

**ERROR-RELATED NEGATIVITIES DURING SPELLING JUDGMENTS EXPOSE  
ORTHOGRAPHIC KNOWLEDGE**

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Lindsay Nicole Harris, M.S.

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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<sup>1</sup>. “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 /'kɔːnəl/, 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<sup>2</sup>. 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 SPELLING 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](http://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 *vacation* 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:  $(\text{number correct}) - [(\text{number incorrect and unanswered})/(\text{number choices})]$ . 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 Lenovo 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.

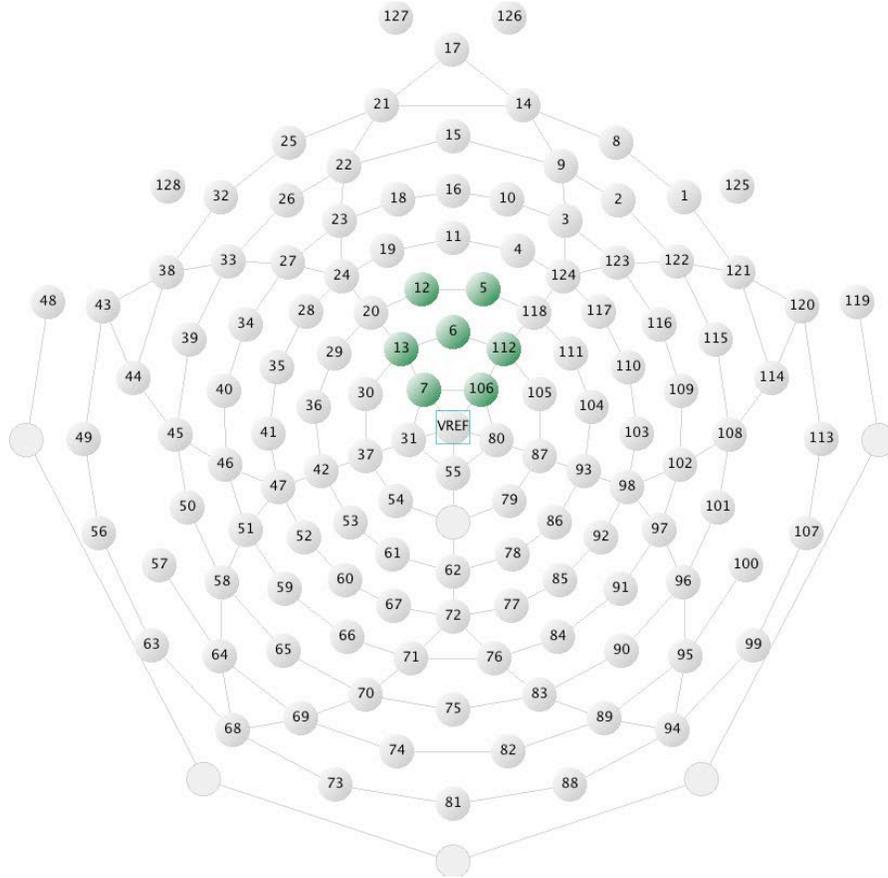
A 20-trial practice block was administered to familiarize participants with the procedure. Subsequently, participants received feedback (black text on a white screen) after every 20 trials; this feedback alternated between providing accuracy information for the round immediately prior to the feedback, 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 impedances generally kept below a threshold of 40 k $\Omega$ .

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*

Stimulus Type	Response	
	Yes	No
	Target	<i>hurricane</i> HIT
Foil	<i>hurricene</i> FALSE ALARM	<i>hurricene</i> 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*

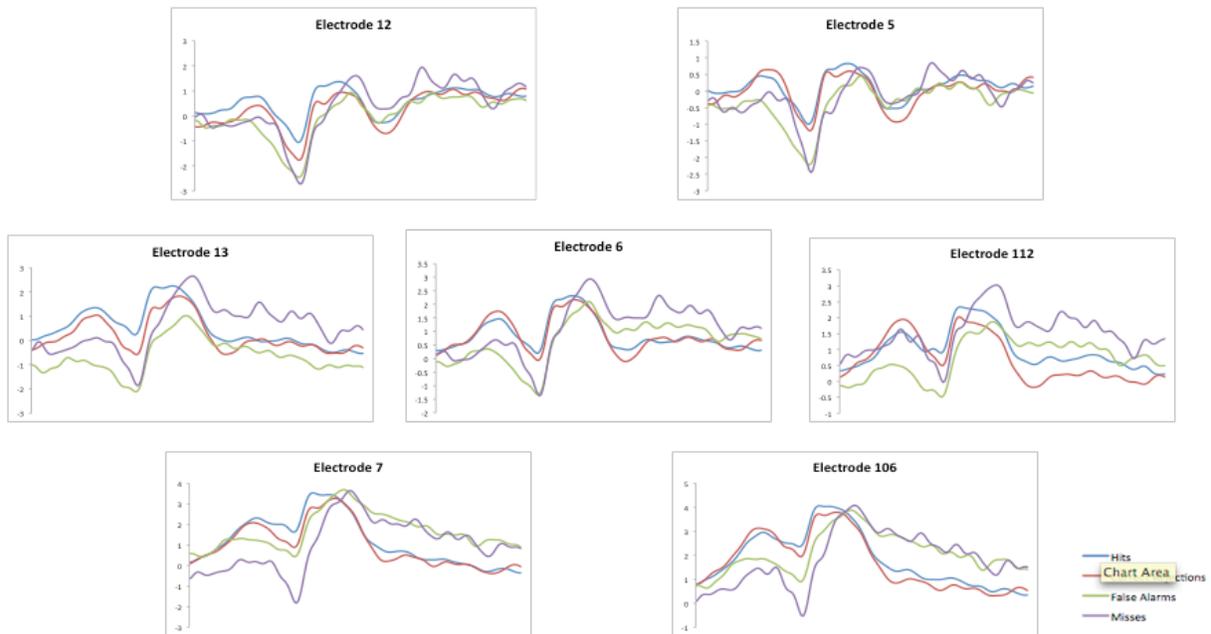
Behavioral measure	Min	Max	Mean	Std. Dev.
Reaction Time (ms)	516.93	981.88	726.17	127.32
Overall Accuracy (%)	71.55	92.56	83.02	6.07
$d'$	1.15	2.91	2.05	0.50

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).

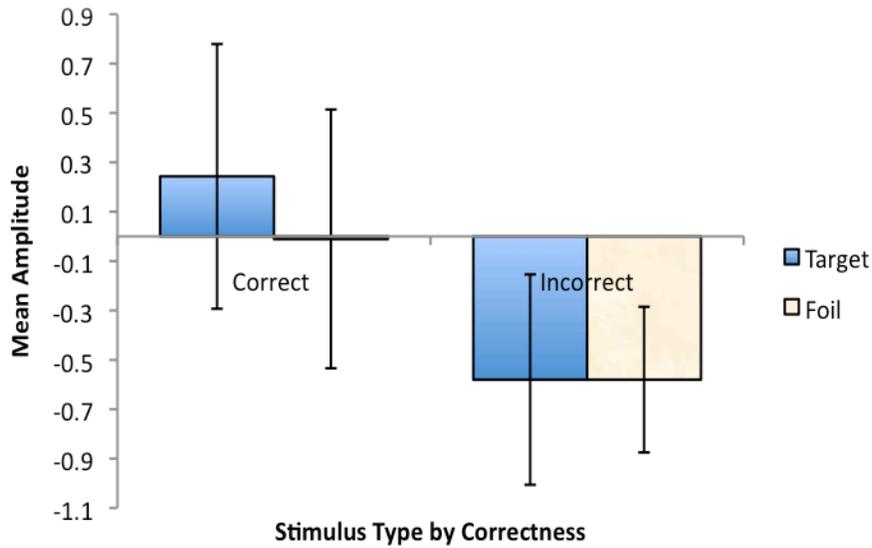
### **3.2.2 ERP Data.**

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  $-0.58 \mu\text{v}$  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.

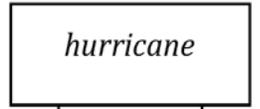
## 4.0 EXPERIMENT 2

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).

**TARGET TRIAL**

1. Visual input



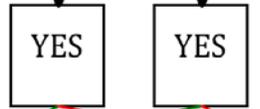
PH                      OR

2. Activation of internal representation



PH                      OR

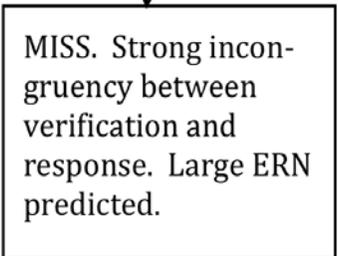
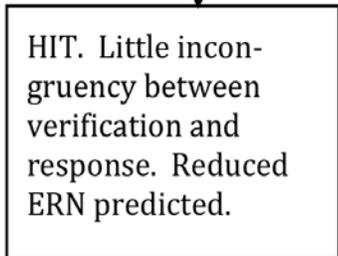
3. Verification of match



4. Selected response

**Yes**                      **No**

5. Trial outcome



*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.

FOIL TRIAL: PHONOLOGY-PRESERVING

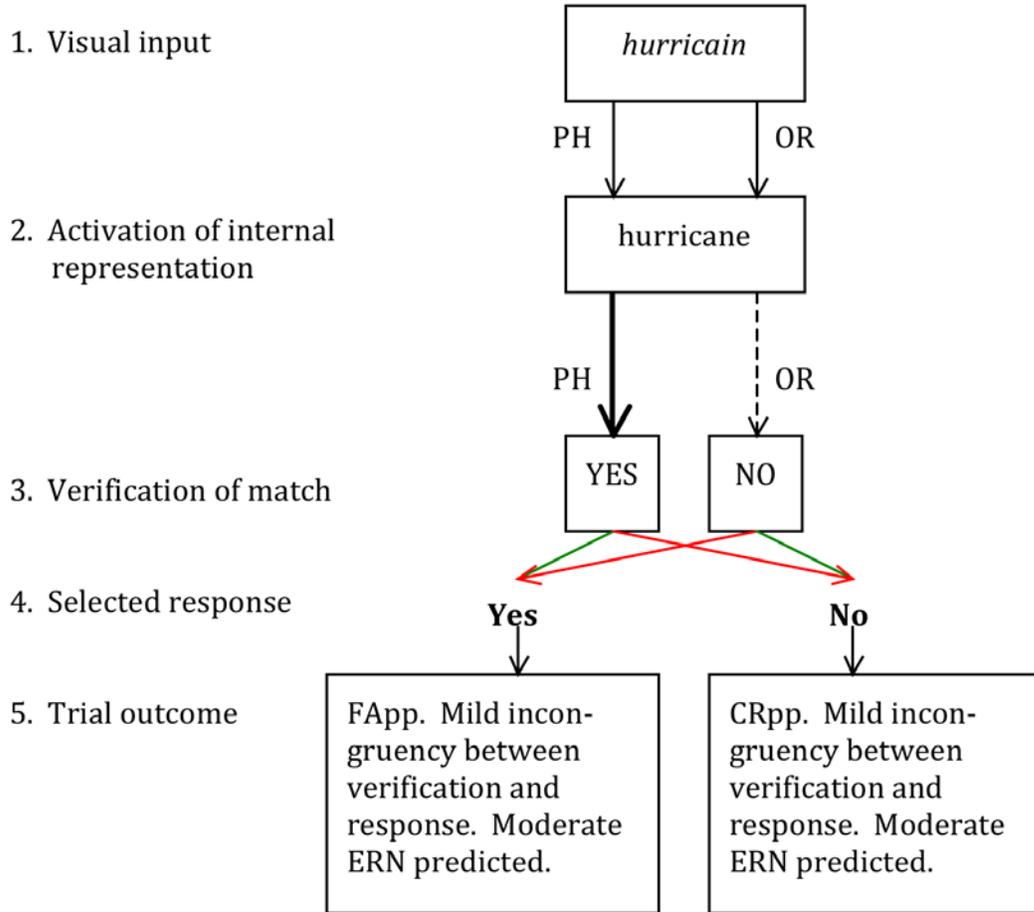


Figure 4b. When the input stimulus is incorrectly spelled but preserves the phonology of the correct spelling, the representation will overlap with the phonology but not with the orthography of the stimulus. These mixed signals will lead to a moderate ERN in the case of either a *Yes* or *No* response.

FOIL TRIAL: PHONOLOGY-ALTERING

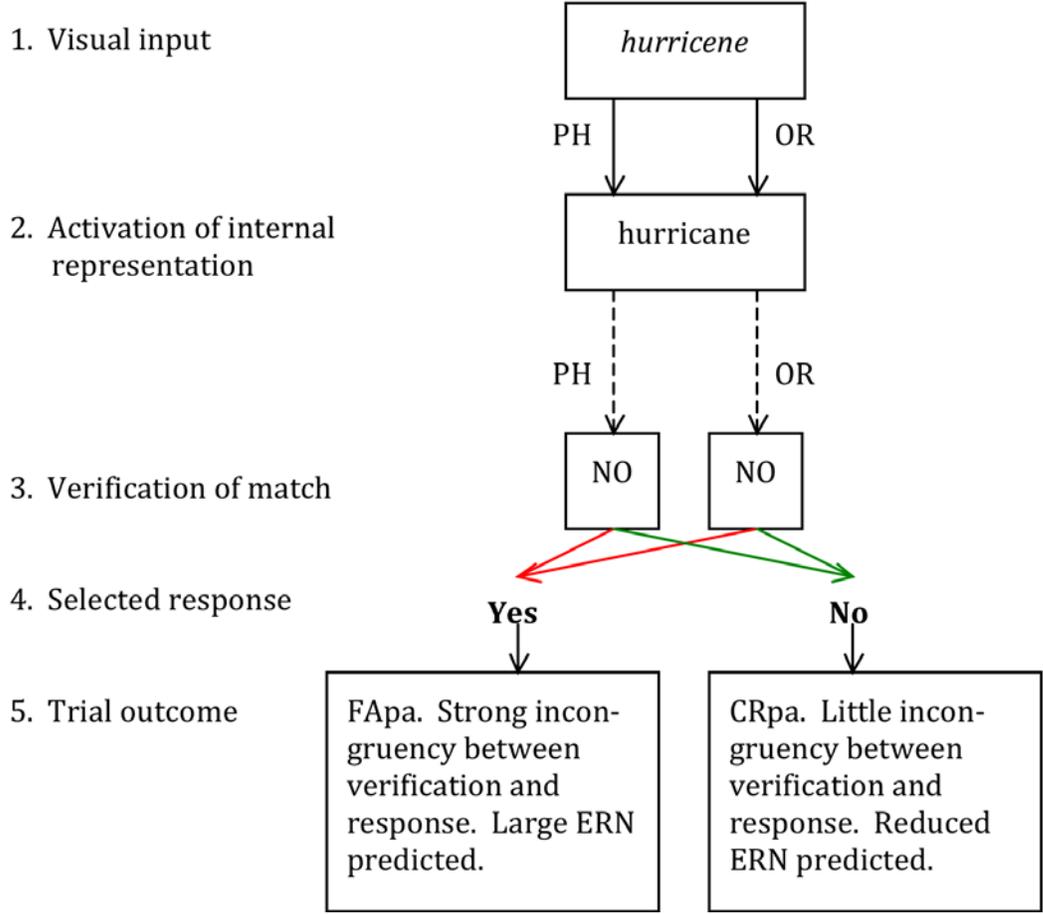


Figure 4c. When the input stimulus is incorrectly spelled and does not preserve the phonology of the correct spelling, neither phonology nor phonology overlap with the representation and a match is not verified. A *Yes* response will create a strong ERN and a *No* response will create a reduced ERN.

**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 *hurricane* (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	<i>hurricane</i> HIT	<i>hurricane</i> MISS
	Foil	<i>hurricain*</i> FALSE ALARM phonology preserving	<i>hurricain*</i> CORRECT REJECTION phonology preserving
		<i>hurricene</i> FALSE ALARM phonology altering	<i>hurricene</i> 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.

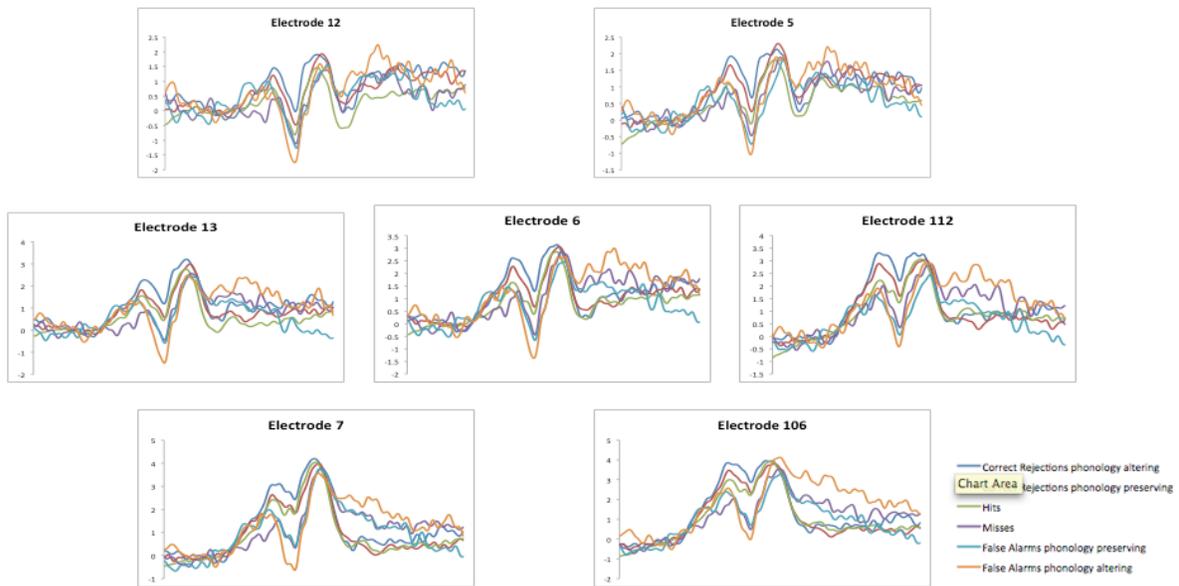
**4.2.1.2 Reaction Times.** As in Experiment 1, we were specifically interested in two comparisons of RT data: whether, when subjects responded *Yes* there was a difference in RTs for hits and FAs and, when subjects responded correctly, there was a difference in RTs for hits and CRs. As to the first 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.

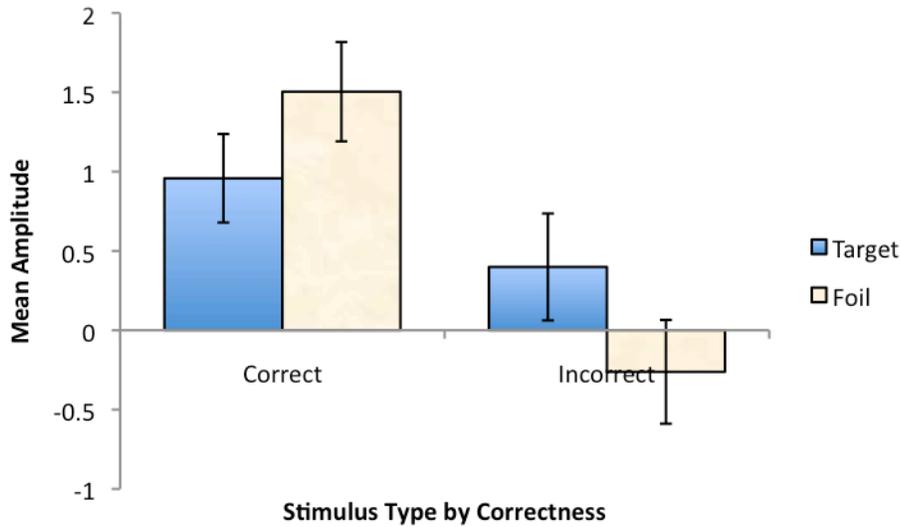
#### **4.2.2 ERP Data.**

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,  $F(1, 23) < 1$ .



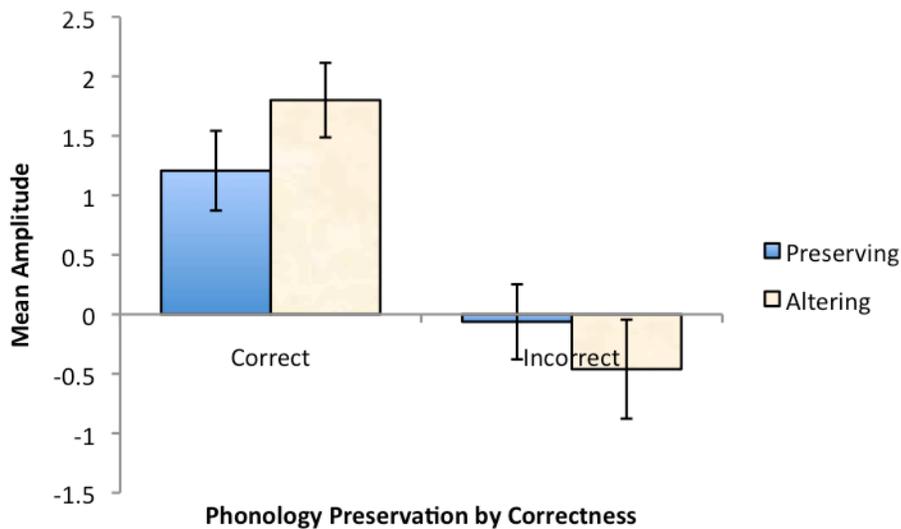
**Figure 6.** Mean amplitude of correct and incorrect target and foil trials for Experiment 2.

#### 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.

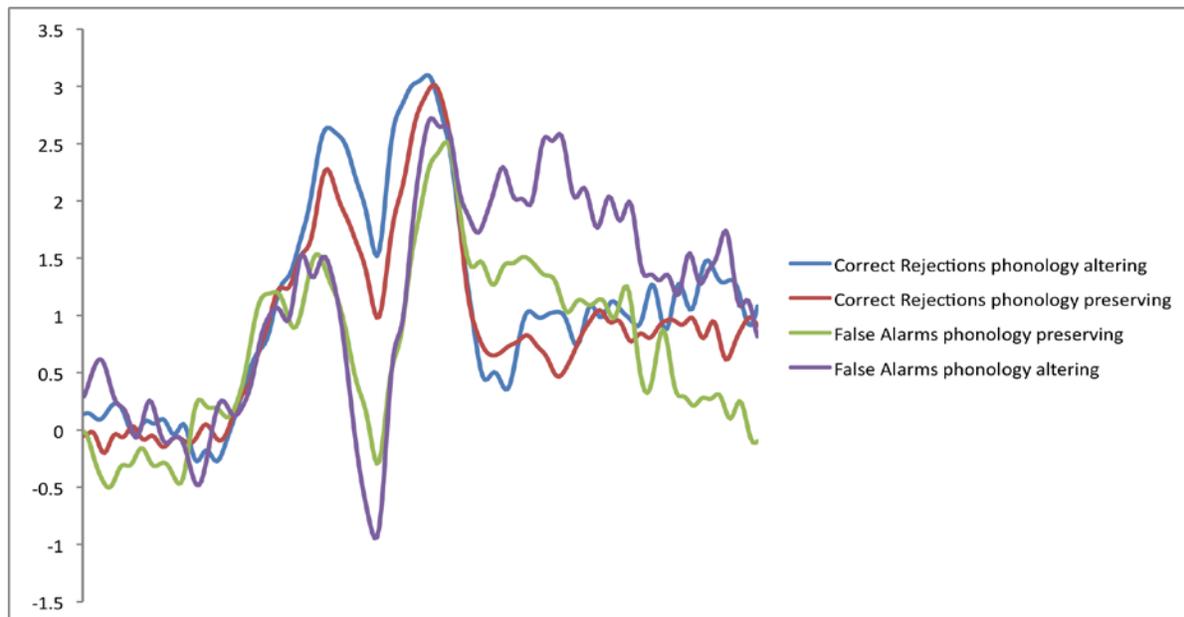
To investigate the relationship between phonology preservation in foil stimuli and ERN patterns, a 2 x 2 ANOVA of correctness (correct, incorrect) by phonology preservation (preserving, altering) was performed. The ANOVA indicated a main effect of correctness,  $F(1, 23) = 26.55$ ,  $p < .001$ , in which 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 FAp 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 FAp 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	alcohol	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	algorithum	asteroid	asteruid	bludgeon	bladgeon
absence	absense	alleged	alledged	astonish	astanish	boisterous	bosterous
abundance	abundence	alligator	alligeter	atrocious	attrocious	bonanza	boninza
accelerate	acelerate	almanac	almunac	attendance	attendence	boomerang	bomerang
accessible	accessable	alphabet	alphanat	attention	atention	boycott	boycot
accessory	acesory	amber	ambur	audible	audable	bribery	bribary
acclaim	aclaim	ambulance	ambulance	audience	audiance	broccoli	broccole
accompany	acompany	amnesia	amnasia	autumn	atumn	brunette	brunnette
accomplice	acomplce	amputate	ampuitate	average	averge	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	antenuh	bandanna	bandenna	caboose	caboase
additional	additonal	antifreeze	antifrieze	banjo	bainjo	cafeteria	cafetaria
address	adress	aortic	ayortic	bankrupt	binkrupt	cajole	cajule
adherent	adherent	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	cashew

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

hundredth	handredth	lantern	laentern	missile	missle	oppress	opress
hunger	hungur	lasagna	lasanga	mistletoe	mistletae	orange	orenge
hurricane	hurricene	legacy	legicy	mocking	moucking	orangutan	orangatan
husband	hasband	legitimate	legitiment	moderate	moderite	orchard	orcherd
hyacinth	hayacinth	leisure	liesure	modified	modafied	oregano	oragano
hybrid	haybrid	lemon	leamon	monarch	moanarch	original	originel
hygiene	hygeine	leotard	leotord	mongoose	mangoose	ostracize	ostricize
hypocrite	hypocrit	library	libary	mongrel	moengrel	outrageous	outragious
iceberg	iceburg	license	licence	monitor	monitir	ovation	ovaotion
ideally	idealy	licorice	licarice	monsoon	mansoon	oxygen	oxygen
ignorance	ignorence	lieutenant	lieutenant	morbid	murbid	padding	padling
iguana	iguona	lightning	leightning	morning	morening	pancake	poncake
imaginary	immaginary	likelihood	likelyhood	morsel	mursel	papaya	papiya
immovable	inmovable	likewise	lekewise	mortgage	morgage	paprika	paprika
immune	imune	lilac	leilac	mortuary	mortuery	papyrus	papayrus
impatient	impetient	limousine	limosine	mosquito	mosquato	paradigm	paradegm
imperial	imperiel	liquid	lequid	mountains	muontains	paradise	paradase
implicit	implicet	loneliness	loneliniss	mouthful	muothful	paradox	paradax
incense	incinse	lottery	lattery	mulberry	muilberry	parallel	paralel
incisor	incesor	loveliest	loevliest	murderous	murderuous	paralyzed	paralized
incognito	incognato	lucrative	lucritive	murmur	murmer	paranoia	paranoa
incumbent	incumbant	ludicrous	luducrous	museum	muesum	paraphrase	pariphrase
indicate	indacate	mafia	mafiuh	mysterious	misterious	parasol	parasoel
indicted	indited	magazine	magizine	mystique	mysteque	parrot	parret
inevitable	inevitable	magically	magicaly	narrative	narriative	particular	particuler
influence	influince	magnolia	magnalia	naughty	nughty	passage	paissage
influenza	infloenza	maiden	maidun	nausea	naseua	pastime	pasttime
innate	inate	malaria	malaria	naval	navel	patriarch	patriurch
innovation	inovation	mammoth	maimmoth	necessary	necenary	pavilion	pavelion
innuendo	inuendo	management	managment	negative	negatuve	pebble	peibble
insomnia	insoimnia	manicure	menicure	negligent	neglagent	peculiar	peculier
insurance	insurence	mannequin	manequin	nemesis	neumesis	pedigree	pedigre
integer	interger	marathon	marathin	neurology	neurolagy	penicillin	penicilin
intercept	intecept	marijuana	marijuona	neutron	nutron	peninsula	penansula
interlude	interluode	marinade	marinede	nibbling	niebbling	perceive	percieve
interpret	interprit	marriage	marrage	ninety	ninty	perilous	pirilous
interrupt	interrupt	maskara	mascaera	nirvana	nirvena	perplex	perplax
irrational	irretional	masquerade	masqueride	nonsense	nensense	persimmon	persemmon
itinerary	itenerary	massage	massoge	normally	normaly	peruse	puruse
ivory	ievory	matinee	matinee	northern	northurn	petroleum	petreleum
jaguar	jaiguar	mattress	matress	nostalgia	nastalgia	petunia	petuonia
jasmine	jismine	maverick	mauverick	nostril	nastril	phoenix	phoenux
jealousy	jealosity	mayonnaise	mayonaïse	notary	notery	physician	physican
jeopardy	jeoperdy	measles	mesles	novice	novace	physique	phisique
jewelry	jewerly	mechanic	mechenic	nuclear	nucular	pickle	pickel
joyful	joivial	medieval	medival	nuisance	nuisence	picnic	picnick
jukebox	jukebox	mediocre	midiocre	obituary	obetuary	pigeon	piegeon
jungle	juingle	melancholy	melanchuly	obliged	obleged	pineapple	pinapple
kangaroo	kangaroo	melody	meloday	obscene	obsene	pinnacle	pennacle
khaki	kakhi	menace	manace	obstacle	obstacle	pistachio	pistaichio
kinetic	kinitic	mesmerize	mesmeraze	occasion	ocasion	pistol	pistul
knapsack	knoapsack	messiah	messeah	occurred	occured	pitiful	pitifull
kneaded	kneadid	metaphor	metiphor	octopus	octopus	placebo	placebo
knowledge	knowlege	mileage	milage	odyssey	odysey	pleasure	plaesure
koala	koula	military	milatary	official	oficial	pocket	pockit
labeled	labelled	mimicked	mimiced	oncology	oncology	poignant	poignent
laboratory	labratory	minimum	minamum	opossum	opposum	polka	polkuh
lackluster	lacklaster	mischief	mischeif	opponent	opponant	popping	poping
lament	lameint	miser	maiser	opposite	oposite	porcelain	percelain

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

## 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	acesory	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	aqire	aqueduct	aquaduct	blizzard	blizard	checkmate	chekmate
across	accross	arena	areuna	blossom	blassom	cheetah	chetah
address	adress	argument	arguement	bludgeon	bladgeon	chemistry	chemastra
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	claurity
alarm	alairm	autumn	atumn	bundle	bundel	cleanser	claenser
alchemy	alchemay	avenue	avunue	bureau	buereau	cobweb	cobwib
alcohol	alcohol	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	algorithn	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	amputate	bargain	bargan	career	carreer	component	component
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	conciuous
anorexia	annorexia	beetle	betle	cashew	cashoew	consistent	consistint
another	anoether	beginning	beginig	category	catagory	constant	constent

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

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

stiletto	stilitto	thousand	thuousand	tyranny	tyrany	waffle	waffel
stranger	strainger	threshold	thrishold	uglier	uiglier	wagon	wagun
strategy	strategy	tickle	tickel	umbrella	umbrulla	walrus	waolrus
subject	subject	tidings	teidings	underdog	underdag	wardrobe	werdrobe
subjugate	subjugite	tiresome	taresome	underwear	underwar	warrant	warrent
success	sucsess	tobacco	tobocco	unhappy	unhaeppy	weird	wierd
sultan	sulten	tomato	tometo	unity	unitay	welcome	waelcome
sunshine	sanshine	tomorrow	tomorrow	usage	usege	welfare	wellfare
support	suppart	tongue	toungue	vacant	vecant	whatever	whataver
supposed	suposed	torch	tortch	vacation	vacotion	whimsical	whemsical
surgery	sergery	tornado	torniedo	vaccine	vaccaine	wicked	wiecked
surprise	suprise	tradition	tradetion	valuable	vailuable	wicker	wickur
swallow	swaillow	tragedy	tradgedy	vampire	vempire	wiggle	wiggel
synthesis	synthasis	treatment	tretment	vanilla	vanella	withered	withured
syringe	syrange	tribunal	tribuonal	vegetable	vegetible	womanly	womenly
tarantula	tarontula	trigger	triggre	velocity	velacity	wonder	wondar
target	targat	trouble	truble	velvet	vealvet	wounded	wuounded
taxation	taxaution	trousers	trouisers	vendetta	vendatta	yacht	yaght
tenacious	tenecious	truncate	trancate	versatile	versitile	zealous	zaelous
tendency	teandency	tsunami	tsunimi	village	vilage	zebra	zibra
Tennessee	Tennessee	tulip	tulup	violin	violan	zenith	zaenith
terrible	terrable	tundra	tuendra	virtuoso	virtuoiiso	zipper	zippar
therefore	therefor	turkey	turkay	visiting	visating	zombie	zambie
thesaurus	thesairus	twelfth	twelth	visitor	vesitor	zucchini	zucchani
thespian	thespien	twenty	tweunty	volcano	volcuno		
thirsty	tharsty	twittered	twettered	voracious	vorecious		
thorough	thurough	typhoon	typhoan	voyage	vayage		

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## FOOTNOTES

<sup>1</sup> 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.

<sup>2</sup> 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.