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Error-Related Negativities During Spelling Judgments Expose Orthographic Knowledge

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Abstract

In two experiments, we demonstrate that error-related negativities (ERNs) recorded during spelling decisions can expose individual differences in lexical knowledge. The first experiment found that the ERN was elicited during spelling decisions and that its magnitude was correlated with independent measures of subjects' 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. Thus, when an error is made in a decision about spelling, the brain processes indexed by the ERN reflect both phonological and orthographic input to the decision process. In both experiments, ERN effect sizes were correlated with assessments of lexical knowledge and reading, including offline spelling ability and spelling-mediated vocabulary knowledge. These results affirm the interdependent nature of orthographic, semantic, and phonological knowledge components while showing that spelling knowledge uniquely influences the ERN during spelling decisions. Finally, the study demonstrates the value of ERNs in exposing individual differences in lexical knowledge.

Keywords

spelling; error-monitoring; orthographic representation; phonological processing; ERPs; error-related negativity

1.0 Introduction

Cognitive neuroscience methods have informed cognitive descriptions of literacy processes and individual differences in two broad ways. 1) Brain imaging methods (fMRI, PET) have identified brain regions associated with skilled processes of word reading, its orthographic, phonological and semantic components, and individual differences in word reading ability (e.g., Shaywitz et al., 1998; Turkletaub et al., 2003). In addition, comparing brain regions as a function of instruction has allowed inferences about learning specific word-reading components (Sandak et al., 2004; Liu et al., 2007). 2) ERP studies with EEGs time-locked to stimulus onset have allowed inferences about the time course of reading, including (among

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others) orthographic identification (N170, Bentin et al., 1999) and meaning selection (N400, Kutas and Hillyard, 1980; Meyer and Federmeier, 2010), while MEGs have shown time-locked activation patterns that link anterior language areas with posterior word recognition areas (Cornelissen et al., 2009). ERPs also have exposed individual differences in reading comprehension skill (St. George et al., 1997; Yang, Perfetti and Schmalhofer, 2005, 2007) and the ability to learn new words (Perfetti et al., 2005), relying again on stimulus-locked latencies and amplitude differences in ERP components (e.g., N400; P600) as indicators of processing.

In general, these studies have informed process descriptions and confirmed individual differences in these processes, rather than directly revealing knowledge differences relevant for literacy. Here we demonstrate the potential of ERPs to expose more directly the knowledge that underlies literacy. Specifically, the response-locked error-related negativity (ERN) may be unique in this potential to expose knowledge: When subjects are induced to make occasional errors in a decision task involving words, ERNs that are associated with these errors can index a subject's knowledge state.

1.1 The Error-Related Negativity

In two experiments, we record ERPs while subjects make spelling decisions, with a focus on the error-related negativity (ERN), a response-locked, negative-going component that has been associated with error detection in decision-making (Falkenstein, Hohnsbein et al., 1991; Gehring, Goss et al., 1993). The ERN generally peaks within 100 ms of a key press, showing a fronto-central scalp distribution. Evidence from dipole modeling (Dehaene, Posner, and Tucker, 1994) converges with evidence from fMRI studies (e.g., Carter et al., 1998) and recordings from nonhuman-primates (Gemba, Sasaki, and Brooks, 1986) to identify the source of the ERN as anterior cingulate cortex (but see Agam et al., 2011). The ERN was taken to signal 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 indexing ongoing conflict between two or more competing responses after one response has been selected (Yeung, Botvinick, and Cohen, 2004; Ganushchak and Schiller, 2009).

Whether the ERN arises directly from error detection through a mismatch process or from an accumulation of conflicting information is beyond the primary goal of the present study, although we return to this question in Section 4.0. Our primary aim is to determine whether the ERN can expose an individual's lexical knowledge as that knowledge is retrieved to guide a decision about the spelling of a presented word.

Prior research suggests the ERN is correlated with at least temporary mental states. For example, 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 discrimination tasks (Pailing and Segalowitz, 2004). (An ERN on correct trials is often termed a correct-related negativity, or CRN.) To the possibility that transient knowledge states (e.g., uncertainty) are associated with ERNs, we add the idea that more permanent knowledge states—e.g., knowledge of written lexical form—can be the cause of the transient mental states (conflict) that produce the ERN. Thus we expect that the "ERN effect"—the difference between the average ERN amplitude on correct and error trials—will reflect both the subject's accuracy in spelling decisions (transient state) and the level of orthographic knowledge (knowledge state) the subject can use to guide the decisions.

The basic understanding of the ERN is grounded in simple perceptual tasks that would be error-free without special conditions imposed by the experiment; e.g., flanker paradigms (e.g., Gehring, Goss et al., 1993; Yeung et al., 2004; Pailing and Segalowitz, 2004; Scheffers and Coles, 2000), which would be virtually error-free if subjects had ample time to examine the visual display. Although linguistic tasks have been much less common than simpler perceptual tasks, Ganushchak and Schiller demonstrated that ERNs can be produced by errors in verbal self-monitoring (2006) and in picture naming (2008) in monolinguals, and Ganushchak and Schiller (2009) and Sebastián-Gallés et al. (2006) used the ERN to explore error monitoring in bilingual subjects during auditory perception of words. In a study of individual differences in reading, Horowitz-Kraus and Breznitz (2008) reported reduced ERN amplitudes for dyslexic readers compared with non-dyslexics for errors in lexical decisions. Together these studies show that ERNs can be sensitive to spoken and written language at multiple linguistic levels (phoneme, word) and to individual differences.

Our focus is on individual differences in lexical knowledge, as reflected in spelling decisions. Although spelling decisions are closely related to lexical decisions, they more directly emphasize the retrieval of detailed word knowledge. Lexical decisions ask whether a letter string is a word, whereas spelling decisions ask whether a letter string is a correct spelling of a (specific) word. Put another way, Norris (2006) notes that a spelling check is an inefficient way to reach a decision about lexicality, practical only when extreme caution is called for. In our task, the subject is led to understand that every string is either a correctly spelled word or misspelling of a specific word. This encourages processes that begin with the activation of lexical entries, extending to the retrieval of the correct spelling, and a comparison of the string with the correct spelling, completing a spelling-verification step. Such processes *can* occur when the judgment is about lexicality as well; our assumption is that a spelling verfication is more likely to occur when the task draws explicit attention to spelling and when the misspelled word represents a variation on a single word that can be retrieved for comparison, as opposed to a large set of similar neighbors.

1.2 Individual Differences in Spelling and Reading

The lexical quality hypothesis (Perfetti and Hart, 2001; Perfetti, 2007) claims that skilled reading emerges from high quality representations of individual words, built on specifications of the three lexical constituents: phonology, orthography, and semantics. In English, because of its nontransparent orthography, spelling can be taken as a single-measure estimate for the quality of orthographic representations, even at the higher levels of reading skill: spelling is error-prone among skilled adult readers (i.e., we can read words that we cannot spell) and takes longer to acquire relative to both phonological knowledge and semantic knowledge. Consistent with this assumption, Chalmers and Burt (2008) showed that individual differences in spelling ability predicted the ability to learn unfamiliar orthographic forms irrespective of training conditions that manipulated phonological and semantic encoding of the forms. They interpreted this as evidence that spelling skill is more than a simple index of reading experience, since all the stimuli in the study were unfamiliar to subjects.

Also showing that spelling ability is something more than reading ability, even among skilled readers, are studies of the effects of form priming by Andrews and colleagues (Andrews and Lo, 2012; Andrews and Hersch, 2010). Their experiments show that inconsistent findings (discussed in Davis and Lupker, 2006) regarding the inhibitory or facilitative effects of backward-masked primes on target word reading are resolved when spelling ability is controlled: 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, 2012; Andrews and Hersch, 2010). As these authors observe, this pattern of results is consistent with an implication of the lexical quality hypothesis: 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.

In the two studies we report in Sections 2.0 and 3.0, we test whether spelling knowledge is sufficiently well specified in adult normal readers to produce an ERN during decisions about a word or its incorrectly spelled foil, when the target word has few orthographic neighbors—i.e., words that differ from the original string by a single letter (Medler and Binder, 2005). This few-neighbors condition supports a decision process that retrieves the correct spelling and compares it with the presented letter string. We hypothesize that, for individuals with sufficiently high orthographic knowledge, ERNs will occur with decision errors. More specifically, we hypothesize an association between ERN amplitude and both online and offline spelling performance, with both higher performance on the spelling task (online) and higher assessed spelling knowledge (offline) associated with large ERN amplitudes. The offline association especially would establish that the ERN can serve as an indicator of lexical knowledge. In the second study, we address whether the ERN can expose the role of phonology in spelling decisions. Because the lexical quality hypothesis predicts that high-quality representations of one lexical constituent both contribute to and result from high-quality representations of other constituents, we also examine the relationship between ERN amplitudes during spelling decisions and performance on a broader range of reading-related measures, including vocabulary knowledge and reading comprehension skill, across both studies.

2.0 Experiment 1

The purpose of Experiment 1 was to demonstrate an ERN effect in a spelling decision task and to test the hypothesis that the ERN magnitude varies with task performance and with individual differences in lexical knowledge, especially orthographic knowledge. Our range of lexical knowledge, especially spelling, had to be narrow. Our claim that ERNs can reflect stable knowledge states entails the idea that only reasonably good spellers will produce ERNs when they commit errors. Indeed, in a pilot study with different materials, we observed very high error rates in spelling decisions and ERNs that were too noisy to be interpretable.

We illustrate our assumption that a spelling decision task relies on specific lexical knowledge in Figure 1. This model applies only to cases in which inputs are either exact matches to real words (thus correctly spelled) or only a letter or two different (foils) from the correctly spelled word.[1] When a subject is instructed to decide whether a stimulus is spelled correctly, the input string will trigger activation of the lexical entry that is the closest match. With high knowledge of the correct spelling, a correctly spelled input finds a quick match, leading to relatively fast decision times (RTs) for target trials. If no exact match is immediately found, as is the case with a misspelled input, the lexical entry most strongly activated by the input is compared with the input string. If orthographic similarity is relatively low (e.g. 2–3 letters different) relative to some threshold, a *No* response is quickly indicated. If orthographic similarity is high, which is the case in this study, the most activated lexical entry is compared with the input (verification) and a mismatch is found.

[1]If the foils were to have no similarity to a real word—say a string of consonants—then there would be little activation of lexical entries. A simple threshold-familiarity process would be sufficient for a decision.

The model shown in Figure 1 merely summarizes the processes that lead to a correct "indication", i.e., what the evidence from the input indicates. Conflict can arise between evidence that indicates a *Yes* response (high overlap in letters) and evidence that indicates a *No* response (less than perfect overlap), which can result in an error (and hence a more negative ERN). Errors may also result from misperceiving the string, incorrectly believing the input spelling is correct, or from some other failure to correctly execute the intended response. Heckhausen and Beckman (1990), Norman (1981), and Reason and Mycielska (1982) offer models that account for so-called "slips", or unintended actions.

Thus, there is no way to know for certain whether a subject has a correct mental representation of a word to which he or she responds incorrectly. However, because our hypothesis rests on the idea that the magnitude of the ERN reflects stable orthographic knowledge, we predict that when errors result from incorrect knowledge of spelling (rather than, for example, from perceptual or motor error) the magnitude of the ERN will be reduced, because there is no mismatch to detect or because there is little conflict, depending on theoretical preferences. If, on the other hand, a correct representation of the word was accessed before the incorrect response was selected, the subject will experience some mismatch between the indicated decision and the executed decision (or, on the alternative perspective, will experience lingering conflict) and the amplitude of the ERN will be greater. Thus, ERN magnitude will provide a window on the orthographic knowledge used in the decision, and better spellers should show greater average ERN effect sizes (i.e., a greater distance between amplitudes on correct and incorrect trials) than poorer spellers.

2.1 Material and methods

2.1.1 Participants—Fifteen University of Pittsburgh undergraduates who had previously completed a variety of reading-related tasks were selected to participate in the study. (Table 1 contains the means, standard deviations, and ranges of relevant reading skills outcomes for our sample.) To ensure that participants would be reasonably good spellers, only students who had performed above average identifying the correctly spelled words on a 140-item checklist were invited to participate. All were right-handed, native speakers of English who had never received a diagnosis of a reading disorder. Participants received financial compensation for their participation.

2.1.2 Stimuli—Stimulus lists included English target words of five to ten letters. A foil (e.g., *hurricene*) was created for each target (e.g., *hurricane*), according to the following rules: (1) The foil must contain no letter strings illegal in English, and thereby represent a plausible misspelling of the target; (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 at least 80% of Amazon Mechanical Turk (AMT) workers during a preliminary materials study (described in the supplementary materials). Eight hundred thirty-three stimulus pairs remained after this process.

The 833 targets and their 833 foils were organized into two lists, with half of the participants performing the experiment with each list, so that the correctly spelled and misspelled versions of the words were viewed an approximately equal number of times across participants. Approximately half the words in each list were targets and half were foils, and a target and its foil were in different lists. Statistics from the orthographic wordform database of the Medical College of Wisconsin (Medler and Binder, 2005) were used to balance the lists on word length, word frequency, orthographic neighborhood frequency, and constrained bigram frequency of targets. Amongst foils, the vast majority (779 of 833) had only one orthographic neighbor, and only 15 had more than two orthographic neighbors. Frequency of target stimuli ranged from 0 (e.g., *chipmunk*) to 647.82 (*children*) per one million, with a mean of 20.63. The complete list of Experiment 1 stimuli is in Appendix A.

2.1.3 Procedure—Stimuli were presented at the center of a computer screen in a random order, using E-Prime (Psychological Software Tools, Pittsburgh, PA) software. Subjects were instructed to hit the *Yes* key if the word they saw was spelled correctly and the *No* key if it was spelled incorrectly. To reduce variance among participants in criterion setting, they 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 350 ms and was followed by an empty black screen for 1150 ms. Participants could respond any time during this 1500-ms interval, after 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 familiarized participants with the procedure. Subsequently, participants received feedback on their performance (black text on a white screen) after every 20 trials. Subjects had a monetary incentive to perform both quickly and accurately: they were offered a bonus for responding within 1500 ms over 98% of the time (all 15 participants earned this bonus) and an additional bonus for every accuracy percentage point of 60 or above. Trials not responded to within 1500 ms were considered errors. The incentive to respond quickly was meant to ensure that subjects occasionally committed errors; the incentive for accuracy was meant to ensure subjects were motivated to perform well (to care about accuracy).

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

Offline, trials were segmented into 700-ms epochs, starting 200 ms before response onset. Segmented data were digitally filtered with a 30-Hz lowpass filter. After bad channels were removed from the recordings and replaced via interpolation of data from surrounding channels, the data were re-referenced to the average of the recording sites. Finally, the ERP segments were corrected relative to a 125-ms baseline ending 75 ms before the response. Electrodes used in statistical analyses correspond to the international 10–20 system electrode FCz (electrode 6) and a cluster of six electrodes surrounding FCz. Data from this cluster, which is the main site of an ERN, was averaged for analyses. To test the effect of conditions on the ERN, we used an adaptive mean amplitude for each participant, defined as the average amplitude for the ERN cluster from +/− 50 ms around the peak negativity that occurred between 25 ms pre-response to 75 ms post-response.

2.2 Results

There were four possible trial outcomes in this experiment. A correct response to a correctly spelled word (target) is a “Hit” and an incorrect response to a target is a “Miss”. A correct response to an incorrectly spelled word (foil) is a “Correct Rejection” (CR) and an incorrect response to a foil is a “False Alarm” (FA). The key data are the participants’ discrimination of target from foil trials, expressed as d-primes, their decision times, and the ERPs associated with the four trial outcomes.

2.2.1 Behavioral Data and Individual Differences

2.2.1.1 Accuracy: Table 2 shows the means, standard deviations, and ranges of the behavioral outcomes for Experiment 1. The average d-prime (d′) of 2.05 indicates high overall accuracy in distinguishing correct from incorrect spellings.

A paired-samples *t*-test indicated more accuracy (i.e., higher percentage correct) on target trials (M = 89.0%) than on foil trials (M = 77.1%), $t(14) = 5.86$, $p < .001$, reflecting a slight *Yes* bias in responding. Discrimination performance (d′) correlated significantly with individual difference measures including performance (assessed by d′) in the offline spelling task ($r = 0.59$, $p < .05$), and the vocabulary composite score ($r = 0.65$, $p < .01$). d′ was also correlated with reading comprehension accuracy ($r = 0.50$, $p = .06$), the reading comprehension composite score ($r = 0.49$, $p = .06$), and phonological awareness ($r = 0.46$, $p = .09$).

2.2.1.2 Reaction Times: A 2 × 2 ANOVA of correctness (correct, incorrect) by stimulus type (target, foil) indicated main effects of correctness, $F(1, 14) = 17.00$, $p < .01$, and stimulus type, $F(1, 14) = 9.36$, $p < .01$. RTs were shorter for correct trials than for incorrect trials and shorter for targets than for foils. However, correctness interacted with stimulus type, $F(1, 14) = 16.62$, $p < .01$, indicating that the correct responses to correctly spelled words were faster than responses to the other three conditions for which RTs did not differ. Moderate correlations between RTs for correct trials and individual difference measures were observed with offline spelling d′ ($r = -0.50$, $p = .06$) and also with the nonverbal intelligence composite score ($r = 0.52$, $p < .05$).

2.2.2 ERP Data and Individual Differences[2]—The grand average ERP reveals a sharp negative deflection at electrode 6 and the surrounding cluster peaking at about 25 ms after the response (Figure 2). Note that negative deflection of the wave towards the peak of the ERN begins roughly 100 ms before the response at each electrode for all trial types. This is unsurprising when considering that conflict or uncertainty surrounding the choice likely arises as soon as a motor sequence, which can take hundreds of milliseconds to execute, is initiated. Use of a keyboard rather than a serial response box also delays recording of the response by approximately 25 ms.

Correct trials were more positive than incorrect trials, confirming a basic ERN effect, $F(1, 14) = 5.65$, $p < .05$. Neither the main effect of stimulus type, $F(1, 14) < 1$, nor the correctness-by-stimulus type interaction, $F(1, 14) < 1$, was significant. To measure the magnitude of 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. In comparing the ERN effect with behavioral data, d′ was used as a measure of behavioral performance, i.e., discrimination between targets and foils. Across participants, the ERN effect and d′ values correlated $r = 0.56$, $p < .05$, confirming the assumption that ERNs reflect performance factors within the experimental task. Moreover, the ERN effect correlated significantly with individual difference measures, especially highly with the offline spelling assessment, which is based on participants' ability to discriminate correctly spelled from incorrectly spelled words ($r = 0.88$, $p < .001$). The ERN effect also correlated with the reading comprehension composite score ($r = 0.55$, $p < .05$) and the vocabulary composite score ($r = 0.62$, $p < .05$).

[2]Although subjects had on average only one error trial for every four correct trials in both this and the following experiment, the ERN is a highly stable component and can be reliably quantified using as few as 6 to 8 error trials (Olvet and Hajcak, 2009; Pontifex et al., 2010). We included all correct and incorrect trials in our analyses, as the ERN should be stable for subjects across the accuracy range.

Because the individual difference measures themselves are inter-correlated, we assessed spelling d′, vocabulary composite score, and reading comprehension composite score as predictors of the ERN effect in a simple linear regression. Whereas offline spelling d′ predicted the ERN effect, $\beta = 0.764$, $t(11) = 5.543$, $p < 0.001$, neither vocabulary ($\beta = 0.363$, $t(11) = 1.798$, $p = 0.100$) nor reading ($\beta = -0.099$, $t(11) = -0.478$, $p = 0.642$) was a significant predictor beyond their shared variance with spelling.

2.3 Discussion

One aim of Experiment 1 was to determine whether ERNs could be elicited in a spelling decision task. The results indicate that, in our sample of competent adult spellers with incentives to be correct, they can. We found more negative ERN amplitudes for Misses than for Hits and for FAs than for CRs. The finding of faster times for *Yes* decisions to correctly spelled words compared with all other conditions is typical in such experiments, and is in line with our model of spelling decisions (Figure 1), which predicts quick *Yes* responses for exact matches of inputs with orthographic representations.

A second aim was to test the hypotheses that ERN magnitudes would depend on spelling performance in the experiment and independently assessed spelling knowledge. Both hypotheses were confirmed. The ERN correlation with in-task performance measured by d′ suggests that the ERN indexes performance factors that determine accuracy, including knowledge states (spelling) and other noncognitive factors that drive performance within the experiment. Furthermore, the correlations of ERN effect size with lexical knowledge (spelling ability, vocabulary) suggest the ERN effect reflects the lexical knowledge that drives spelling decisions. The remarkably high correlation ($r = 0.88$) of ERN magnitude with offline spelling suggests that the ERN obtained during spelling decisions is an indicator of an individual’s spelling-specific lexical knowledge.

Our finding that vocabulary and comprehension measures did not predict the ERN effect when offline spelling performance was included in a regression model echoes the finding of Andrews and Hersch (2010) that spelling but not vocabulary contributed unique variance to reaction times in a masked orthographic neighbor priming task. They suggested that the failure of vocabulary to independently influence performance on orthographic judgments rules out the possibility that poor spellers’ impaired performance is driven solely by the reduction in neighborhood size accompanying smaller vocabularies.

In summary, Experiment 1 showed that the ERN can be elicited during a spelling task and is strongly associated with independent offline measures of spelling knowledge. Experiment 2 builds on these outcomes to address the components of lexical knowledge that are exposed in spelling error detection. Our hypotheses in Experiment 1 were based on a model of spelling decisions that considers only the orthographic similarity between an input and an internal representation. However, phonology and semantic constituents of lexical identity are activated during word identification and therefore could be available to influence decisions about orthography. Experiment 2 proceeds on the assumption that both orthographic and phonological forms are activated by the input string.

3.0 Experiment 2

The purpose of Experiment 2 was to examine the sublexical sources (orthography and phonology) of the error signal(s) produced during a spelling decision, as reflected in the ERN. During the spelling decision process, participants must use their word-specific orthographic knowledge but phonological knowledge, which is closely linked to orthography, may also be used.

Figure 1 illustrated a simple model of spelling decisions in which orthographic similarity between the stimulus and a participant's lexical representation determines spelling decision. We need to complicate the model a little to reflect the conclusion that phonology is activated by the presentation of a written word. (See Halderman, Ashby, and Perfetti (2012) for a recent review of the evidence for phonological activation during printed word reading.) Figure 3 illustrates how signals from both orthographic and phonological sources can lead to errors and to ERNs on incorrect foil trials, i.e., when a participant wrongly says *Yes* to an incorrectly spelled stimulus. If both the orthography and the phonology of the input stimulus have limited overlap with their respective internal representations—e.g., *hurricene* is what is presented and *hurricane* is what is represented—then there are two sources in support of a *No* decision (Figure 3a). The signal from orthography is "no" and the signal from phonology is "no". If the subject, despite these signals for "no", selects *Yes*, indicating that *hurricene* is spelled correctly, a strong error signal—a large ERN—is expected. However, when phonology does not send a "no" signal, as when *hurricain* is presented, then overall evidence for a "no" decision is somewhat weaker, based only on the signal from orthography. If the subject makes an error (selects a *Yes* response), the ERN will be correspondingly weaker (Figure 3b). Faced with competing information from phonological activation, 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 verification stage is needed in many models in which a decision is subject to various sources of competing "noise" from the input (e.g. Van Orden, 1987).

In Experiment 2, we manipulated the phonology of our misspellings to evaluate this model, which is based on the assumption that phonology is activated before a spelling decision is reached. Although the evidence for routine activation of phonology is strong, its occurrence can depend on specific task requirements and an instruction to focus on spelling could lead to some suppression of phonology. Indeed, in lexical decision tasks, phonological effects are often not found (e.g., Davis, Castles, and Iakovidis, 1998; Holyk and Pexman, 2004; but see Kinoshita and Norris, 2012). Thus, if the ERN is affected by phonological information, this will extend the evidence for phonological activation to a situation, spelling decisions, in which suppression of phonology might be advantageous.

3.1 Material and methods

3.1.1 Participants—A new sample of 27 participants who had not participated in Experiment 1 was selected to take part in the experiment. All participants performed above average on the offline spelling assessment and otherwise met the same criteria established for Experiment 1. Data from three participants were excluded from analysis because of excessive EEG artifact or equipment malfunction during recording. Table 3 contains the means, standard deviations, and ranges of relevant reading skills outcomes for our sample.

3.1.2 Stimuli—Targets and foils of 10 letters in the Experiment 1 stimuli were replaced with shorter stimuli to ensure that participants would perceive the full string without an eye movement in the allotted presentation time, and stimuli that led to a disproportionate number of errors in Experiment 1 were replaced with targets and foils that were less difficult. The foils were also manipulated (in accordance with the previously described 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 the preliminary materials study by AMT workers. Foils for which at least six of ten raters indicated that the pronunciation of target and foil were *about the same* were tagged as "phonology-preserving". Examples of phonology-preserving foils include *floride* (target *fluoride*), and *orenge* (target *orange*). Foils for which six of ten raters chose *not the same* were tagged as "phonology-altering". Examples of phonology-altering foils include *hurricene* (target *hurricane*) and *gazille* (target *gazelle*). Thirty-six foils produced an even split among raters judging their phonology, and these were excluded from the analyses in which phonology preservation was included as a variable.

Eight hundred thirty-seven (837) stimulus pairs remained after this process, with 741 of the Experiment 1 stimuli retained. As in Experiment 1, the targets and foils were organized into two lists: half of the stimuli on each list were foils, and half of the foils were phonology-altering. 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. (Thus for *hurricane*, only *hurricene* actually appeared as a foil; *hurricain* did not. This was because it was not possible to have both kinds of foils for all words.)

The two lists were again balanced to control for word length, word frequency, orthographic neighborhood frequency, and constrained bigram frequency of targets, and half the participants performed the experiment with each list. Within and across lists, phonology altering foils and phonology preserving foils were balanced for length and frequency of their targets. Among foils, the vast majority (768 of 837) had only one orthographic neighbor, and only 26 had more than two orthographic neighbors. Frequency of target stimuli ranged from 0 (e.g., *algorithm*) to 1,317.05 (*people*) per one million, with a mean of 29.01. The complete list of Experiment 2 stimuli is listed in Appendix B.

3.1.3 Procedure—The procedure for Experiment 2 was identical to that of Experiment 1.

3.1.4 ERP Data Acquisition and Preprocessing—Data were collected in a manner identical to that of Experiment 1 except for a longer analysis (1200-ms) epoch and a baseline of 200 ms prior to stimulus onset. 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.

3.2 Results

There were six possible trial outcomes in this experiment. Unlike Experiment 1, there were two types of Correct Rejection trials, phonology-preserving (CRpp) and phonology-altering (CRpa), and two types of False Alarm trials, phonology-preserving (FApp) and phonology-altering (FApa). As in Experiment 1, the critical data are 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 assess the effect of phonology preservation.

3.2.1 Behavioral Data and Individual Differences

3.2.1.1 Accuracy: Table 4 contains the means, standard deviations, and ranges of the behavioral outcomes for Experiment 2. The average d′ of 1.96 indicates sufficient accuracy in spelling decisions. Participants were more accurate on target trials (M = 87.5%) than on foil trials (M = 76.7%), $t(23) = 6.11$, $p < .001$, showing a *Yes* bias, as in Experiment 1. They were also more accurate on phonology-altering foils (M = 84.2%) than phonology-preserving foils (M = 69.6%), paired-samples *t*-test, $t(23) = -13.44$, $p < .001$. The maximum accuracy within a given condition was 94.92%, for phonology-altering foils (Table 4), leaving approximately 10 error trials for analysis for the most accurate subject. This is more than the minimum needed to produce a stable ERN (Olvet and Hajcak, 2009; Pontifex et al., 2010). Discrimination performance (d′) correlated significantly with individual difference measures including d′ in the offline spelling task ($r = 0.55$, $p < .01$), vocabulary accuracy ($r = 0.44$, $p < .05$), the vocabulary composite score ($r = 0.44$, $p < .05$), and phonological awareness ($r = 0.62$, $p < .01$).

3.2.1.2 Reaction Times: A 2 × 3 ANOVA of correctness (correct, incorrect) by stimulus type (target, phonology-preserving foil, phonology-altering foil) as a function of response time revealed a significant correctness-by-stimulus type interaction, $F(1, 23) = 24.23$, $p < .001$. A test of the simple main effect of correctness for targets found participants responded faster when responding correctly to a target (684.22 ms) than when responding incorrectly to a target (740.93 ms), $F(1, 23) = 41.63$, $p < .001$. By contrast, a test of the simple main effect of correctness for phonology-preserving foils found participants responded faster when responding incorrectly to a phonology-preserving foil (726.62 ms) than when responding correctly to a phonology-preserving foil (763.96 ms), $F(1, 23) = 13.61$, $p < .01$. No significant simple main effect of correctness for phonology-altering foils was found, $F(1, 23) = 2.24$ (Figure 4). Thus, whether correct decisions were reached more quickly than incorrect decisions was moderated by the type of stimulus.

A test of the simple main effect of stimulus type for correct trials found significant differences between response times for targets (684.22 ms) and phonology-preserving foils (763.96 ms), $p < .001$; for targets and phonology-altering foils (742.85 ms), $p < .001$; and for phonology-preserving foils and phonology-altering foils, $p < .01$. No significant differences were found between response times to targets (740.93 ms), phonology-preserving foils (726.62 ms), and phonology-altering foils (721.82 ms) for incorrect trials. Thus, reaction times were statistically identical for all stimulus types when participants responded incorrectly to the input stimulus, but were reliably different for each stimulus type when participants responded correctly, with targets eliciting the fastest responses and phonology-preserving foils eliciting the slowest responses. These results are consistent with the model of spelling decisions (Figure 1).

Unlike Experiment 1, we found no correlations of reaction times with any individual difference measures.

3.2.2 ERP Data and Individual Differences—As in Experiment 1, the grand average of the Experiment 2 data reveals a clear ERN at the ERN-defined cluster, peaking about 25 ms after the response for all six trial types (Figure 5).

A 2 × 2 ANOVA of correctness (correct, incorrect) by stimulus type (target, foil) indicated a main effect of correctness, $F(1, 23) = 24.97$, $p < .001$, with correct trials more positive than incorrect trials; this finding replicates the correctness main effect reported in Experiment 1. Although the ERN occurred for both targets and foils, the ANOVA showed a correctness-by-stimulus type interaction, $F(1, 23) = 7.71$, $p < .05$, indicating that the effect was larger for foil trials. Such an interaction was not observed in Experiment 1 (note that Miss ERN amplitudes are generally more negative than False Alarm ERN amplitudes in Figure 2, particularly for the two bottommost electrodes in the cluster). This difference between experiments is likely attributable to the fact that the set of stimuli were in general easier in Experiment 2, with foils more recognizable as foils. When foils are hard to identify as such (as in Experiment 1), the participant is more sure of errors to targets, resulting in the more negative amplitude for Misses. When foils are obvious misspellings, participants are more sure of errors to foils, resulting in more negative ERNs for False Alarms.

The magnitude of the ERN was again correlated with the behavioral measure of task performance (d′), $r = 0.46$, $p < .05$. Again as in Experiment 1, the ERN effect correlated significantly with individual difference measures of offline spelling d′ ($r = 0.66$, $p < .001$). The ERN effect also correlated with vocabulary accuracy ($r = 0.45$, $p < .05$) and with phonological awareness ($r = 0.49$, $p < .05$). (Reading comprehension did not produce a significant correlation, unlike Experiment1).

To assess the unique contributions of the individual differences measures to ERN magnitude, we carried out a simple regression analysis. Spelling d′ again significantly predicted the ERN effect, $\beta= 0.542$, $t(19) = 2.474$, $p < 0.05$. As in Experiment 1, with spelling accounted for, neither vocabulary ($\beta = 0.218$, $t(19) = 1.143$, $p = 0.267$) nor phonological awareness ($\beta = 0.044$, $t(19) = 0.200$, $p = 0.844$) was a significant predictor of ERN magnitude. The entire model explained a significant proportion of variance in the ERN effect, $R^2 = 0.494$, $F(3, 19) = 6.191$, $p < 0.01$.

3.2.3 Phonology Preservation—An ANOVA showed an interaction of correctness (correct, incorrect) with phonology (preserving, altering), $F(1, 23) = 7.50$, $p < .05$, indicating that the ERN effect (the difference between correct and incorrect responses) was larger when foils altered the phonology of the target than when they preserved its phonology. To examine further the ERN indicators of phonology-preserving and phonology-altering, we defined the phonology-altering ERN effect (the difference in ERN magnitude between FApa and CRpa trials) and the phonology-preserving ERN effect (the difference in ERN magnitude between FApp and CRpp trials). The phonology-altering ERN effect correlated with offline spelling ability $r = 0.62$, $p < .01$, and the phonology-preserving ERN effect correlated with offline spelling ability $r = 0.70$, $p < .01$. These similar and moderately high correlations suggest that spelling ability is involved in the ERN whether an error is signaled only by orthography or by phonology as well.

3.3 Discussion

The aim of Experiment 2 was to test the hypothesis that both orthography and phonology contribute information to the spelling decision process by whether differences in the phonological similarity of the foil to its target influence the magnitude of the ERN. The results were that the ERN was greater when a correct *No* decision was supported by discrepancies of both phonology and orthography than when the correct *No* decision was supported only by discrepant orthography—that is, the ERN was least negative for correct phonology-altering trials and most negative for incorrect phonology-altering trials.

To elaborate this point, we infer that when there is evidence from both orthography and phonology to support a (correct) decision about a foil (that it is misspelled), the participant experiences less conflict about the correct decision; hence the very positive ERN on CRpa trials. In contrast, with a foil for which there is neither strong phonological nor orthographic evidence that it is correctly spelled, making an error (saying *Yes*) produces error signals from two sources and the very negative average ERN for FApa trials occurs. In FApp trials, an incorrect *Yes* decision is supported by shared phonology and only orthography provides an error signal, so the ERN is less negative than in FApa trials, in which both phonology and orthography signal that an incorrect choice has been made.

In addition, ERN magnitudes were once again correlated with spelling ability as measured by both offline and online tasks. Better spellers showed greater ERN magnitudes, reflecting the role of spelling knowledge in spelling verification (Figure 3). As in Experiment 1, the magnitude of the ERN correlated with other reading-related measures, consistent with the assumption that the spelling ERN may reflect a general literacy ability beyond spelling. However, the dominance of spelling assessment as the best predictor of the spelling ERN indicates a specific orthographic knowledge is most relevant in this task. The somewhat lower correlation of the ERN effect with spelling ability in Experiment 2 compared with Experiment 1 may be 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 prior observations on phonological activation in reading. Phonology becomes activated early enough to affect decisions about whether a word is spelled correctly. We see this effect both in the ERN magnitude and in the behavioral data: foils that altered phonology were responded to 21 ms faster and 14.6% more accurately than phonology-preserving foils.

4.0 General Discussion

The two studies demonstrate that, in adult readers of English who are good spellers, 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, as indicated by spelling assessments. Both experiments also found vocabulary knowledge to be correlated with the ERN. It is reasonable to assume that it is experience with words—thus, knowledge of word meanings—that drives spelling knowledge. However, the results of the regression analyses suggest that the contribution of vocabulary knowledge is absorbed by spelling, which is the more direct window on the knowledge needed to make spelling decisions. It may be surprising to find these effects of spelling knowledge, given the restricted range of spelling scores in our sample. The important implication is that, even among samples of relatively high spelling knowledge, variations in knowledge are functional in tasks that require decisions about spelling. The experiments also found that phonological information is activated early enough in the word-reading process to influence 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 noncognitive explanation for the correlation between ERN magnitude and spelling ability. The best spellers in our sample may have demonstrated the largest ERN effects because they felt they had more at stake in the task than did less good spellers. This motivational explanation implies that better spellers produced ERNs of greater magnitude because they cared more about avoiding an error, and were engaged in more careful monitoring of performance as a result. Ganushchak and Schiller (2008) did find motivational effects on the ERN in a linguistc task: trials tied to a monetary reward produced ERNs of greater amplitude than trials on which no reward was possible. By restricting our sample to individuals who had already performed well on a spelling assessment (and informing them of this fact upon being invited to participate in the study), then offering monetary incentives for good performance to all participants on all trials, the possibility of a motivational effect on the ERN was so well controlled as to be negligible.

Furthermore, the differential error rates between better and poorer spellers are themselves an indicator that cognitive factors were at play. Although we cannot know at the level of individual trials which errors were the result of *mistakes*, i.e., incorrect or incomplete orthographic representations of the word in the mental lexicon, and which were caused by *slips*[3], i.e., motor errors that prevented the intended response from being executed, we would expect the number of slips across participants to vary independently of spelling ability. Any differences between better and poorer spellers with regards to error rates (e.g., the correlation of experimental accuracy with offline spelling in both experiments) should therefore be attributable to mistakes—which, unlike slips, are cognitive in nature—because

[3]"The division [between the two error types] occurs at the level of the intention: A person establishes an intention to act. If the intention is not appropriate, this is a *mistake*. If the action is not what was intended, this is a *slip*" (Lewis and Norman, 1986, p. 414).

we would expect poorer spellers to make relatively more of them. Furthermore, when a better speller does commit a mistake, he or she will be more likely to doubt the selected response, and this increased doubt should be reflected in the amplitude of the ERN. Hence, the larger ERN effect size for better spellers in the present study is additional evidence for our conclusion of a cognitive source for the ERN.

The question of the mechanism that produces the ERN is beyond what our study can address. However, whether a mismatch explanation (e.g., Falkenstein et al., 1991) or a conflict-monitoring explanation (e.g., Yeung, Botvinick, and Cohen, 2004) is more nearly correct does matter for how our primary conclusion—that ERNs can reveal cognitive states, including knowledge representations—is elaborated. On the mismatch account, incorrect spelling responses produce ERNs when they fail to match the intended decision, which in turn depends on the spelling knowledge that is accessed for comparison with the input. This explanation thus assumes that knowledge of spelling is revealed in the ERN.

On the conflict-monitoring hypothesis, the ERN does not arise directly from a mismatch between intention (and thus spelling knowledge) and action. Instead it arises when evidence continues to accumulate after a decision to respond has already been made. For example, if a decision has been reached to say *Yes* to a foil based on its orthographic and phonological overlap with its corresponding lexical entry, that decision can be undermined by late-arriving evidence from a spelling verification process. The ERN then reflects an increase in conflict that arises from this additional accumulation of evidence. On both explanations, it is clear that knowledge states—what the person has been able to retrieve from memory to compare with the input—play an important role. Thus the conclusion that orthographic knowledge is used in the task and that the ERN reflects the use of this knowledge is supported.

Our results add to those of Horowitz-Kraus and Breznitz (2008) in demonstrating systematic individual differences in linguistic ERNs, specifically showing that the ERN can reflect lexical knowledge variability within a population of skilled adults. Beyond these substantive results is the question of the added value of ERN beyond behavior-only measures. In general, we find task performance and reaction times to correlate with spelling knowledge. However, in both experiments the ERN effect correlated more highly with spelling knowledge (i.e., performance on the offline spelling assessment) than did these behavioral measures. We think the ERN recorded during a spelling decision provides a graded view of how much conflict or how severe a mismatch occurs. Theoretically, the ERN can reflect the degree to which orthography is fully specified for an individual across words and for a word across individuals. Practically, however, the mean ERN magnitude of a single participant in this study is an average of widely varying amplitudes recorded for over 800 individual trials, and individual item data, unfortunately, are not assessed.

Our results need also to be considered in relation to those of Andrews and colleagues (Andrews and Lo, 2012; Andrews and Hersch, 2010), who found that orthographic neighbors (e.g., *node* NOTE) and transposed-letter versions of the target (e.g., *clam* CALM) did not prime word targets in good spellers as they did in poor spellers. As these authors pointed out, this result suggests that better spellers have formed more precise lexical representations. The better spellers in the present study can also be characterized as having more precise orthographic representations for more words. Note, though, that in our study, a nonword "prime"—i.e., an incorrect spelling—does prime the (unpresented) correct spelling for skilled spellers, even more than for less skilled spellers, as evidenced by the large ERN following errors by skilled spellers. An important difference between the studies by Andrews and colleagues and the present studies is the neighborhood sizes of the "prime" stimuli. Our foils (primes) were generally a neighbor of only the target word. By contrast, the average number of orthographic neighbors for nonword primes in Andrews and Lo (2012) was 3.3. Additionally, our misspelled words were typically longer than the four- and five-letter words of priming experiments. A recent study consisting of a lexical decision task in which length and neighborhood size of input stimuli were manipulated found reliable phonological priming effects for longer stimuli drawn from sparse orthographic neighborhoods (Kinoshita and Norris, 2012). The findings of the present study corroborate those of Kinoshita and Norris (2012) and suggest that the length and neighborhood-size effects they discovered might be enhanced as spelling skill improves.

The results of the experiments reported here also contribute to the literature on the components of spelling ability. A factor analysis by Perfetti and Hart (2002) suggested that for less-skilled adult readers, orthographic knowledge is not well integrated with knowledge of other lexical components, decoding and vocabulary. Thus, differences in reading ability, defined by comprehension, are associated with lexical knowledge integration across form and meaning. Experiment 1's finding that, within our sample of reasonably skilled spellers, reading comprehension ability is correlated with individual participants' knowledge of orthography (which drives the amplitude of the ERN) provides further evidence for this notion. The models presented here serve as frameworks for spelling decision processes.

The models assume spelling decisions are made across at least two phases when the misspelling is close to a single correct spelling. First is an activation phase, in which an input stimulus activates lexical candidates and spurs the retrieval of a corresponding lexical representation. Second is a verification phase, in which the input stimulus is compared with the representation and verified as a correct spelling only if it shows complete overlap with the orthographic representation.

In summary, the studies give evidence that the ERN can index linguistic knowledge, spelling knowledge in this case, even across a relatively narrow range of individual differences. ERN correlations with lexical knowledge, especially spelling ability, support this conclusion. Furthermore, the studies provide unique evidence that multiple sources of information can contribute to an error signal. The strength of the ERN depended on both phonological and orthographic information that a misspelled word shared with a correctly spelled word. The use of these information sources was observed without significant individual differences in this range of skilled adult readers. As a tentative generalization, it is possible that relatively simple components of lexical knowledge can be exposed through ERNs, e.g., semantic, syntactic, and morpho-syntactic information as well phonological and orthographic.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Appendix A

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

aardvark	aardvirk
abacus	aibacus
abbreviate	abreviate
abdomen	abdomin
abnormal	abnormel
abolition	abulition
absence	absense
abundance	abundence
accelerate	acelerate
accessible	accessable
accessory	accesory
acclaim	aclaim
accompany	acompany
accomplice	acomplice
accomplish	acomplish
accountant	acountant
accumulate	accumalate
acquainted	aquainted
acquiesce	acquiese
acquire	aquire
across	accross
additional	addtional
address	adress
adherent	adherant
adjacent	adjacint
adjacent	ajacent
adjourn	adjurn
admiral	admirel
adobe	aduobe
adolescent	adolesent
aesthetic	asthetic
afraid	affraid
aggravate	aggrivate
aggressive	aggresive
alarm	alairm
albatross	albatrass

alchemy	alchemay
alcohol	alchohol
alcove	alcuove
alfalfa	alfelfa
algebra	algibra
algorithm	algorethm
alleged	alledged
alligator	alligetor
almanac	almunac
alphabet	alphabat
amber	ambur
ambulance	ambulence
amnesia	amnasia
amputate	ampuitate
anatomy	anatamy
anchor	ancor
anchovy	anchavy
annihilate	annhilate
anorexia	annorexia
antecedent	anticedent
antenna	antennuh
antifreeze	antifrieze
aortic	ayortic
apologize	appologize
apparent	apparant
appearance	apearance
appendix	apendix
apples	aepples
apprehend	aprehend
apprentice	aprentice
apricot	apricut
apron	aupron
apropos	apropo
aqueduct	aquaduct
arena	areuna
argument	arguement
argument	argumint
armature	armiture
arsenal	arsinal
artichoke	artichake
ascend	accend
asteroid	asteruid
astonish	astanish

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atrocious	attrocious
attendance	attendence
attention	atention
audible	audable
audience	audiance
autumn	atumn
average	averege
bachelor	bauchelor
balance	ballance
balcony	bailcony
ballerina	ballerana
balloon	baloon
banana	banuna
bandanna	bandenna
banjo	bainjo
bankrupt	binkrupt
barbecue	barbecoe
bargain	bargan
basically	basicaly
bayou	bauyou
bazooka	bazookuh
beaker	beakur
beginning	begining
belief	beleif
believe	beleive
beneath	beneth
benefit	benifit
bequeath	bequeth
biscuit	biscut
blatant	bletant
bleachers	bleechers
blister	blistur
blizzard	blizard
blossom	blassom
bludgeon	bladgeon
boisterous	bosterous
bonanza	boninza
boomerang	bomerang
boycott	boycot
bribery	bribary
broccoli	broccole
brunette	brunnette
budget	budgit

buffalo	buffalao
bundle	bundel
bureau	buereau
burning	buerning
business	buisiness
butterfly	buetterfly
caboose	caboase
cafeteria	cafetaria
cajole	cajule
caliber	calaber
camouflage	camoflage
campus	campis
cannibal	cannibel
capitalism	capitolism
capsize	cepsize
caravan	caraven
career	carreer
caribou	coaribou
caricature	caracature
carpenter	corpenter
cartilage	cartiladge
cashew	cashoew
category	catagory
cathedral	cathidral
cauldron	culdron
cautious	catious
ceiling	ceilling
celibacy	celabacy
ceremony	ceremany
chameleon	cameleon
chandelier	chandalier
changeable	changable
charitable	charitible
chauffeur	chaufeur
checkmate	chekmate
cheetah	chetah
chemistry	chemastry
cherub	chirub
chief	cheif
children	cheldren
chimney	chemney
chimpanzee	chimpanze
chipmunk	chepmunk

chocolate	chacolate
cinnamon	ciennamon
cipher	ciphur
circuit	circut
clarity	claority
cleanser	claenser
coffee	coeffee
coffin	couffin
collision	colision
cologne	colone
colonel	colonell
column	colomn
commission	comission
committed	commited
committee	commitee
comparable	comprable
compare	compair
competent	compatent
completely	completly
component	cumponent
concede	conceed
condemn	condem
condescend	condesend
condolence	condolance
confetti	confatti
conscience	concience
conscious	concious
consistent	consistint
consistent	consitant
conspiracy	conspiricy
continuous	continous
contraband	contrabend
convenient	conveniant
corrupt	corruopt
cotton	coutton
cougar	cuogar
courage	cuorage
courteous	curteous
coyote	coyoute
creature	craeture
crescent	creascent
crimson	cremson
critical	critacal

criticize	critisize
crocodile	crucodile
cupboard	cuboard
daylight	dauylight
dazzling	daizzling
dealership	dealershep
debacle	debecle
debit	deabit
decayed	decuyed
decibel	decible
defense	deffense
defiance	defience
deficits	defacits
definitely	definately
delicate	deilicate
delightful	deleghtful
delivery	delivary
deluxe	delaxe
denture	dinture
deodorant	deoderant
dependent	dependant
descend	decend
desirable	desireable
desperate	desparate
deterrence	deterrance
devoured	devuored
difference	diference
dinosaur	dinosar
diploma	diplama
discipline	disipline
dissident	dissadent
dissonant	dissonent
document	documnet
doesn’t	dosen’t
dollar	doller
dominant	dominent
domineer	domaneer
dowry	dowery
dreadful	draedful
dribbling	dribbiling
drowsy	drawsy
dyslexia	dyslixia
easel	easle

ebony	ebonay
eccentric	eccentrec
ecstasy	extasy
ecstatic	ecstatec
efficiency	efficiancy
eighth	eigth
elaborate	elaberate
elegance	elagance
elegant	eilegant
element	elament
elephant	ealephant
eligible	eligable
elixir	elexir
embargo	embergo
embarrass	embarass
embassy	embussy
embellish	embelish
embrace	embroce
emergency	emergancy
enterprise	enteprise
entice	entaice
enzyme	eunzyme
equinox	equinax
equipment	equipmant
equipped	equiped
eradicate	eradacate
errand	errend
escape	escepe
especially	especialy
establish	establush
eternal	etarnal
etiquette	etiquitte
evenness	eveness
eventually	eventualy
evidently	evidantly
exceed	excede
excellent	excelent
exercise	excercise
exertion	exhertion
exhaust	exhast
experience	experiance
explaining	explaning
extension	extention

extremely	extremley
eyelids	eyeleds
facsimile	faximile
factor	facter
fallacy	falacy
familiar	familliar
fanatic	fanaitic
farewell	farewill
fathom	faethom
fatigue	fategue
feathers	faethers
fiasco	fiesco
fiery	firey
filibuster	filibaster
finesse	fineisse
fission	fision
flamboyant	flambayant
flammable	flamable
flounder	floundur
flourishes	florishes
fluoride	floride
fluttered	flutturеd
foliage	faoliage
forcibly	forcebly
forecast	forcast
foreign	foriegn
forfeit	forfit
forlorn	forlern
forsake	forseke
fortune	furtune
forty	fourty
fragrant	fregrant
frequently	frequintly
frolic	froluc
frustrated	fustrated
fulfill	fufill
furlough	fuerlough
galoshes	guhloshes
garage	garege
garden	gairden
gathered	gaithered
gazelle	gazille
generally	generaly

genesis	geanesis
genius	genious
gerbil	gerbel
gingivitis	gingivatis
giraffe	girrafe
glamour	glaemour
glittered	gliettered
gloomy	gloamy
gnawing	gnaiwing
gorgeous	gergeous
gospel	goespel
government	goverment
governor	govenor
graceful	grauceful
graffiti	grafitti
grammar	grammer
granite	granate
guarantee	guarentee
guard	gaurd
guidance	guidence
guidelines	guidlines
guitar	guitair
handsome	hendsome
happily	happilly
harass	harrass
harmonica	harmanica
harpoon	harpoin
hazard	haizard
heavenly	haevenly
helicopter	helicupter
helpful	helpfull
heretic	heratic
hesitate	heisitate
hickory	heckory
history	hestory
holocaust	holocust
hominy	hominay
honorific	honorifec
hooligan	hoiligan
hopeful	hopefull
horizon	horezon
human	huiman
humorous	humerous

hundredth	handredth
hunger	hungur
hurricane	hurricene
husband	hasband
hyacinth	hayacinth
hybrid	haybrid
hygiene	hygeine
hypocrite	hypocrit
iceberg	iceburg
ideally	idealy
ignorance	ignorence
iguana	iguona
imaginary	immaginary
immovable	inmovable
immune	imune
impatient	impetient
imperial	imperiel
implicit	implicet
incense	incinse
incisor	incesor
incognito	incognato
incumbent	imcumbant
indicate	indacate
indicted	indited
inevitable	inevitible
influence	influince
influenza	infloenza
innate	inate
innovation	inovation
innuendo	inuendo
insomnia	insoimnia
insurance	insurence
integer	interger
intercept	intecept
interlude	interluode
interpret	interprit
interrupt	interupt
irrational	irretional
itinerary	itenerary
ivory	ievory
jaguar	jaiguar
jasmine	jismine
jealousy	jealosy

jeopardy	jeoperdy
jewelry	jewerly
jovial	joivial
jukebox	juokebox
jungle	juingle
kangaroo	kangaro
khaki	kakhi
kinetic	kinitic
knapsack	knoapsack
kneaded	kneadid
knowledge	knowlege
koala	koula
labeled	labelled
laboratory	labratory
lackluster	lacklaster
lament	lameint
lantern	laentern
lasagna	lasanga
legacy	legicy
legitimate	legitiment
leisure	liesure
lemon	leamon
leotard	leotord
library	libary
license	licence
licorice	licarice
lieutenant	lieutenent
lightning	leightning
likelihood	likelyhood
likewise	lekewise
lilac	leilac
limousine	limosine
liquid	lequid
loneliness	loneliniss
lottery	lattery
loveliest	loevliest
lucrative	lucritive
ludicrous	luducrous
mafia	mafiuh
magazine	magizine
magically	magicaly
magnolia	magnalia
maiden	maidun

malaria	malauria
mammoth	maimmoth
management	managment
manicure	menicure
mannequin	manequin
marathon	marathin
marijuana	marijuona
marinade	marinede
marriage	marrage
mascara	mascaera
masquerade	masqueride
massage	massoge
matinee	mattinee
mattress	matress
maverick	mauverick
mayonnaise	mayonaise
measles	mesles
mechanic	mechenic
medieval	medival
mediocre	midiocre
melancholy	melanchuly
melody	meloday
menace	manace
mesmerize	mesmeraze
messiah	messeah
metaphor	metiphor
mileage	milage
military	milatary
mimicked	mimiced
minimum	minamum
mischief	mischeif
miser	maiser
missile	missle
mistletoe	mistletae
mocking	moucking
moderate	moderite
modified	modafied
monarch	moanarch
mongoose	mangoose
mongrel	moengrel
monitor	monitir
monsoon	mansoon
morbid	murbid

morning	morening
morsel	mursel
mortgage	morgage
mortuary	mortuery
mosquito	mosquato
mountains	muontains
mouthful	muothful
mulberry	muilberry
murderous	murderuous
murmur	murmer
museum	muesum
mysterious	misterious
mystique	mysteque
narrative	narriative
naughty	nughty
nausea	naseua
naval	navel
necessary	necesary
negative	negatuve
negligent	neglagent
nemesis	neumesis
neurology	neurolagy
neutron	nutron
nibbling	niebbling
ninety	ninty
nirvana	nirvena
nonsense	nensense
normally	normaly
northern	northurn
nostalgia	nastalgia
nostril	nastril
notary	notery
novice	novace
nuclear	nuculear
nuisance	nuisence
obituary	obetuary
obliged	obleged
obscene	obsene
obstacle	obsticle
occasion	ocasion
occurred	occured
octopus	octupus
odyssey	odysey

official	oficial
oncology	onculogy
opossum	opposum
opponent	opponant
opposite	oposite
oppress	opress
orange	orenge
orangutan	orangatan
orchard	orcherd
oregano	oragano
original	originel
ostracize	ostricize
outrageous	outragious
ovation	ovaotion
oxygen	oexygen
paddling	padling
pancake	poncake
papaya	papiya
paprika	papraika
papyrus	papayrus
paradigm	paradegm
paradise	paradase
paradox	paradax
parallel	paralel
paralyzed	paralized
paranoia	paranoa
paraphrase	pariphrase
parasol	parasoel
parrot	parret
particular	particuler
passage	paissage
pastime	pasttime
patriarch	patriurch
pavilion	pavelion
pebble	peibble
peculiar	peculier
pedigree	pedigre
penicillin	penicilin
peninsula	penansula
perceive	percieve
perilous	pirilous
perplex	perplax
persimmon	persemmon

peruse	puruse
petroleum	petreleum
petunia	petuonia
phoenix	phoenux
physician	physican
physique	phisique
pickle	pickel
picnic	picnick
pigeon	piegeon
pineapple	pinapple
pinnacle	pennacle
pistachio	pistaichio
pistol	pistul
pitiful	pitifull
placebo	placeubo
pleasure	plaesure
pocket	pockit
poignant	poignent
polka	polkuh
popping	poping
porcelain	percelain
porch	portch
portfolio	portfalio
possess	posess
possible	possable
postulate	poustulate
potato	potatoe
power	poawer
precedent	preicedent
precious	pracious
precocious	precacious
preferred	perferred
pregnant	pregnent
prejudice	predjudice
pretended	pretinded
pretzel	pritzel
probably	probally
proceed	procede
promenade	promenede
prominent	prominant
protect	protict
provolone	provolune
prudent	pruodent

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pyramid	payramid
qualify	qualifay
quality	qualaty
quartet	quartit
quinine	quanine
quiver	quiever
quotient	quoitient
raccoon	raccoan
racquet	racquit
receipt	reciept
received	recieved
reckless	reickless
recommend	recomend
reconcile	reconcale
reference	refrence
referred	refered
refurbish	reforbish
rehearsal	rehersal
rejoiced	rejouced
relevant	relivant
religious	religous
remember	remimber
remnants	remnents
renegade	renegode
renowned	reknowned
represent	reprisent
reservoir	resevoir
resilient	risilient
response	responce
restaurant	restarant
restored	restuored
reviewing	reveiwing
revival	reveval
revolution	revalution
rhapsody	rapsody
rheumatism	reumatism
rhinoceros	rhineceros
rhubarb	rhabarb
rhyme	ryhme
rhythm	rythm
ribbon	riebbon
ricochet	ricachet
ridiculous	rediculous

righteous	rightious
rigorous	rigerous
rooster	roostir
sabotage	sabotege
safari	saferi
salami	salomi
salivary	salivery
samurai	samarai
sandal	sandel
sapphire	sopphire
sarcasm	sercasm
satellite	satallite
satin	satinn
saxophone	saxophane
scarlet	scaurlet
scattered	scaittered
scenario	scenurio
schedule	schedual
scolded	scoilded
secretary	secratary
seizure	saizure
separate	seperate
sequin	seuquin
shampoo	shampo
shepherd	shephard
shivered	shevered
shouldn’t	shoudln’t
silver	silvur
similar	simillar
simile	similie
sincerly	sincerely
sinister	senister
skeleton	skeileton
slaughter	slaighter
sleuth	slooth
smuggler	smugglir
sobriety	sobraety
sodium	sodiumn
solitaire	soilitaire
sophomore	sophmore
soprano	sopreno
sorcerer	surcerer
souvenir	souvener

spaghetti	spaghatti
spectrum	spectrim
spinach	spenach
spiral	speiral
splendid	splandid
splinter	splintre
sporadic	sporedic
squalid	squaolid
standard	staendard
stereotype	stireotype
stiletto	stilitto
strategy	strutegy
stupendous	stupandous
subjugate	subjugite
success	sucess
sultan	sulten
sunshine	sanshine
supposed	suposed
surgery	sergery
surprise	suprise
suspension	suspention
swallow	swaillow
synonymous	synonomous
synthesis	synthasis
syringe	syrange
tangerine	tangerane
tantalize	tantaleize
tarantula	tarontula
taxation	taxaution
tenacious	tenecious
tendency	teandency
Tennessee	Tennesee
therefore	therefor
thesaurus	thesairus
thespian	thespien
thorough	thurough
thousand	thuosand
threshold	thrishold
tickle	tickel
tidings	teidings
tiresome	taresome
tobacco	tobocco
tomato	tometo

tomorrow	tommorrow
tongue	toungue
tornado	torniedo
tournament	tournement
tradition	tradetion
tragedy	tradgedy
trajectory	trajactory
tribunal	tribuonal
trigger	triggre
trousers	trouisers
truncate	trancate
tsunami	tsunimi
tulip	tulup
tundra	tuendra
turbulence	turbulance
twelfth	twelth
twenty	tweunty
twittered	twettered
typhoon	typhoan
tyranny	tyrany
uglier	uiglier
umbrella	umbrulla
unity	unitay
usage	usege
useable	usable
usually	usualy
vaccine	vaccaine
valuable	vailuable
vampire	vempire
vanilla	vanella
velocity	velacity
velvet	vealvet
vendetta	vendatta
vernacular	vernaculer
versatile	versitile
vicarious	vicaurious
vigilante	vigilainte
village	vilage
violin	violan
virtuoso	virtuoiso
visitor	vesitor
volcano	volcuno
voracious	vorecious

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

Appendix B

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

Phonology-preserving	
absence	absense
acquire	aquire
adjacent	ajacent
afraid	affraid
ambulance	ambulence
anorexia	annorexia
apparent	apparant
aqueduct	aquaduct
attention	atention
audible	audable
benefit	benifit
bleachers	bleechers
blister	blistur
ceiling	ceilling
collision	colision

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cologne	colone
compare	compair
concede	conceed
defense	deffense
donkey	donky
easel	easle
elegance	elagance
embassy	embussy
emergency	emergancy
encourage	encurage
extension	extention
fluoride	floride
forever	fourever
forty	fourty
furniture	furnature
gallery	gallary
giraffe	girrafe
governor	govenor
grammar	grammer
guardian	gardian
harass	harrass
health	helth
helpful	helpfull
hopeful	hopefull
humorous	humerous
increase	increese
influence	influince
insurance	insurence
khaki	kakhi
leather	lether
license	licence
limousine	limosine
locket	lockit
lucrative	lucritive
mafia	mafiuh
mattress	matress
murmur	murmer
neurology	neurolagy
octopus	octupus
opposite	oposite
orange	orenge
ostracize	ostricize
paralyzed	paralized

pistol	pistul
pitiful	pitifull
poison	poisen
polka	polkuh
porch	portch
possess	posess
proceed	procede
range	rainge
received	recieved
rehearsal	rehersal
remnants	remnents
rhapsody	rapsody
rhyme	ryhme
secretary	secratary
silver	silvur
similar	simillar
speedy	speady
steam	steem
stranger	strainger
supposed	suposed
surgery	sergery
synthesis	synthasis
Tennessee	Tennesee
terrible	terrable
therefore	therefor
tomorrow	tommorrow
torch	tortch
vegetable	vegetible
versatile	versitile
warrant	warrent
welfare	wellfare
wiggle	wiggel
abdomen	abdomin
accessory	accesory
acclaim	aclaim
accompany	acompany
across	accross
adjourn	adjurn
admiral	admirel
aesthetic	asthetic
aggravate	aggrivate
algebra	algibra
anatomy	anatamy

antenna	antennuh
apprehend	aprehend
ascend	accend
audience	audiance
balloon	baloon
bargain	bargan
bazooka	bazookuh
beaker	beakur
beginning	begining
blame	blaime
boycott	boycot
bribery	bribary
cactus	cactas
category	catagory
channel	channal
chauffeur	chaufeur
checkmate	chekmate
cipher	ciphur
committee	commitee
component	cumponent
confirm	conferm
consistent	consistint
constant	constent
courteous	curteous
criticize	critisize
currency	currancy
decorator	decarator
delivery	delivary
deodorant	deoderant
dependent	dependant
dirty	dirtey
dominant	dominent
element	elament
embellish	embelish
equipment	equipmant
equipped	equiped
eradicate	eradacate
errand	errend
exceed	excede
excellent	excelent
exertion	exhertion
factor	facter
familiar	familliar

fiery	firey
flavor	flaver
forcibly	forcebly
forecast	forcast
forfeit	forfit
glory	glorey
group	groop
guarantee	guarentee
guidance	guidence
happily	happilly
hunger	hungur
ignorance	ignorence
immune	imune
implicit	implicet
industry	indistry
interrupt	interupt
knowledge	knowlege
loyal	loyel
magazine	magizine
maiden	maidun
marriage	marrage
military	milatary
missile	missle
modified	modafied
mortgage	morgage
motor	moter
negligent	neglagent
neutron	nutron
northern	northurn
notary	notery
nuisance	nuisence
obscene	obsene
occasion	ocasion
opponent	opponant
orchard	orcherd
original	originel
paddling	padling
pardon	pardan
peculiar	peculier
physique	phisique
pocket	pockit
possible	possable
potato	potatoe

pregnant	pregnent
prominent	prominant
receipt	reciept
relevant	relivant
reservoir	resevoir
response	responce
rhythm	rythm
rigorous	rigerous
royal	royel
satellite	satallite
schedule	schedual
scream	screem
square	squaire
thespian	thespien
thorough	thurough
tickle	tickel
waffle	waffel
wagon	wagun
wicker	wickur
yacht	yaght
answer	anser
celibacy	celabacy
disguise	disgise
exhale	exhail
flounder	floundur
galoshes	guhloshes
gerbil	gerbel
honorific	honorifec
hypocrite	hypocrit
icicle	icecle
indicted	indited
orangutan	orangatan
people	peeple
skate	skaite
sultan	sulten
surprise	suprise
address	adress
aortic	ayortic
appendix	apendix
argument	arguement
arsenal	arsinal
belief	beleif
blizzard	blizard

budget	budgit
bundle	bundel
caliber	calaber
campus	campis
career	carreer
careless	careliss
chemistry	chemastry
chief	cheif
colony	colany
column	colomn
committed	commited
conscious	concious
customer	custamer
daily	dayly
decibel	decible
defiance	defience
descend	decend
destroy	distroy
doesn’t	dosen’t
domineer	domaneer
dowry	dowery
ecstasy	extasy
ecstatic	ecstatec
elixir	elexir
exercise	excercise
famous	famos
flammable	flamable
fluttered	fluttured
funeral	funural
general	genaral
genius	genious
heavily	heavaly
imperial	imperiel
indicate	indacate
innuendo	inuendo
interpret	interprit
jealousy	jealosy
kitchen	kichen
labeled	labelled
lawyer	lauyer
legacy	legicy
mannequin	manequin
marijuana	marijuona

market	markit
matinee	mattinee
mediocre	midiocre
metal	metel
mileage	milage
mortuary	mortuery
mystique	mysteque
necessary	necesary
normally	normaly
obstacle	obsticle
odyssey	odysey
official	oficial
papaya	papiya
parallel	paralel
parrot	parret
pastime	pasttime
perceive	percieve
pickle	pickel
picnic	picnick
poignant	poignent
quality	qualaty
railway	railwey
recommend	recomend
reference	refrence
referred	refered
renowned	reknowned
sophomore	sophmore
spectrum	spectrim
tenacious	tenecious
tragedy	tradgedy
tulip	tulup
twelfth	twelth
tyranny	tyrany
usage	usege
village	vilage
withered	withured
abundance	abundence
amber	ambur
aware	awaire
carrot	carrit
dissident	dissadent
dissonant	dissonent
everyone	evryone

extremely	extremley
fallacy	falacy
incense	incinse
jeopardy	jeoperdy
mascara	mascaera
minimum	minamum
reviewing	reveiwing
ricochet	ricachet
rooster	roostir
salami	salomi
weird	wierd
abnormal	abnormel
acoustic	acustic
anchor	ancor
annual	annuel
balance	ballance
brunette	brunnette
bureau	buereau
coffin	couffin
crimson	cremson
critical	critacal
dollar	doller
eccentric	eccentrec
etiquette	etiquitte
facsimile	faximile
hyacinth	hayacinth
hygiene	hygeine
innate	inate
occurred	occured
oppress	opress
papyrus	papayrus
pedigree	pedigre
religious	religous
righteous	rightious
samurai	samarai
satin	satinn
shepherd	shephard
simile	similie
splinter	splintre
trigger	triggre
vanilla	vanella
biscuit	biscut
competent	compatent

deficits	defacits
eligible	eligable
fission	fision
ludicrous	luducrous
popping	poping
preschool	prescool
sleeve	sleve
success	sucess
alchemy	alchemay
alcohol	alchohol
algorithm	algorethm
armature	armiture
avoid	avoyd
believe	beleive
boomerang	bomerang
cathedral	cathidral
cauldron	culdron
circuit	circut
cupboard	cuboard
eighth	eigth
establish	establush
evidently	evidantly
fatigue	fategue
freeze	freze
furlough	fuerlough
image	imege
kangaroo	kangaro
language	lenguage
massage	massoge
medieval	medival
mischief	mischeif
monarch	moanarch
paradigm	paradegm
position	pusition
pretended	pretinded
represent	reprisent
sandal	sandel
scarlet	scaurlet
sinister	senister
sleuth	slooth
smuggler	smugglir
target	targat
tradition	tradetion

trouble	truble
womanly	womenly
zebra	zibra
Phonology-altering	
another	anoether
baseball	basball
cabbage	cabboge
cherub	chirub
debacle	debecle
lilac	leilac
mechanic	mechenic
promenade	promenede
quinine	quanine
resilient	risilient
shrimp	shremp
unhappy	unhaeppy
walrus	waolrus
wicked	wiecked
abolition	abulition
arena	areuna
bequeath	bequeth
blossom	blassom
breakfast	brakfast
cajole	cajule
cashew	cashoew
chocolate	chacolate
cinnamon	ciennamon
crescent	creascent
decayed	decuyed
entice	entaice
equinox	equinax
exactly	exatly
glamour	glaemour
guideline	guidline
harpoon	harpoin
impatient	impetient
incumbent	imcumbant
integer	interger
ivory	ievory
jaguar	jaiguar
kinetic	kinitic
lantern	laentern
loveliest	loevliest

marinade	marinede
melody	meloday
mongoose	mangoose
monsoon	mansoon
morning	morening
negative	negatuve
ninety	ninty
novice	novace
obituary	obetuary
paradox	paradax
pavilion	pavelion
perilous	pirilous
shampoo	shampo
sodium	sodiumn
spaghetti	spaghatti
tidings	teidings
tribunal	tribuonal
twenty	tweunty
virtuoso	virtuoiso
visiting	visating
welcome	waelcome
wonder	wondar
beneath	beneth
capsize	cepsize
cattle	caettle
chimney	chemney
cleanser	claenser
exist	exest
finesse	fineisse
nausea	naseua
nostalgia	nastalgia
provolone	provolune
station	stetion
unity	unitay
vacant	vecant
zealous	zaelous
zipper	zippar
advice	advaice
alarm	alairm
alligator	alligetor
amputate	ampuitate
apartment	apertment
apricot	apricut

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asteroid	asteruid
balcony	bailcony
bayou	bauyou
broccoli	broccole
burning	buerning
century	centiry
children	cheldren
coffee	coeffee
colonel	colonell
confetti	confatti
corrupt	corruopt
courage	cuorage
denture	dinture
devoured	devuored
document	documnet
dreadful	draedful
dyslexia	dyslixia
ebony	ebonay
eggnog	eggnag
elegant	eilegant
eternal	etarnal
exhaust	exhast
explode	exploide
eyelids	eyeleds
fanatic	fanaitic
forsake	forseke
fragrant	fregrant
garage	garege
gathered	gaithered
goldfish	goldfesh
grapefruit	grapefrit
grateful	gratful
guitar	guitair
handsome	hendsome
hazard	haizard
hesitate	heisitate
hickory	heckory
horizon	horezon
household	househald
human	huiman
immovable	inmovable
incisor	incesor
insomnia	insoimnia

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intercept	intecept
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leotard	leotord
menace	manace
mongrel	moengrel
museum	muesum
nirvana	nirvena
nostril	nastril
paranoia	paranoa
peninsula	penansula
perhaps	perheps
perplex	perplax
physician	physican
pigeon	piegeon
pleasure	plaesure
popcorn	papcorn
portfolio	portfalio
professor	profassor
pyramid	payramid
qualify	qualifay
quiver	quiever
quotient	quoitient
reckless	reickless
regular	regalar
remember	remimber
restored	restuored
ribbon	riebbon
scenario	scenurio
souvenir	souvener
spiral	speiral
standard	staendard
strategy	strutegy
thirsty	tharsty
threshold	thrishold
tobacco	tobocco
tomato	tometo
treatment	tretment
trousers	trouisers
valuable	vailuable
vampire	vempire
vendetta	vendatta
violin	violan
voracious	vorecious

wounded	wuonded
zombie	zambie
aardvark	aardvirk
ballerina	ballerana
blatant	bletant
bludgeon	bladgeon
cougar	cuogar
coyote	coyoute
delicate	deilicate
detriment	ditriment
entertain	entertan
gnawing	gnaiwing
graceful	grauceful
gravey	gravay
hooligan	hoiligan
income	incume
influenza	infloenza
kidnap	kidnep
lottery	lattery
magnolia	magnalia
mailbox	mailbax
manicure	menicure
medicine	midicine
midnight	midneght
morsel	mursel
parasol	parasoel
pebble	peibble
petunia	petuonia
porcelain	percelain
quartet	quartit
shallow	shellow
shivered	shevered
smoke	smoike
sobriety	sobraety
squalid	squaolid
turkey	turkay
zenith	zaenith
alfalfa	alfelfa
apron	aupron
astonish	astanish
autumn	atumn
bachelor	bauchelor
bonanza	boninza

caboose	caboase
cannibal	cannibel
ceremony	ceremany
clarity	claority
comfort	camfort
dazzling	daizzling
debit	deabit
devotion	devoition
dinosaur	dinosar
diploma	diplama
fathom	faethom
feathers	faethers
fiasco	fiesco
forlorn	forlern
fortune	furtune
garden	gairden
genesis	geanesis
gloomy	gloamy
gorgeous	gergeous
gospel	goespel
hundredth	handredth
jewelry	jewerly
jovial	joivial
jukebox	juokebox
leisure	liesure
library	libary
malaria	malauria
maverick	mauverick
mesmerize	mesmeraze
messiah	messeah
mimicked	mimiced
oncology	onculogy
oregano	oragano
ovation	ovaotion
patriarch	patriurch
pillow	pilluw
pineapple	pinapple
placebo	placeubo
popular	papular
power	poawer
precious	pracious
probably	probally
prudent	pruodent

raccoon	raccoan
rainstorm	rainsturm
rejoiced	rejouced
return	retarn
sabotage	sabotege
sarcasm	sercasm
scolded	scoilded
shouldn’t	shoudln’t
skeleton	skeileton
splendid	splandid
sporadic	sporedic
stiletto	stilitto
subject	subjact
sunshine	sanshine
tarantula	tarontula
tendency	teandency
tiresome	taresome
tornado	torniedo
twittered	twettered
typhoon	typhoan
underdog	underdag
velocity	velacity
visitor	vesitor
volcano	volcuno
wardrobe	werdrobe
adobe	aduobe
beetle	betle
dishonest	dishanest
gazelle	gazille
invent	invint
junction	juntion
monkey	mankey
mosquito	mosquato
mouthful	muothful
myself	mysilf
nonsense	nensense
reconcile	reconcale
refurbish	reforbish
renegade	renegode
seashore	seashare
thousand	thuosand
umbrella	umbrulla
vacation	vacotion

velvet	vealvet
almost	almoist
amnesia	amnasia
anchovy	anchavy
banana	banuna
banjo	bainjo
bankrupt	binkrupt
business	buisiness
cafeteria	cafetaria
caravan	caraven
carpenter	corpenter
cautious	catious
cobweb	cobwib
cotton	coutton
crocodile	crucodile
drowsy	drawsy
embargo	embergo
embrace	embroce
enzyme	eunzyme
escape	escepe
farewell	farewill
garbage	gerbage
haircut	haircat
halfway	halfwoy
heavenly	haevenly
history	hestory
hurricane	hurricene
husband	hasband
hybrid	haybrid
hydrant	haydrant
incognito	incognato
jasmine	jismine
jellyfish	jillyfish
lament	lameint
lemon	leamon
likewise	lekewise
liquid	lequid
mammoth	maimmoth
marathon	marathin
moderate	moderite
Monday	Mondoy
morbid	murbid
mountains	muontains

mulberry	muilberry
naughty	nughty
nemesis	neumesis
nibbling	niebbling
oatmeal	oatmel
obliged	obleged
paradise	paradase
petroleum	petreleum
plastic	plestic
pretzel	pritzel
pronounce	pronunce
recover	recaver
revival	reveval
sapphire	sopphire
saxophone	saxophane
seizure	saizure
sideways	sidewuys
slaughter	slaighter
soprano	sopreno
subjugate	subjugite
swallow	swaillow
syringe	syrange
taxation	taxaution
truncate	trancate
tundra	tuendra
vaccine	vaccaine
voyage	vayage
airplane	airplone
alcove	alcuove
artichoke	artichake
barbecue	barbecoe
caribou	coaribou
creature	craeture
damage	demage
daughter	dughter
daylight	dauylight
elbow	elbaw
holocaust	holocust
ignore	ignare
jungle	juingle
knapsack	knoapsack
mistletoe	mistletae
pancake	poncake

paprika	papraika
protect	protict
quicksand	quicksond
remark	remerk
rhubarb	rhabarb
safari	saferi
scarecrow	scarecraw
sequin	seuquin
support	suppart
tsunami	tsunimi
uglier	uiglier
underwear	underwar
zucchini	zucchani
Even Splits	
awkward	akward
enough	enogh
frolic	froluc
itinerary	itenerary
lasagna	lasanga
licorice	licarice
phoenix	phoenux
pinnacle	pennacle
racquet	racquit
tongue	toungue
whimsical	whemsical
almanac	almunac
alphabet	alphabat
apples	aepples
avenue	avunue
buffalo	buffalao
cheetah	chetah
elephant	ealephant
evenness	eveness
foreign	foriegn
fulfill	fufill
granite	granate
guard	gaurd
harmonica	harmanica
helmet	helmat
heretic	heratic
journal	jornal
metaphor	metiphor
monitor	monitir

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nuclear	nuculear
oxygen	oexygen
preferred	perferred
shoulder	shulder
spinach	spenach
thesaurus	thesairus
whatever	whataver

Highlights

- An ERN can be elicited in a spelling decision task
- ERN magnitude in the task varies with individual differences in lexical knowledge
- Both phonological and orthographic sources of information affect an error signal
- Stable knowledge states underlie transient knowledge states that produce the ERN
- Findings support original models of spelling decision processes

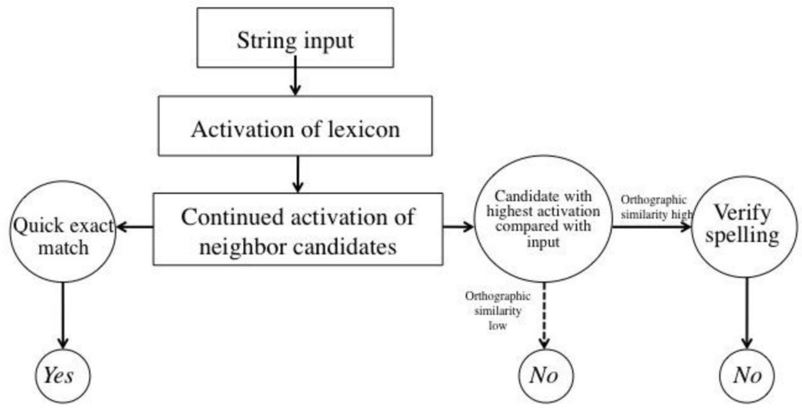

Figure 1.
Process model of spelling decisions. When instructed to decide if a stimulus is spelled correctly, the input string will trigger activation of the lexicon and then continued activation of similar orthographic entries. If an exact match is quickly identified, a quick *Yes* response (or *No* response, if the participant's threshold for responding is low) is indicated. If no exact match is immediately identified, the lexical entry most strongly activated by the input is compared with the input string. If orthographic similarity is low, a *No* response is quickly indicated. If orthographic similarity is high, spelling verification occurs before the *No* response is indicated.

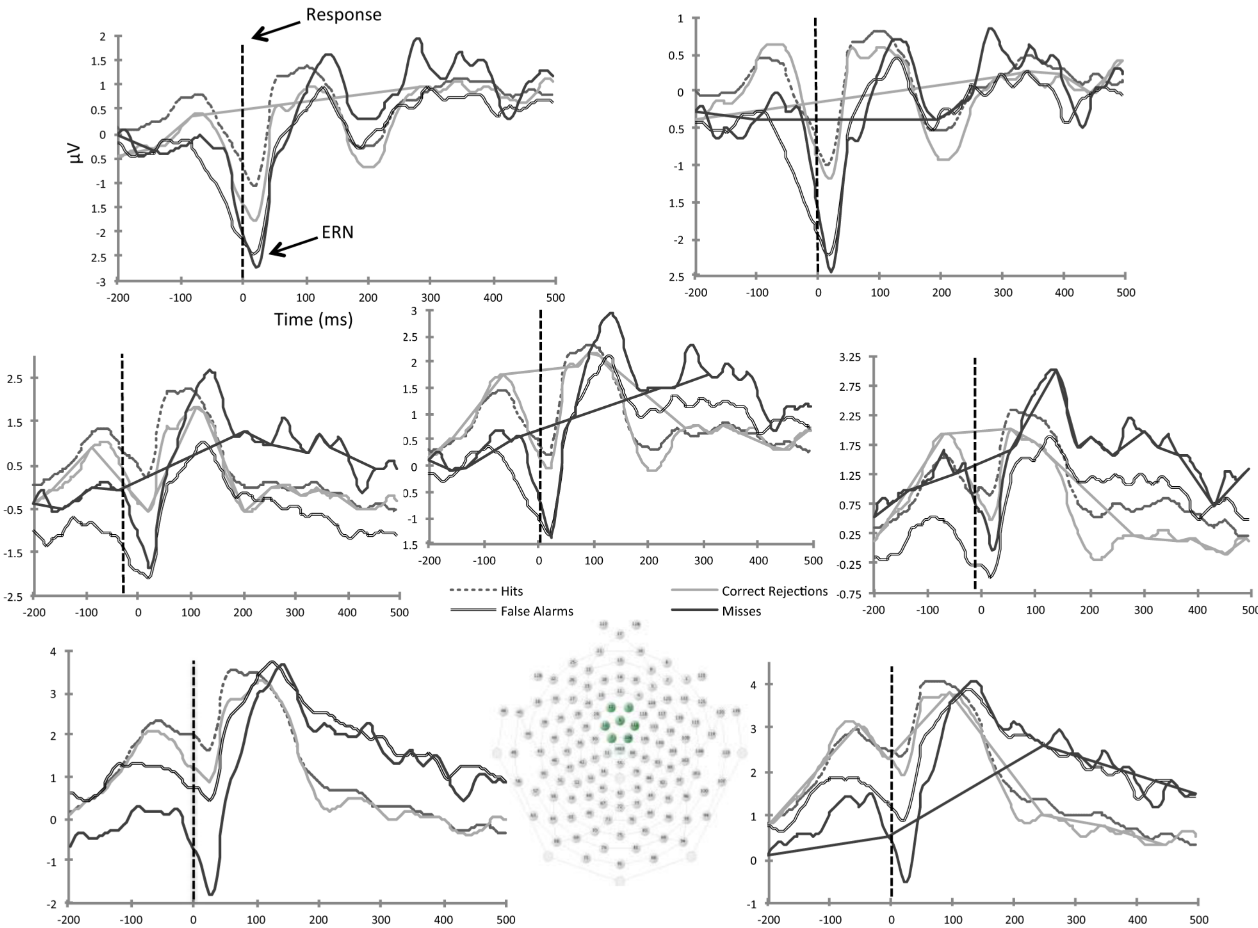

Figure 2.
The grand average of EEG activity surrounding the response for each electrode in our cluster of interest for Experiment 1 (note that positive voltages are plotted upwards and negative voltages are plotted downwards throughout the present study). Here and in Figure 5, the electrodes shown correspond to EGI electrodes 6 (center) and (clockwise from top left) 12, 5, 112, 106, 7, and 13. The ERN's peaking shortly after the response is likely due to the delay between the response decision and the key press.

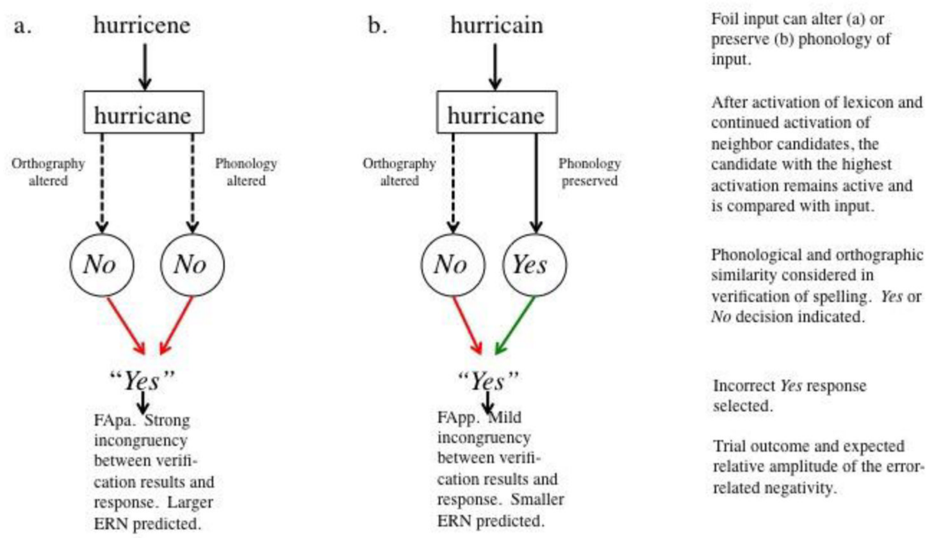

Figure 3.
Process model of errors made to foils and ERN outcomes. a.) When the input stimulus is incorrectly spelled and does not preserve the phonology of the correct spelling, both the orthographic and phonological similarity between the stimulus and the orthographic representation will be relatively low. An incorrect *Yes* response (i.e., a False Alarm) will create a larger ERN. b.) When the input stimulus is incorrectly spelled but preserves the phonology of the correct spelling, the orthographic similarity between the stimulus and the orthographic representation will be relatively low but the phonological similarity between the two will be higher. These mixed signals will lead to a smaller ERN in the case of an incorrect *Yes* (i.e., False Alarm)response. FApa = phonology-altering False Alarm; FApp = phonology-preserving False Alarm

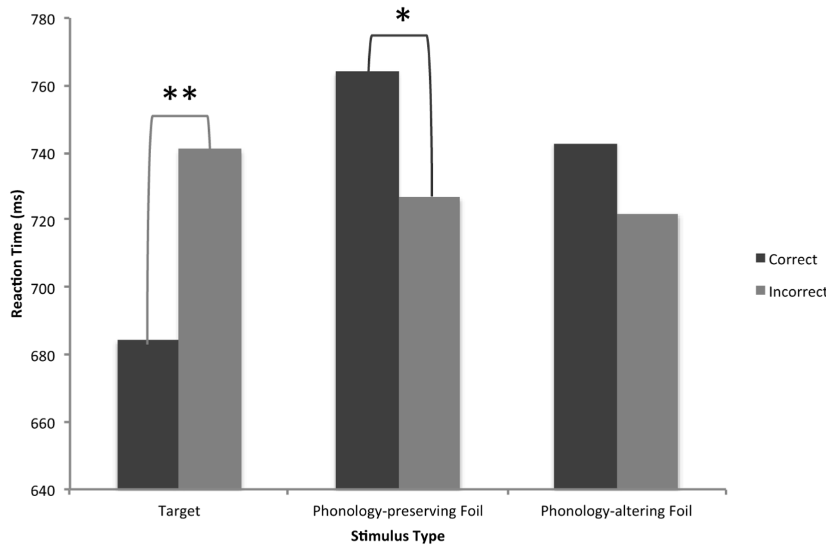

Figure 4.
Mean reaction times as a function of stimulus type (target; phonology-preserving foil; phonology-altering foil) and trial outcome (correct; incorrect) for Experiment 2.

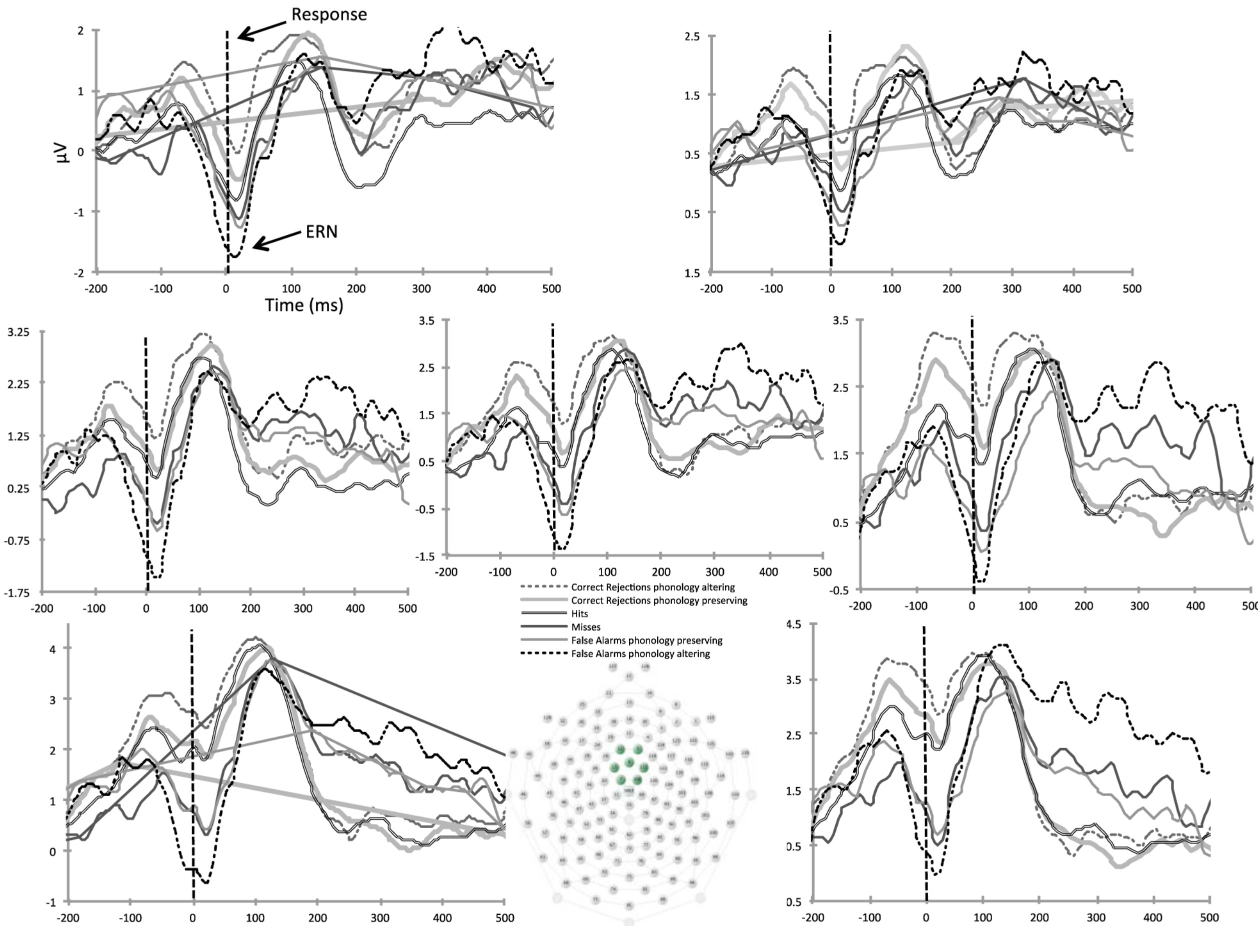

Figure 5.

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

Table 1

Descriptive Statistics for Selected Individual-Differences Variables in Experiment 1 [a]

Reading-Related Skill	Measure	Min	Max	Mean	Std. Dev.
Spelling ability	d′	1.86	3.02	2.41	0.31
Reading comprehension	Composite score	7.20	30.00	20.88	6.88
	% Accuracy	62.00	94.00	82.90	9.70
Vocabulary knowledge	Composite score	7.60	94.00	53.28	21.14
	% Accuracy	50.00	100.00	85.00	12.10
Nonverbal intelligence	Composite score	−1.13	14.63	6.98	4.95
	% Accuracy	1.00	88.00	47.20	26.10
Phonological awareness	% Accuracy	42.00	100.00	80.60	19.60

[a] N = 15 for all variables. Spelling skills and phonological awareness were assessed using the Lexical Knowledge Battery developed by Perfetti and Hart (2001). 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 defined as (number correct) – [(number incorrect and unanswered)/(number response choices].

Table 2

Descriptive Statistics for the Behavioral Outcome Measures in Experiment 1 [a]

Behavioral measure	Min	Max	Mean	Std. Dev.
Overall Accuracy (%)	71.60	92.60	83.00	6.10
d′	1.15	2.91	2.05	0.50
Overall Reaction Time (ms)	517.00	982.00	726.00	127.00
Hits RT	511.54	957.95	697.82	122.77
Misses RT	506.45	1026.76	765.18	140.13
Correct Rejections RT	522.36	1007.42	759.32	133.26
False Alarms RT	508.09	1025.18	748.52	146.66

[a]N=15. Note that only correct trials were considered in the overall reaction time measure.

Table 3

Descriptive Statistics for Selected Individual-Differences Variables in Experiment 2 [a]

Reading-Related Skill	Measure	Min	Max	Mean	Std. Dev.
Spelling ability	d′	1.72	3.26	2.22	0.37
Reading comprehension	Composite score	0.00	33.60	21.40	7.42
	% Accuracy	68.00	94.00	81.40	7.20
Vocabulary knowledge	Composite score	6.40	95.20	49.09	19.42
	% Accuracy	58.00	96.00	83.30	10.60
Nonverbal intelligence	Composite score	−2.25	12.38	5.86	4.55
	% Accuracy	00.00	85.00	43.80	26.40
Phonological awareness	% Accuracy	27.00	98.00	80.00	16.90

[a] 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.

Table 4

Descriptive Statistics for the Behavioral Outcome Measures in Experiment 2[a]

Behavioral measure	Min	Max	Mean	Std. Dev.
Overall Accuracy (%)	67.00	92.80	82.10	6.50
Phon-Altering Foils	60.62	94.92	84.20	8.22
Phon-Preserving Foils	40.71	91.67	69.60	11.98
d′	1.06	2.93	1.96	0.48
Overall Reaction Time (ms)	541.00	864.00	716.00	91.00
Hits RT	499.00	825.43	684.22	89.73
Misses RT	516.46	985.49	740.92	113.56
Correct Rejections RT	588.85	909.61	753.01	94.42
False Alarms RT	488.09	916.32	724.87	116.01

[a]N=24. Note that only correct trials were considered in the overall reaction time measure.