activation of orthographic representations when presented with a correctly spelled word (or a word that is an obvious misspelling of a correctly spelled word), will experience the largest incongruencies and therefore the strongest ERNs.

Under the conflict-monitoring hypothesis, the ERN does not arise directly from a clash between the degree of overlap of internal and external orthographic representations with the selected response. Rather, what transpires is that the degree of overlap can be reevaluated after a response has been selected. When, after a decision has been made, evidence accumulates that the extent of the overlap between the input stimulus and the internal representation is considerably more or considerably less than was judged in the first instant of exposure to the stimulus, the ERN appears. Again, it is the specificity of the internal representation that determines the strength of the ERN, and therefore the best spellers who evince the largest ERN effects.

The present study expands the literature on the use of ERNs for understanding linguistic processes, and is the first demonstration of an ERN produced during a spelling task. An ERP study, unlike a behavioral investigation of spelling ability, provides real-time information about orthographic processes, and the ERN magnitude, which can take on an infinite number of values, provides a more nuanced view of spelling knowledge than can be obtained from a spelling test, whose answers are either right or wrong. An ERN recorded during a spelling decision is at its core a reflection of the fullness of the specification of a single orthographic representation for an individual. The mean ERN magnitude of a single participant in this study is an average of widely varying amplitudes recorded for over 800 individual trials. Thus, a Nelson-Denny or verbal SAT score can belie a raft of individual differences amongst the people who share it. Horowitz-Kraus and Breznitz (2008) also related individual difference measures to the ERN, but across skill groups of readers. The present study emphasized the variability of individual difference measures within normal readers who were all skilled spellers.

We were able to observe correlations in both experiments of average ERN effect size with spelling performance (both online and off-) and vocabulary knowledge, as well as with reading comprehension skill (Experiment 1) and phonological awareness (Experiment 2) because orthographic quality is not an independent phenomenon. High-quality orthographic representations develop from skill at decoding encountered strings, which leads to higher-quality representations of the meanings of words, which improves text comprehension, which leads to more experience with text, which involves more exposure to orthographic forms, and so on. All of these skills underpinning reading ability are interrelated, and rehearsal of any one of them has the effect of strengthening the others. Having a high-quality orthographic representation for one given lexeme, therefore, does not necessitate having a quality orthographic representation for a second, nor does it ensure a well specified phonological representation for either—but it does make these outcomes much more likely. Someone with poor decoding ability, meanwhile, will develop lower-quality orthographic representations of words, a smaller vocabulary, and reduced comprehension skill, all of which will lead to fewer encounters with words on a page, and the cycle will continue.

The results of the experiments reported here also contribute to the literature on the components of spelling ability. Perfetti and Hart's (2002) factor analysis revealed that for less-skilled readers orthographic knowledge is not well integrated with knowledge of other lexical components, so that even adequate spellers can be poor readers if orthographic information is not supporting phonological and semantic information during reading as efficiently as it does for skilled readers. This situation is consistent with our Experiment 1 finding that, within our sample of reasonably skilled spellers, reading comprehension ability is correlated with individual participants' knowledge of orthography, as reflected in the amplitude of the ERN.

Our results also complement those of Andrews and colleagues (Andrews and Lo, 2011; Andrews and Hersch, 2010), in which orthographic neighbors (e.g., *node* NOTE) and transposed-letter versions of the target (e.g., *clam* CALM) did not prime the target as efficiently in good spellers as they did in poor spellers, suggesting that better spellers have formed more precise lexical representations of words, which require primes with a very high degree of orthographic overlap to activate. We can also assume more precise lexical representations in better spellers in the present study, who showed evidence of more thorough activation of orthographic representations than poorer spellers when presented with an input stimulus that was a correctly spelled word. However, better spellers also showed evidence of more thorough orthographic representations when presented with an incorrectly spelled word, i.e., an input stimulus that did not overlap perfectly with the representation. This would at first seem to contradict previous research (e.g., Andrews and Lo, 2011), which suggests that prompting activation of a representation with a string containing a letter altered from that of the target should put better spellers at a relative disadvantage to poorer spellers. But there is a key difference between the stimuli used to activate representations in a priming study versus a spelling study. Facilitatory priming effects have been reliably observed for words that have very few orthographic neighbors, regardless of length (Forster et al., 1987). This evidence suggests that words with high neighborhood densities become very "narrowly tuned" (Forster and Taft, 1994) and are resistant to activation by strings that vary in even a single letter from the representation. Tuning is narrower in better spellers than in poorer spellers, so the inhibitory effects of neighbor priming are more pronounced in that population.

The stimuli in our study were not orthographic neighbors of the target representation, however. Although the neighborhood sizes of our foil stimuli were not measured, they would never have survived the norming process if they weren't exactly one a large majority of the time. Recall that a potential foil was eliminated if more than one out of five AMT workers, when asked to produce the word of which it was a misspelling, provided the wrong target. Misspellings that had more than one orthographic neighbor, i.e., the target, would have prompted responses other than the target and have been eliminated. A misspelling, then, is most like a prime with a very small neighborhood size in the priming literature. Thus, the same good spellers who are slow to activate a representation that is an orthographic neighbor of a prime seem adept at retrieving a correct spelling when presented with an incorrect spelling. A stimulus that well approximates a single orthographic representation will activate that representation in better spellers more completely than in poorer spellers, who tend to have less well-defined orthographic representations overall. The verification process (Figure 4) therefore proceeds more efficiently in better spellers, resulting in larger ERN magnitudes in those participants.

The model of spelling verification presented here also contributes to the literature a new framework for considering spelling ability. We have offered evidence of a process in which spelling decisions are arrived at in essentially two stages—an activation stage, in which an input stimulus spurs the retrieval of a corresponding internal representation, and a verification stage, in which the input stimulus is compared with the representation and verified as a correct spelling only if it overlaps orthographically and phonologically with the representation. Perfect orthographic overlap of the input stimulus and representation ensures perfect phonological overlap, and such a stimulus will be verified; a stimulus that overlaps neither orthographically nor phonologically with a representation will be rejected. Phonological overlap in the absence of orthographic overlap will prevent verification, but can provoke uncertainty in one's decision. Thus is phonology not only activated early enough in word reading to influence spelling decisions, it would appear to be integral in our evaluation of spellings. Just as phonology has been shown to be involved in word reading even when it is unnecessary—e.g., in Chinese—we have shown that phonology is involved in spelling decisions even though orthography alone should suffice. The present research contributes to a deeper understanding of orthographic knowledge in adults but also reaffirms what has been repeatedly observed in cognitive research, namely, that written language is built on a scaffold of spoken language and cannot be extricated from it.

APPENDIX A

EXPERIMENT 1 STIMULI

Target and Foil pairs used as experimental stimuli in Experiment 1.

aardvark	aardvirk	alchemy	alchemay	argument	argumint	blatant	bletant
abacus	aibacus	alcohol	alchohol	armature	armiture	bleachers	bleechers
abbreviate	abreviate	alcove	alcuove	arsenal	arsinal	blister	blistur
abdomen	abdomin	alfalfa	alfelfa	artichoke	artichake	blizzard	blizard
abnormal	abnormel	algebra	algibra	ascend	accend	blossom	blassom
abolition	abulition	algorithm	algorethm	asteroid	asteruid	bludgeon	bladgeon
absence	absense	alleged	alledged	astonish	astanish	boisterous	bosterous
abundance	abundence	alligator	alligetor	atrocious	attrocious	bonanza	boninza
accelerate	acelerate	almanac	almunac	attendance	attendence	boomerang	bomerang
accessible	accessable	alphabet	alphabat	attention	atention	boycott	boycot
accessory	accesory	amber	ambur	audible	audable	bribery	bribary
acclaim	aclaim	ambulance	ambulence	audience	audiance	broccoli	broccole
accompany	acompany	amnesia	amnasia	autumn	atumn	brunette	brunnette
accomplice	acomplice	amputate	ampuitate	average	averege	budget	budgit
accomplish	acomplish	anatomy	anatamy	bachelor	bauchelor	buffalo	buffalao
accountant	acountant	anchor	ancor	balance	ballance	bundle	bundel
accumulate	accumalate	anchovy	anchavy	balcony	bailcony	bureau	buereau
acquainted	aquainted	annihilate	annhilate	ballerina	ballerana	burning	buerning
acquiesce	acquiese	anorexia	annorexia	balloon	baloon	business	buisiness
acquire	aquire	antecedent	anticedent	banana	banuna	butterfly	buetterfly
across	accross	antenna	antennuh	bandanna	bandenna	caboose	caboase
additional	addtional	antifreeze	antifrieze	banjo	bainjo	cafeteria	cafetaria
address	adress	aortic	ayortic	bankrupt	binkrupt	cajole	cajule
adherent	adherant	apologize	appologize	barbecue	barbecoe	caliber	calaber
adjacent	adjacint	apparent	apparant	bargain	bargan	camouflage	camoflage
adjacent	ajacent	appearance	apearance	basically	basicaly	campus	campis
adjourn	adjurn	appendix	apendix	bayou	bauyou	cannibal	cannibel
admiral	admirel	apples	aepples	bazooka	bazookuh	capitalism	capitolism
adobe	aduobe	apprehend	aprehend	beaker	beakur	capsize	cepsize
adolescent	adolesent	apprentice	aprentice	beginning	begining	caravan	caraven
aesthetic	asthetic	apricot	apricut	belief	beleif	career	carreer
afraid	affraid	apron	aupron	believe	beleive	caribou	coaribou
aggravate	aggrivate	apropos	apropo	beneath	beneth	caricature	caracature
aggressive	aggresive	aqueduct	aquaduct	benefit	benifit	carpenter	corpenter
alarm	alairm	arena	areuna	bequeath	bequeth	cartilage	cartiladge
albatross	albatrass	argument	arguement	biscuit	biscut	cashew	cashoew

category	catagory
cathedral	cathidral
cauldron	culdron
cautious	catious
ceiling	ceilling
celibacy	celabacy
ceremony	ceremany
chameleon	cameleon
chandelier	chandalier
changeable	changable
charitable	charitible
chauffeur	chaufeur
checkmate	chekmate
cheetah	chetah
chemistry	chemastry
cherub	chirub
chief	cheif
children	cheldren
chimney	chemney
chimpanzee	chimpanze
chipmunk	chepmunk
chocolate	chacolate
cinnamon	ciennamon
cipher	ciphur
circuit	circut
clarity	claority
cleanser	claenser
coffee	coeffee
coffin	couffin
collision	colision
cologne	colone
colonel	colonell
column	colomn
commission	comission
committed	commited
committee	commitee
comparable	comprable
compare	compair
competent	compatent
completely	completly
component	cumponent
concede	conceed
condemn	condem
condescend	condesend
condolence	condolance
confetti	confatti
conscience	concience
conscious	concious
consistent	consistint
consistent	consitant
conspiracy	conspiricy
continuous	continous
contraband	contrabend
convenient	conveniant
corrupt	corruopt
cotton	coutton
cougar	cuogar
courage	cuorage
courteous	curteous
coyote	coyoute
creature	craeture
crescent	creascent
crimson	cremson
critical	critacal
criticize	critisize
crocodile	crucodile
cupboard	cuboard
daylight	dauylight
dazzling	daizzling
dealership	dealershep
debacle	debecle
debit	deabit
decayed	decuyed
decibel	decible
defense	deffense
defiance	defience
deficits	defacits
definitely	definately
delicate	deilicate
delightful	deleghtful
delivery	delivary
deluxe	delaxe
denture	dinture
deodorant	deoderant
dependent	dependant
descend	decend
desirable	desireable
desperate	desparate
deterrence	deterrance
devoured	devuored
difference	diference
dinosaur	dinosar
diploma	diplama
discipline	disipline
dissident	dissadent
dissonant	dissonent
document	documnet
doesn't	dosen't
dollar	doller
dominant	dominent
domineer	domaneer
dowry	dowery
dreadful	draedful
dribbling	dribbiling
drowsy	drawsy
dyslexia	dyslixia
easel	easle
ebony	ebonay
eccentric	eccentrec
ecstasy	extasy
ecstatic	ecstatec
efficiency	efficiancy
eighth	eigth
elaborate	elaberate
elegance	elagance
elegant	eilegant
element	elament
elephant	ealephant
eligible	eligable
elixir	elexir
embargo	embergo
embarrass	embarass
embassy	embussy
embellish	embelish
embrace	embroce
emergency	emergancy
enterprise	enteprise
entice	entaice
enzyme	eunzyme
equinox	equinax
equipment	equipmant
equipped	equiped
eradicate	eradacate
errand	errend
escape	escepe
especially	especialy
establish	establush
eternal	etarnal
etiquette	etiquitte
evenness	eveness
eventually	eventualy
evidently	evidantly
exceed	excede
excellent	excelent
exercise	excercise
exertion	exhertion
exhaust	exhast
experience	experiance
explaining	explaning
extension	extention
extremely	extremley
eyelids	eyeleds
facsimile	faximile
factor	facter
fallacy	falacy
familiar	familliar
fanatic	fanaitic
farewell	farewill
fathom	faethom
fatigue	fategue
feathers	faethers
fiasco	fiesco
fiery	firey
filibuster	filibaster
finesse	fineisse
fission	fision
flamboyant	flambayant
flammable	flamable
flounder	floundur
flourishes	florishes
fluoride	floride
fluttered	fluttured
foliage	faoliage
forcibly	forcebly
forecast	forcast
foreign	foriegn
forfeit	forfit
forlorn	forlern
forsake	forseke
fortune	furtune
forty	fourty
fragrant	fregrant
frequently	frequintly
frolic	froluc
frustrated	fustrated
fulfill	fufill
furlough	fuerlough
galoshes	guhloshes
garage	garege
garden	gairden
gathered	gaithered
gazelle	gazille
generally	generaly
genesis	geanesis
genius	genious
gerbil	gerbel
gingivitis	gingivatis
giraffe	girrafe
glamour	glaemour
glittered	gliettered
gloomy	gloamy
gnawing	gnaiwing
gorgeous	gergeous
gospel	goespel
government	goverment
governor	govenor
graceful	grauceful
graffiti	grafitti
grammar	grammer
granite	granate
guarantee	guarentee
guard	gaurd
guidance	guidence
guidelines	guidlines
guitar	guitair
handsome	hendsome
happily	happilly
harass	harrass
harmonica	harmanica
harpoon	harpoin
hazard	haizard
heavenly	haevenly
helicopter	helicupter
helpful	helpfull
heretic	heratic
hesitate	heisitate
hickory	heckory
history	hestory
holocaust	holocust
hominy	hominay
honorific	honorifec
hooligan	hoiligan
hopeful	hopefull
horizon	horezon
human	huiman
humorous	humerous

hundredth	handredth
hunger	hungur
hurricane	hurricene
husband	hasband
hyacinth	hayacinth
hybrid	haybrid
hygiene	hygeine
hypocrite	hypocrit
iceberg	iceburg
ideally	idealy
ignorance	ignorence
iguana	iguona
imaginary	immaginary
immovable	inmovable
immune	imune
impatient	impetient
imperial	imperiel
implicit	implicet
incense	incinse
incisor	incesor
incognito	incognato
incumbent	imcumbant
indicate	indacate
indicted	indited
inevitable	inevitible
influence	influince
influenza	infloenza
innate	inate
innovation	inovation
innuendo	inuendo
insomnia	insoimnia
insurance	insurence
integer	interger
intercept	intecept
interlude	interluode
interpret	interprit
interrupt	interupt
irrational	irretional
itinerary	itenerary
ivory	ievory
jaguar	jaiguar
jasmine	jismine
jealousy	jealosy
jeopardy	jeoperdy
jewelry	jewerly
jovial	joivial
jukebox	juokebox
jungle	juingle
kangaroo	kangaro
khaki	kakhi
kinetic	kinitic
knapsack	knoapsack
kneaded	kneadid
knowledge	knowlege
koala	koula
labeled	labelled
laboratory	labratory
lackluster	acklaster
lament	lameint

lantern	laentern
lasagna	lasanga
legacy	legicy
legitimate	legitiment
leisure	liesure
lemon	leamon
leotard	leotord
library	libary
license	licence
licorice	licarice
lieutenant	lieutenent
lightning	leightning
likelihood	likelyhood
likewise	lekewise
lilac	leilac
limousine	limosine
liquid	lequid
loneliness	loneliniss
lottery	lattery
loveliest	loevliest
lucrative	lucritive
ludicrous	luducrous
mafia	mafiuh
magazine	magizine
magically	magicaly
magnolia	magnalia
maiden	maidun
malaria	malauria
mammoth	maimmoth
management	managment
manicure	menicure
mannequin	manequin
marathon	marathin
marijuana	marijuona
marinade	marinede
marriage	marrage
mascara	mascaera
masquerade	masqueride
massage	massoge
matinee	mattinee
mattress	matress
maverick	mauverick
mayonnaise	mayonaise
measles	mesles
mechanic	mechenic
medieval	medival
mediocre	midiocre
melancholy	melanchuly
melody	meloday
menace	manace
mesmerize	mesmeraze
messiah	messeah
metaphor	metiphor
mileage	milage
military	milatary
mimicked	mimiced
minimum	minamum
mischief	mischeif
miser	maiser

missile	missle
mistletoe	mistletae
mocking	moucking
moderate	moderite
modified	modafied
monarch	moanarch
mongoose	mangoose
mongrel	moengrel
monitor	monitir
monsoon	mansoon
morbid	murbid
morning	morening
morsel	mursel
mortgage	morgage
mortuary	mortuery
mosquito	mosquato
mountains	muontains
mouthful	muothful
mulberry	muilberry
murderous	murderuous
murmur	murmer
museum	muesum
mysterious	misterious
mystique	mysteque
narrative	narriative
naughty	nughty
nausea	naseua
naval	navel
necessary	necesary
negative	negatuve
negligent	neglagent
nemesis	neumesis
neurology	neurolagy
neutron	nutron
nibbling	niebbling
ninety	ninty
nirvana	nirvena
nonsense	nensense
normally	normaly
northern	northurn
nostalgia	nastalgia
nostril	nastril
notary	notery
novice	novace
nuclear	nuculear
nuisance	nuisence
obituary	obetuary
obliged	obleged
obscene	obsene
obstacle	obsticle
occasion	ocasion
occurred	occured
octopus	octupus
odyssey	odysey
official	oficial
oncology	onculogy
opossum	opposum
opponent	opponant
opposite	oposite

oppress	opress
orange	orenge
orangutan	orangatan
orchard	orcherd
oregano	oragano
original	originel
ostracize	ostricize
outrageous	outragious
ovation	ovaotion
oxygen	oexygen
paddling	padling
pancake	poncake
papaya	papiya
paprika	papraika
papyrus	papayrus
paradigm	paradegm
paradise	paradase
paradox	paradax
parallel	paralel
paralyzed	paralized
paranoia	paranoa
paraphrase	pariphrase
parasol	parasoel
parrot	parret
particular	particuler
passage	paissage
pastime	pasttime
patriarch	patriurch
pavilion	pavelion
pebble	peibble
peculiar	peculier
pedigree	pedigre
penicillin	penicilin
peninsula	penansula
perceive	percieve
perilous	pirilous
perplex	perplax
persimmon	persemmon
peruse	puruse
petroleum	petreleum
petunia	petuonia
phoenix	phoenux
physician	physican
physique	phisique
pickle	pickel
picnic	picnick
pigeon	piegeon
pineapple	pinapple
pinnacle	pennacle
pistachio	pistaichio
pistol	pistul
pitiful	pitifull
placebo	placeubo
pleasure	plaesure
pocket	pockit
poignant	poignent
polka	polkuh
popping	poping
porcelain	percelain

porch	portch
portfolio	portfalio
possess	posess
possible	possable
postulate	poustulate
potato	potatoe
power	poawer
precedent	preicedent
precious	pracious
precocious	precacious
preferred	perferred
pregnant	pregnent
prejudice	predjudice
pretended	pretinded
pretzel	pritzel
probably	probally
proceed	procede
promenade	promenede
prominent	prominant
protect	protict
provolone	provolune
prudent	pruodent
pyramid	payramid
qualify	qualifay
quality	qualaty
quartet	quartit
quinine	quanine
quiver	quiever
quotient	quoitient
raccoon	raccoan
racquet	racquit
receipt	reciept
received	recieved
reckless	reickless
recommend	recomend
reconcile	reconcale
reference	refrence
referred	refered
refurbish	reforbish
rehearsal	rehersal
rejoiced	rejouced
relevant	relivant
religious	religous
remember	remimber
remnants	remnents
renegade	renegode
renowned	reknowned
represent	reprisent
reservoir	resevoir
resilient	risilient
response	responce
restaurant	restarant
restored	restuored
reviewing	reveiwing
revival	reveval
revolution	revalution
rhapsody	rapsody
rheumatism	reumatism
rhinoceros	rhineceros
rhubarb	rhabarb
rhyme	ryhme
rhythm	rythm
ribbon	riebbon
ricochet	ricachet
ridiculous	rediculous
righteous	rightious
rigorous	rigerous
rooster	roostir
sabotage	sabotege
safari	saferi
salami	salomi
salivary	salivery
samurai	samarai
sandal	sandel
sapphire	sopphire
sarcasm	sercasm
satellite	satallite
satin	satinn
saxophone	saxophane
scarlet	scaurlet
scattered	scaittered
scenario	scenurio
schedule	schedual
scolded	scoilded
secretary	secratary
seizure	saizure
separate	seperate
sequin	seuquin
shampoo	shampo
shepherd	shephard
shivered	shevered
shouldn't	shoudln't
silver	silvur
similar	simillar
simile	similie
sincerly	sincerely
sinister	senister
skeleton	skeileton
slaughter	slaighter
sleuth	slooth
smuggler	smugglir
sobriety	sobraety
sodium	sodiumn
solitaire	soilitaire
sophomore	sophmore
soprano	sopreno
sorcerer	surcerer
souvenir	souvener
spaghetti	spaghatti
spectrum	spectrim
spinach	spenach
spiral	speiral
splendid	splandid
splinter	splintre
sporadic	sporedic
squalid	squaolid
standard	staendard
stereotype	stireotype
stiletto	stilitto
strategy	strutegy
stupendous	stupandous
subjugate	subjugite
success	sucess
sultan	sulten
sunshine	sanshine
supposed	suposed
surgery	sergery
surprise	suprise
suspension	suspention
swallow	swaillow
synonymous	synonomous
synthesis	synthasis
syringe	syrange
tangerine	tangerane
tantalize	tantaleize
tarantula	tarontula
taxation	taxaution
tenacious	tenecious
tendency	teandency
Tennessee	Tennesee
therefore	therefor
thesaurus	thesairus
thespian	thespien
thorough	thurough
thousand	thuosand
threshold	thrishold
tickle	tickel
tidings	teidings
tiresome	taresome
tobacco	tobocco
tomato	tometo
tomorrow	tommorrow
tongue	toungue
tornado	torniedo
tournament	tournement
tradition	tradetion
tragedy	tradgedy
trajectory	trajactory
tribunal	tribuonal
trigger	triggre
trousers	trouisers
truncate	trancate
tsunami	tsunimi
tulip	tulup
tundra	tuendra
turbulence	turbulance
twelfth	twelth
twenty	tweunty
twittered	twettered
typhoon	typhoan
tyranny	tyrany
uglier	uiglier
umbrella	umbrulla
unity	unitay
usage	usege
useable	usable
usually	usualy
vaccine	vaccaine
valuable	vailuable
vampire	vempire
vanilla	vanella
velocity	velacity
velvet	vealvet
vendetta	vendatta
vernacular	vernaculer
versatile	versitile
vicarious	vicaurious
vigilante	vigilainte
village	vilage
violin	violan
virtuoso	virtuoiso
visitor	vesitor
volcano	volcuno
voracious	vorecious
vulnerable	vulnerible
waffle	waffel
wagon	wagun
walrus	waolrus
wardrobe	werdrobe
warrant	warrent
weird	wierd
welcome	waelcome
welfare	wellfare
whimsical	whemsical
wicked	wiecked
wicker	wickur
wiggle	wiggel
windshield	windsheild
withered	withured
womanly	womenly
wounded	wuonded
yacht	yaght
zealous	zaelous
zebra	zibra
zenith	zaenith
zombie	zambie
zucchini	zucchani

APPENDIX B

EXPERIMENT 2 STIMULI

Target and Foil pairs used as experimental stimuli in Experiment 2.

aardvark	aardvirk	answer	anser	belief	beleif	cathedral	cathidral
abdomen	abdomin	antenna	antennuh	believe	beleive	cattle	caettle
abnormal	abnormel	aortic	ayortic	beneath	beneth	cauldron	culdron
abolition	abulition	apartment	apertment	benefit	benifit	cautious	catious
absence	absense	apparent	apparant	bequeath	bequeth	ceiling	ceilling
abundance	abundence	appendix	apendix	biscuit	biscut	celibacy	celabacy
accessory	accesory	apples	aepples	blame	blaime	century	centiry
acclaim	aclaim	apprehend	aprehend	blatant	bletant	ceremony	ceremany
accompany	acompany	apricot	apricut	bleachers	bleechers	channel	channal
acoustic	acustic	apron	aupron	blister	blistur	chauffeur	chaufeur
acquire	aquire	aqueduct	aquaduct	blizzard	blizard	checkmate	chekmate
across	accross	arena	areuna	blossom	blassom	cheetah	chetah
address	adress	argument	arguement	bludgeon	bladgeon	chemistry	chemastry
adjacent	ajacent	armature	armiture	bonanza	boninza	cherub	chirub
adjourn	adjurn	arsenal	arsinal	boomerang	bomerang	chief	cheif
admiral	admirel	artichoke	artichake	boycott	boycot	children	cheldren
adobe	aduobe	ascend	accend	breakfast	brakfast	chimney	chemney
advice	advaice	asteroid	asteruid	bribery	bribary	chocolate	chacolate
aesthetic	asthetic	astonish	astanish	broccoli	broccole	cinnamon	ciennamon
afraid	affraid	attention	atention	brunette	brunnette	cipher	ciphur
aggravate	aggrivate	audible	audable	budget	budgit	circuit	circut
airplane	airplone	audience	audiance	buffalo	buffalao	clarity	claority
alarm	alairm	autumn	atumn	bundle	bundel	cleanser	claenser
alchemy	alchemay	avenue	avunue	bureau	buereau	cobweb	cobwib
alcohol	alchohol	avoid	avoyd	burning	buerning	coffee	coeffee
alcove	alcuove	aware	awaire	business	buisiness	coffin	couffin
alfalfa	alfelfa	awkward	akward	cabbage	cabboge	collision	colision
algebra	algibra	bachelor	bauchelor	caboose	caboase	cologne	colone
algorithm	algorethm	balance	ballance	cactus	cactas	colonel	colonell
alligator	alligetor	balcony	bailcony	cafeteria	cafetaria	colony	colany
almanac	almunac	ballerina	ballerana	cajole	cajule	column	colomn
almost	almoist	balloon	baloon	caliber	calaber	comfort	camfort
alphabet	alphabat	banana	banuna	campus	campis	committed	commited
amber	ambur	banjo	bainjo	cannibal	cannibel	committee	commitee
ambulance	ambulence	bankrupt	binkrupt	capsize	cepsize	compare	compair
amnesia	amnasia	barbecue	barbecoe	caravan	caraven	competent	compatent
amputate	ampuitate	bargain	bargan	career	carreer	component	cumponent
anatomy	anatamy	baseball	basball	careless	careliss	concede	conceed
anchor	ancor	bayou	bauyou	caribou	coaribou	confetti	confatti
anchovy	anchavy	bazooka	bazookuh	carpenter	corpenter	confirm	conferm
annual	annuel	beaker	beakur	carrot	carrit	conscious	concious
anorexia	annorexia	beetle	betle	cashew	cashoew	consistent	consistint
another	anoether	beginning	begining	category	catagory	constant	constent

corrupt	corruopt
cotton	coutton
cougar	cuogar
courage	cuorage
courteous	curteous
coyote	coyoute
creature	craeture
crescent	creascent
crimson	cremson
critical	critacal
criticize	critisize
crocodile	crucodile
cupboard	cuboard
currency	currancy
customer	custamer
daily	dayly
damage	demage
daughter	dughter
daylight	dauylight
dazzling	daizzling
debacle	debecle
debit	deabit
decayed	decuyed
decibel	decible
decorator	decarator
defense	deffense
defiance	defience
deficits	defacits
delicate	deilicate
delivery	delivary
denture	dinture
deodorant	deoderant
dependent	dependant
descend	decend
destroy	distroy
detriment	ditriment
devotion	devoition
devoured	devuored
dinosaur	dinosar
diploma	diplama
dirty	dirtey
disguise	disgise
dishonest	dishanest
dissident	dissadent
dissonant	dissonent
document	documnet
doesn't	dosen't
dollar	doller
dominant	dominent
domineer	domaneer
donkey	donky
dowry	dowery
dreadful	draedful
drowsy	drawsy
dyslexia	dyslixia
easel	easle
ebony	ebonay
eccentric	eccentrec
ecstasy	extasy
ecstatic	ecstatec
eggnog	eggnag
eighth	eigth
elbow	elbaw
elegance	elagance
elegant	eilegant
element	elament
elephant	ealephant
eligible	eligable
elixir	elexir
embargo	embergo
embassy	embussy
embellish	embelish
embrace	embroce
emergency	emergancy
encourage	encurage
enough	enogh
entertain	entertan
entice	entaice
enzyme	eunzyme
equinox	equinax
equipment	equipmant
equipped	equiped
eradicate	eradacate
errand	errend
escape	escepe
establish	establush
eternal	etarnal
etiquette	etiquitte
evenness	eveness
everyone	evryone
evidently	evidantly
exactly	exatly
exceed	excede
excellent	excelent
exercise	excercise
exertion	exhertion
exhale	exhail
exhaust	exhast
exist	exest
explode	exploide
extension	extention
extremely	extremley
eyelids	eyeleds
facsimile	faximile
factor	facter
fallacy	falacy
familiar	familliar
famous	famos
fanatic	fanaitic
farewell	farewill
fathom	faethom
fatigue	fategue
feathers	faethers
fiasco	fiesco
fiery	firey
finesse	fineisse
fission	fision
flammable	flamable
flavor	flaver
flounder	floundur
fluoride	floride
fluttered	fluttured
forcibly	forcebly
forecast	forcast
foreign	foriegn
forever	fourever
forfeit	forfit
forlorn	forlern
forsake	forseke
fortune	furtune
forty	fourty
fragrant	fregrant
freeze	freze
frolic	froluc
fulfill	fufill
funeral	funural
furlough	fuerlough
furniture	furnature
gallery	gallary
galoshes	guhloshes
garage	garege
garbage	gerbage
garden	gairden
gathered	gaithered
gazelle	gazille
general	genaral
genesis	geanesis
genius	genious
gerbil	gerbel
giraffe	girrafe
glamour	glaemour
gloomy	gloamy
glory	glorey
gnawing	gnaiwing
goldfish	goldfesh
gorgeous	gergeous
gospel	goespel
governor	govenor
graceful	grauceful
grammar	grammer
granite	granate
grapefruit	grapefrit
grateful	gratful
gravey	gravay
group	groop
guarantee	guarentee
guard	gaurd
guardian	gardian
guidance	guidence
guideline	guidline
guitar	guitair
haircut	haircat
halfway	halfwoy
handsome	hendsome
happily	happilly
harass	harrass
harmonica	harmanica
harpoon	harpoin
hazard	haizard
health	helth
heavenly	haevenly
heavily	heavaly
helmet	helmat
helpful	helpfull
heretic	heratic
hesitate	heisitate
hickory	heckory
history	hestory
holocaust	holocust
honorific	honorifec
hooligan	hoiligan
hopeful	hopefull
horizon	horezon
household	househald
human	huiman
humorous	humerous
hundredth	handredth
hunger	hungur
hurricane	hurricene
husband	hasband
hyacinth	hayacinth
hybrid	haybrid
hydrant	haydrant
hygiene	hygeine
hypocrite	hypocrit
icicle	icecle
ignorance	ignorence
ignore	ignare
image	imege
immovable	inmovable
immune	imune
impatient	impetient
imperial	imperiel
implicit	implicet
incense	incinse
incisor	incesor
incognito	incognato
income	incume
increase	increese
incumbent	imcumbant
indicate	indacate
indicted	indited
industry	indistry
influence	influince
influenza	infloenza
innate	inate
innuendo	inuendo
insomnia	insoimnia
insurance	insurence
integer	interger
intercept	intecept
interpret	interprit
interrupt	interupt
invent	invint
itinerary	itenerary
ivory	ievory
jaguar	jaiguar
jasmine	jismine
jealousy	jealosy
jellyfish	jillyfish
jeopardy	jeoperdy
jewelry	jewerly
journal	jornal
jovial	joivial
jukebox	juokebox
junction	juntion
jungle	juingle
kangaroo	kangaro
khaki	kakhi
kidnap	kidnep
kinetic	kinitic
kitchen	kichen
knapsack	knoapsack
knowledge	knowlege
koala	koula
labeled	labelled
lament	lameint
language	lenguage
lantern	laentern
lasagna	lasanga
lawyer	lauyer
leather	lether
legacy	legicy
leisure	liesure
lemon	leamon
leotard	leotord
library	libary
license	licence
licorice	licarice
likewise	lekewise
lilac	leilac
limousine	limosine
liquid	lequid
locket	lockit
lottery	lattery
loveliest	loevliest
loyal	loyel
lucrative	lucritive
ludicrous	luducrous
mafia	mafiuh

magazine	magizine
magnolia	magnalia
maiden	maidun
mailbox	mailbax
malaria	malauria
mammoth	maimmoth
manicure	menicure
mannequin	manequin
marathon	marathin
marijuana	marijuona
marinade	marinede
market	markit
marriage	marrage
mascara	mascaera
massage	massoge
matinee	mattinee
mattress	matress
maverick	mauverick
mechanic	mechenic
medicine	midicine
medieval	medival
mediocre	midiocre
melody	meloday
menace	manace
mesmerize	mesmeraze
messiah	messeah
metal	metel
metaphor	metiphor
midnight	midneght
mileage	milage
military	milatary
mimicked	mimiced
minimum	minamum
mischief	mischeif
missile	missle
mistletoe	mistletae
moderate	moderite
modified	modafied
monarch	moanarch
Monday	Mondoy
mongoose	mangoose
mongrel	moengrel
monitor	monitir
monkey	mankey
monsoon	mansoon
morbid	murbid
morning	morening
morsel	mursel
mortgage	morgage
mortuary	mortuery
mosquito	mosquato
motor	moter
mountains	muontains
mouthful	muothful
mulberry	muilberry
murmur	murmer
museum	muesum
myself	mysilf
mystique	mysteque
naughty	nughty
nausea	naseua
necessary	necesary
negative	negatuve
negligent	neglagent
nemesis	neumesis
neurology	neurolagy
neutron	nutron
nibbling	niebbling
ninety	ninty
nirvana	nirvena
nonsense	nensense
normally	normaly
northern	northurn
nostalgia	nastalgia
nostril	nastril
notary	notery
novice	novace
nuclear	nuculear
nuisance	nuisence
oatmeal	oatmel
obituary	obetuary
obliged	obleged
obscene	obsene
obstacle	obsticle
occasion	ocasion
occurred	occured
octopus	octupus
odyssey	odysey
official	oficial
oncology	onculogy
opponent	opponant
opposite	oposite
oppress	opress
orange	orenge
orangutan	orangatan
orchard	orcherd
oregano	oragano
original	originel
ostracize	ostricize
ovation	ovaotion
oxygen	oexygen
paddling	padling
pancake	poncake
papaya	papiya
paprika	papraika
papyrus	papayrus
paradigm	paradegm
paradise	paradase
paradox	paradax
parallel	paralel
paralyzed	paralized
paranoia	paranoa
parasol	parasoel
pardon	pardan
parrot	parret
pastime	pasttime
patriarch	patriurch
pavilion	pavelion
pebble	peibble
peculiar	peculier
pedigree	pedigre
peninsula	penansula
people	peeple
perceive	percieve
perhaps	perheps
perilous	pirilous
perplex	perplax
petroleum	petreleum
petunia	petuonia
phoenix	phoenux
physician	physican
physique	phisique
pickle	pickel
picnic	picnick
pigeon	piegeon
pillow	pilluw
pineapple	pinapple
pinnacle	pennacle
pistol	pistul
pitiful	pitifull
placebo	placeubo
plastic	plestic
pleasure	plaesure
pocket	pockit
poignant	poignent
poison	poisen
polka	polkuh
popcorn	papcorn
popping	poping
popular	papular
porcelain	percelain
porch	portch
portfolio	portfalio
position	pusition
possess	posess
possible	possable
potato	potatoe
power	poawer
precious	pracious
preferred	perferred
pregnant	pregnent
preschool	prescool
pretended	pretinded
pretzel	pritzel
probably	probally
proceed	procede
professor	profassor
promenade	promenede
prominent	prominant
pronounce	pronunce
protect	protict
provolone	provolune
prudent	pruodent
pyramid	payramid
qualify	qualifay
quality	qualaty
quartet	quartit
quicksand	quicksond
quinine	quanine
quiver	quiever
quotient	quoitient
raccoon	raccoan
racquet	racquit
railway	railwey
rainstorm	rainsturm
range	rainge
receipt	reciept
received	recieved
reckless	reickless
recommend	recomend
reconcile	reconcale
recover	recaver
reference	refrence
referred	refered
refurbish	reforbish
regular	regalar
rehearsal	rehersal
rejoiced	rejouced
relevant	relivant
religious	religous
remark	remerk
remember	remimber
remnants	remnents
renegade	renegode
renowned	reknowned
represent	reprisent
reservoir	resevoir
resilient	risilient
response	responce
restored	restuored
return	retarn
reviewing	reveiwing
revival	reveval
rhapsody	rapsody
rhubarb	rhabarb
rhyme	ryhme
rhythm	rythm
ribbon	riebbon
ricochet	ricachet
righteous	rightious
rigorous	rigerous
rooster	roostir
royal	royel
sabotage	sabotege
safari	saferi
salami	salomi
samurai	samarai
sandal	sandel
sapphire	sopphire
sarcasm	sercasm
satellite	satallite
satin	satinn
saxophone	saxophane
scarecrow	scarecraw
scarlet	scaurlet
scenario	scenurio
schedule	schedual
scolded	scoilded
scream	screem
seashore	seashare
secretary	secratary
seizure	saizure
sequin	seuquin
shallow	shellow
shampoo	shampo
shepherd	shephard
shivered	shevered
shoulder	shulder
shouldn't	shoudln't
shrimp	shremp
sideways	sidewuys
silver	silvur
similar	simillar
simile	similie
sinister	senister
skate	skaite
skeleton	skeileton
slaughter	slaighter
sleeve	sleve
sleuth	slooth
smoke	smoike
smuggler	smugglir
sobriety	sobraety
sodium	sodiumn
sophomore	sophmore
soprano	sopreno
souvenir	souvener
spaghetti	spaghatti
spectrum	spectrim
speedy	speady
spinach	spenach
spiral	speiral
splendid	splandid
splinter	splintre
sporadic	sporedic
squalid	squaolid
square	squaire
standard	staendard
station	stetion
steam	steem

stiletto	stilitto
stranger	strainger
strategy	strutegy
subject	subjact
subjugate	subjugite
success	sucess
sultan	sulten
sunshine	sanshine
support	suppart
supposed	suposed
surgery	sergery
surprise	suprise
swallow	swaillow
synthesis	synthasis
syringe	syrange
tarantula	tarontula
target	targat
taxation	taxaution
tenacious	tenecious
tendency	teandency
Tennessee	Tennesee
terrible	terrable
therefore	therefor
thesaurus	thesairus
thespian	thespien
thirsty	tharsty
thorough	thurough

thousand	thuosand
threshold	thrishold
tickle	tickel
tidings	teidings
tiresome	taresome
tobacco	tobocco
tomato	tometo
tomorrow	tommorrow
tongue	toungue
torch	tortch
tornado	torniedo
tradition	tradetion
tragedy	tradgedy
treatment	tretment
tribunal	tribuonal
trigger	triggre
trouble	truble
trousers	trouisers
truncate	trancate
tsunami	tsunimi
tulip	tulup
tundra	tuendra
turkey	turkay
twelfth	twelth
twenty	tweunty
twittered	twettered
typhoon	typhoan

tyranny	tyrany
uglier	uiglier
umbrella	umbrulla
underdog	underdag
underwear	underwar
unhappy	unhaeppy
unity	unitay
usage	usege
vacant	vecant
vacation	vacotion
vaccine	vaccaine
valuable	vailuable
vampire	vempire
vanilla	vanella
vegetable	vegetible
velocity	velacity
velvet	vealvet
vendetta	vendatta
versatile	versitile
village	vilage
violin	violan
virtuoso	virtuoiso
visiting	visating
visitor	vesitor
volcano	volcuno
voracious	vorecious
voyage	vayage

waffle	waffel
wagon	wagun
walrus	waolrus
wardrobe	werdrobe
warrant	warrent
weird	wierd
welcome	waelcome
welfare	wellfare
whatever	whataver
whimsical	whemsical
wicked	wiecked
wicker	wickur
wiggle	wiggel
withered	withured
womanly	womenly
wonder	wondar
wounded	wuonded
yacht	yaght
zealous	zaelous
zebra	zibra
zenith	zaenith
zipper	zippar
zombie	zambie
zucchini	zucchani

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FOOTNOTES

[1] It is worth keeping in mind, however, that the conclusion about phonology is more complex at a level of detail. There may be reading without phonology among deaf readers (research on the elusive role of phonology in this population continues), and while its presence in Chinese reading has been established, its exact role in Chinese (for example, it might be automatic without being “essential”) might not be 100 percent clear.

[2] Not all psycholinguists have overlooked spelling skill; a notable exception to the trend is Rebecca Treiman and colleagues, who have published over 50 articles on spelling knowledge and development, primarily in children. See Pollo, Treiman, and Kessler (2007) for an overview of current approaches to the study of spelling development, with an emphasis on research that has considered spelling crosslinguistically within alphabetic writing systems.