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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.

1. 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; Turkeltaub, Gareau, Flowers, Zeffiro, & Eden, 2003). In addition, comparing brain regions as a function of instruction has allowed inferences about learning specific word-reading components (Liu, Dunlap, Fiez, & Perfetti, 2007; Sandak et al., 2004). (2) ERP studies with EEGs time-locked to stimulus onset have allowed inferences about the time course of reading, including (among others) orthographic identification (N170, Bentin et al., 1999) and meaning selection (N400, Kutas & Hillyard, 1980; Meyer & 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, Mannes, & Hoffman, 1997; Yang, Perfetti, & 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, Hoormann, & Blanke, 1991; Gehring, Goss, Coles, Meyer, & Donchin, 1993). The ERN generally peaks within 100 ms of a key press, showing a fronto-central scalp distribution. Evidence from dipole modeling (Dehaene, Posner, & Tucker, 1994) converges with evidence from fMRI studies (e.g., Carter et al., 1998) and recordings from nonhuman-primates (Gemba, Sasaki, & Brooks, 1986) to identify the

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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 (Coles, Scheffers, & Holroyd, 2001; Falkenstein et al., 1991). 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 (Ganushchak & Schiller, 2009; Yeung, Botvinick, & Cohen, 2004).

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. 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 & 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 & 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; Pailing & Segalowitz, 2004; Scheffers & Coles, 2000; Yeung et al., 2004), 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 (2006) demonstrated that ERNs can be produced by errors in verbal self-monitoring and in picture naming (Ganushchak & Schiller, 2008) in monolinguals, and Ganushchak and Schiller (2009) and Sebastián-Gallés, Rodríguez-Fornells, de Diego-Balaguer, and Díaz (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, 2007; Perfetti & Hart, 2001) 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 & Hersch, 2010; Andrews & Lo, 2012). Their experiments show that inconsistent findings (discussed in Davis & 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 & Hersch, 2010; Andrews & Lo, 2012). 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 and 3, 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 & 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. 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 Fig. 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.

The model shown in Fig. 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 Beckmann (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.

[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.

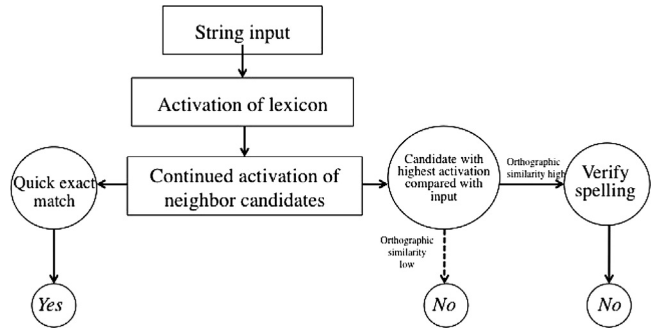

Fig. 1. Process model of spelling decisions. When instructed to decide if a stimulus is spelled correctly, the input string will trigger activation of the lexicon and then continued activation of similar orthographic entries. If an exact match is quickly identified, a quick Yes response (or No response, 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.

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

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, & 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)].

[a] $N=15$ for all variables.

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 & 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 provided 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 (150–400 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 0.1–200 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 and 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.

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

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

A paired-samples *t*-test indicated more accuracy (i.e., higher percentage correct) on target trials ($M=89.0\%$) than on foil trials ($M=77.1\%$), $t(14)=5.86$, $p<0.001$, 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 ($r=0.59$, $p<0.05$), and the vocabulary composite score ($r=0.65$, $p<0.01$). d' was also correlated with reading comprehension accuracy ($r=0.50$, $p=0.06$), the reading comprehension composite score ($r=0.49$, $p=0.06$), and phonological awareness ($r=0.46$, $p=0.09$).

2.2.1.2. Reaction times. A 2×2 ANOVA of correctness (correct, incorrect) by stimulus type (target, foil) indicated main effects of correctness, $F(1, 14)=17.00$, $p<0.01$, and stimulus type, $F(1, 14)=9.36$, $p<0.01$. RTs were shorter for correct trials than for incorrect trials and shorter for targets than for foils. However, correctness interacted with stimulus type, $F(1, 14)=16.62$, $p<0.01$, 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' ($r=-0.50$, $p=0.06$) and also with the nonverbal intelligence composite score ($r=0.52$, $p<0.05$).

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 (Fig. 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, $F(1, 14)=5.65$, $p<0.05$. 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 $r=0.56$, $p<0.05$, confirming the assumption that ERNs reflect

[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 6–8 error trials (Olvet & 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.

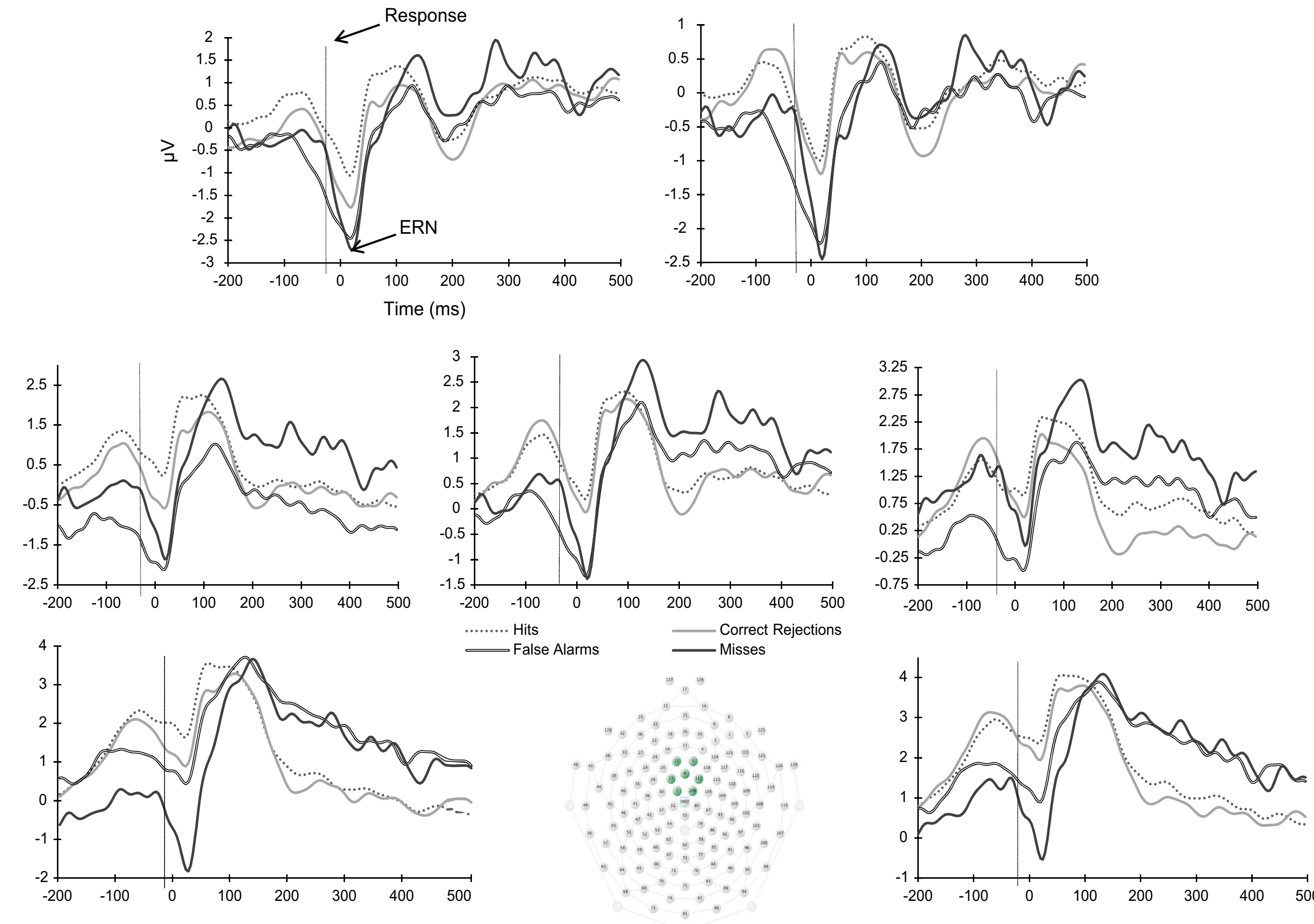

Fig. 2. The grand average of EEG activity surrounding the response for each electrode in our cluster of interest for Experiment 1 (note that positive voltages are plotted upwards and negative voltages are plotted downwards throughout the present study). Here and in Fig. 5, the electrodes shown correspond 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.

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 ($r=0.88$, $p<0.001$). The ERN effect also correlated with the reading comprehension composite score ($r=0.55$, $p<0.05$) and the vocabulary composite score ($r=0.62$, $p<0.05$).

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 (Fig. 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. 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.

Fig. 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.) Fig. 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 (Fig. 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 (Fig. 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, & Iakovidis, 1998; Holyk & Pexman, 2004; but see Kinoshita & 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

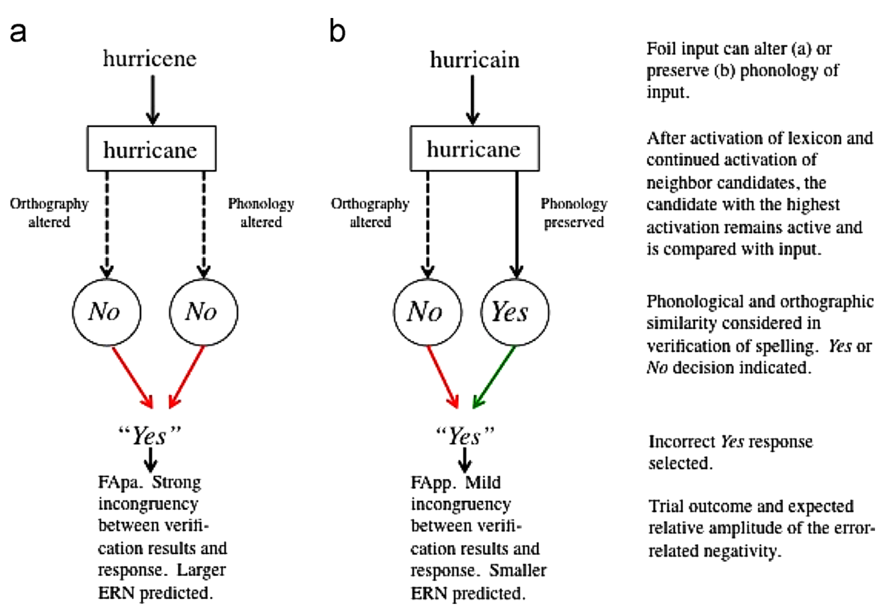

Fig. 3. Process model of errors made to foils and ERN outcomes: (a) When the input stimulus is incorrectly spelled and does not preserve the phonology of the correct spelling, both the orthographic and phonological similarity between the stimulus and the orthographic representation will be relatively 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

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 1317.05 (*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.

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

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.

[a] $N=24$ for all variables except phonological awareness.

3.2.1. Behavioral data and individual differences

3.2.1.1. Accuracy. Table 4 shows 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 ($M=76.7\%$), $t(23)=6.11$, $p<0.001$, 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, $t(23)=-13.44$, $p<0.001$. 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 number needed to produce a stable ERN (Olvet & Hajcak, 2009; Pontifex et al., 2010). Discrimination performance (d') correlated significantly with individual difference measures including d' in the offline spelling task ($r=0.55$, $p<0.01$), vocabulary accuracy ($r=0.44$, $p<0.05$), the vocabulary composite score ($r=0.44$, $p<0.05$), and phonological awareness ($r=0.62$, $p<0.01$).

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, $F(1, 23)=24.23$, $p<0.001$. 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), $F(1, 23)=41.63$, $p<0.001$. 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), $F(1, 23)=13.61$, $p<0.01$. No significant simple main effect of correctness for phonology-altering foils was found, $F(1, 23)=2.24$ (Fig. 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), $p<0.001$; for targets and phonology-altering foils (742.85 ms), $p<0.001$; and for phonology-preserving foils and phonology-altering foils, $p<0.01$. 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

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

Note that only correct trials were considered in the overall reaction time measure.

[a] $N=24$.

foils eliciting the slowest responses. These results are consistent with the model of spelling decisions (Fig. 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 (Fig. 5).

A 2×2 ANOVA of correctness (correct, incorrect) by stimulus type (target, foil) indicated a main effect of correctness, $F(1, 23)=24.97$, $p<0.001$, 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, $F(1, 23)=7.71$, $p<0.05$, 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 Fig. 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'), $r=0.46$, $p<0.05$. Again as in Experiment 1, the ERN effect correlated significantly with individual difference measures of offline spelling d' ($r=0.66$, $p<0.001$). The ERN effect also correlated with vocabulary accuracy ($r=0.45$, $p<0.05$) and with phonological awareness ($r=0.49$, $p<0.05$). (Reading comprehension did not produce a significant correlation, unlike Experiment 1.)

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, $R^2=0.494$, $F(3, 19)=6.191$, $p<0.01$.

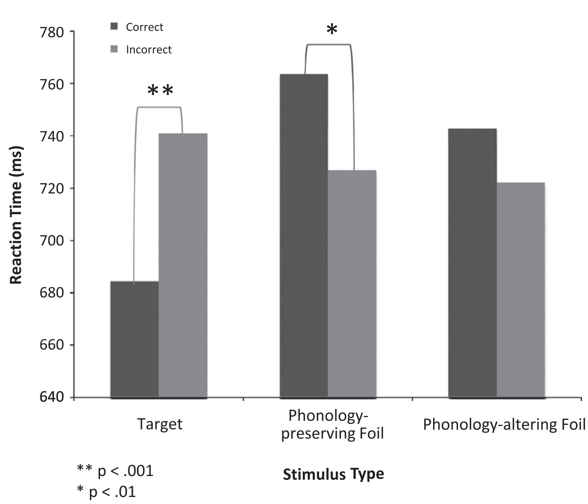

Fig. 4. Mean reaction times as a function of stimulus type (target; phonology-preserving foil; phonology-altering foil) and trial outcome (correct; incorrect) for Experiment 2.

3.2.3. Phonology preservation

An ANOVA showed an interaction of correctness (correct, incorrect) with phonology (preserving, altering), $F(1, 23)=7.50$, $p<0.05$, 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 $r=0.62$, $p<0.01$, and the phonology-preserving ERN effect correlated with offline spelling ability $r=0.70$, $p<0.01$. 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 (Fig. 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.

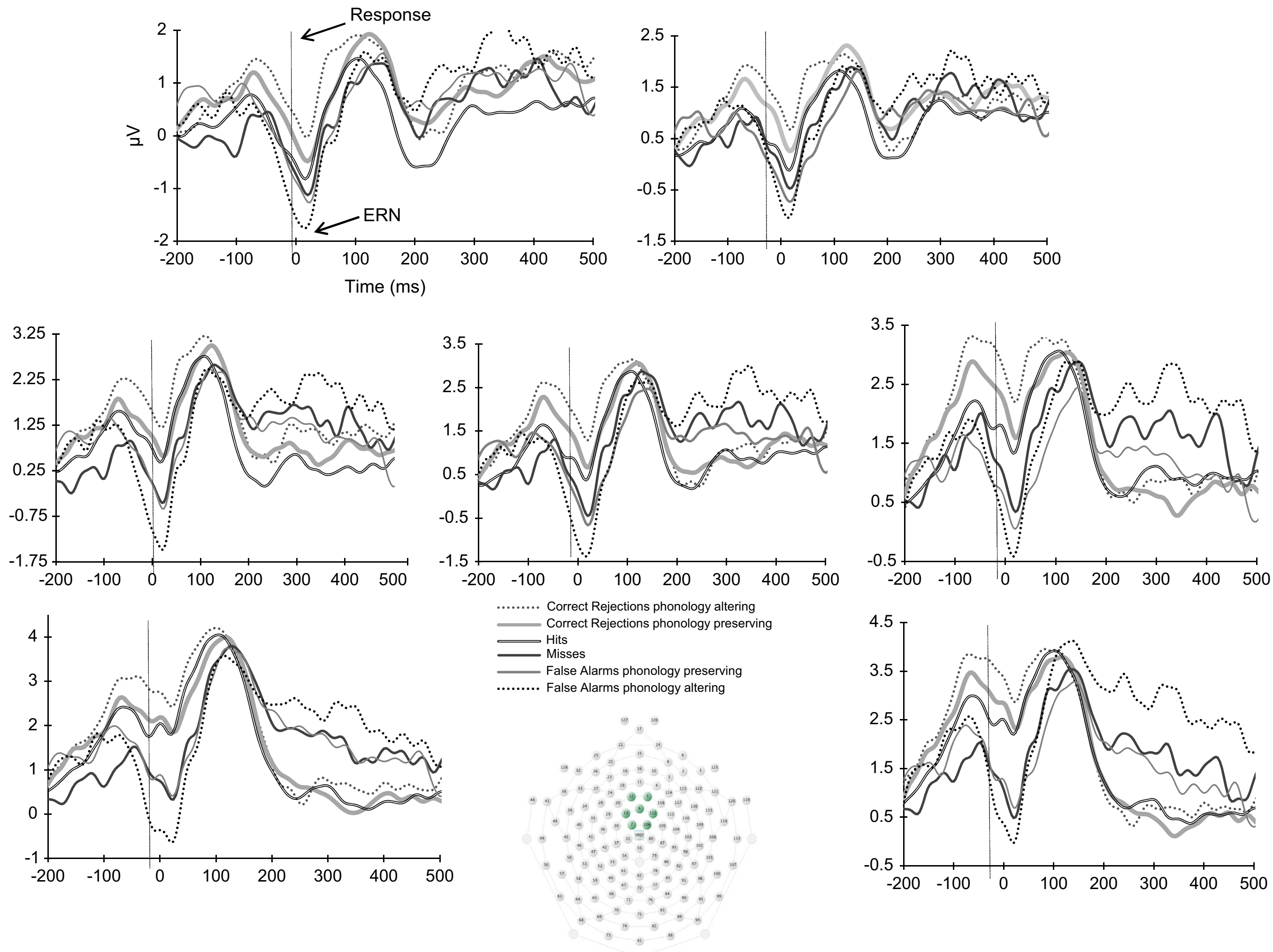

Fig. 5. The grand average of EEG activity surrounding the response for each electrode in our cluster of interest for Experiment 2.

4. 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

[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 & Norman, 1986, p. 414).

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 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 et al., 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 & Hersch, 2010; Andrews & Lo, 2012), 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 & 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 morphosyntactic information as well phonological and orthographic.

Acknowledgments

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Appendix A

See Table A1.

Table A1
Target and foil pairs used as experimental stimuli in Experiment 1.

aardvark	aardvirk	argument	arguement	cartilage	cartiladge	dealership	dealershep
abacus	aibacus	argument	argumint	cashew	cashoew	debacle	debecle
abbreviate	abreviate	armature	armiture	category	catagory	debit	deabit
abdomen	abdomin	arsenal	arsinal	cathedral	cathidral	decayed	decuyed
abnormal	abnormel	artichoke	artichake	cauldron	culdron	decibel	decible
abolition	abulition	ascend	accend	cautious	catious	defense	deffense
absence	absense	asteroid	asteruid	ceiling	ceilling	defiance	defience
abundance	abundence	astonish	astanish	celibacy	celabacy	deficits	defacits
accelerate	acelerate	atrocious	attrocious	ceremony	ceremany	definitely	definately
accessible	accessable	attendance	attendence	chameleon	cameleon	delicate	deilicate
accessory	accesory	attention	atention	chandelier	chandalier	delightful	deleghtful
acclaim	aclaim	audible	audable	changeable	changable	delivery	delivary
accompany	acompany	audience	audiance	charitable	charitible	deluxe	delaxe
accomplice	acomplice	autumn	atumn	chauffeur	chaufeur	denture	dinture
accomplish	acomplish	average	averege	checkmate	chekmate	deodorant	deoderant
accountant	acountant	bachelor	bauchelor	cheetah	chetah	dependent	dependant
accumulate	accumalate	balance	ballance	chemistry	chemastry	descend	decend
acquainted	aquainted	balcony	bailcony	cherub	chirub	desirable	desireable
acquiesce	acquiese	ballerina	ballerana	chief	cheif	desperate	desparate
acquire	aquire	balloon	baloon	children	cheldren	deterrence	deterrance
across	accross	banana	banuna	chimney	chemney	devoured	devuored
additional	addtional	bandanna	bandenna	chimpanzee	chimpanze	difference	diference
address	adress	banjo	bainjo	chipmunk	chepmunk	dinosaur	dinosar
adherent	adherant	bankrupt	binkrupt	chocolate	chacolate	diploma	diplama
adjacent	adjacint	barbecue	barbecoe	cinnamon	ciennamon	discipline	disipline
adjacent	ajacent	bargain	bargan	cipher	ciphur	dissident	dissadent
adjourn	adjurn	basically	basicaly	circuit	circut	dissonant	dissonent
admiral	admirel	bayou	bauyou	clarity	claority	document	documnet
adobe	aduobe	bazooka	bazookuh	cleanser	claenser	doesn′t	dosen′t
adolescent	adolesent	beaker	beakur	coffee	coeffee	dollar	doller
aesthetic	asthetic	beginning	begining	coffin	couffin	dominant	dominent
afraid	affraid	belief	beleif	collision	colision	domineer	domaneer
aggravate	aggrivate	believe	beleive	cologne	colone	dowry	dowery
aggressive	aggresive	beneath	beneth	colonel	colonell	dreadful	draedful
alarm	alairm	benefit	benifit	column	colomn	dribbling	dribbiling
albatross	albatrass	bequeath	bequeth	commission	comission	drowsy	drawsy
alchemy	alchemay	biscuit	biscut	committed	commited	dyslexia	dyslixia
alcohol	alchohol	blatant	bletant	committee	commitee	easel	easle
alcove	alcuove	bleachers	bleechers	comparable	comprable	ebony	ebonay
alfalfa	alfelfa	blister	blistur	compare	compair	eccentric	eccentrec
algebra	algibra	blizzard	blizard	competent	compatent	ecstasy	extasy
algorithm	algorethm	blossom	blassom	completely	completly	ecstatic	ecstatec
alleged	alledged	bludgeon	bladgeon	component	cumponent	efficiency	efficiancy
alligator	alligetor	boisterous	bosterous	concede	conceed	eighth	eigth
almanac	almunac	bonanza	boninza	condemn	condem	elaborate	elaberate
alphabet	alphabat	boomerang	bomerang	condescend	condesend	elegance	elagance
amber	ambur	boycott	boycot	condolence	condolance	elegant	eilegant
ambulance	ambulence	bribery	bribary	confetti	confatti	element	elament
amnesia	amnasia	broccoli	broccole	conscience	concience	elephant	ealephant
amputate	ampuitate	brunette	brunnette	conscious	concious	eligible	eligable
anatomy	anatamy	budget	budgit	consistent	consistint	elixir	elexir
anchor	ancor	buffalo	buffalao	consistent	consitant	embargo	embergo
anchovy	anchavy	bundle	bundel	conspiracy	conspiricy	embarrass	embarass
annihilate	annhilate	bureau	buereau	continuous	continous	embassy	embussy
anorexia	annorexia	burning	buerning	contraband	contrabend	embellish	embelish
antecedent	anticedent	business	buisiness	convenient	conveniant	embrace	embroce
antenna	antennuh	butterfly	buetterfly	corrupt	corruopt	emergency	emergancy
antifreeze	antifrieze	caboose	caboase	cotton	coutton	enterprise	enteprise
aortic	ayortic	cafeteria	cafetaria	cougar	cuogar	entice	entaice
apologize	appologize	cajole	cajule	courage	cuorage	enzyme	eunzyme
apparent	apparant	caliber	calaber	courteous	curteous	equinox	equinax
appearance	apearance	camouflage	camoflage	coyote	coyoute	equipment	equipmant
appendix	apendix	campus	campis	creature	craeture	equipped	equiped
apples	aepples	cannibal	cannibel	crescent	creascent	eradicate	eradacate
apprehend	aprehend	capitalism	capitolism	crimson	cremson	errand	errend
apprentice	aprentice	capsize	cepsize	critical	critacal	escape	escepe
apricot	apricut	caravan	caraven	criticize	critisize	especially	especialy
apron	aupron	career	carreer	crocodile	crucodile	establish	establush
apropos	apropo	caribou	coaribou	cupboard	cuboard	eternal	etarnal
aqueduct	aquaduct	caricature	caracature	daylight	dauylight	etiquette	etiquitte
arena	areuna	carpenter	corpenter	dazzling	daizzling	evenness	eveness
eventually	eventualy	harmonica	harmanica	lasagna	lasanga	murmur	murmer
evidently	evidantly	harpoon	harpoin	legacy	legicy	museum	muesum
exceed	excede	hazard	haizard	legitimate	legitiment	mysterious	misterious
excellent	excelent	heavenly	haevenly	leisure	liesure	mystique	mysteque
exercise	excercise	helicopter	helicupter	lemon	leamon	narrative	narriative
exertion	exhertion	helpful	helpfull	leotard	leotord	naughty	nughty

Table A1 (*continued*)

exhaust	exhast	heretic	heratic	library	libary	nausea	naseua
experience	experiance	hesitate	heisitate	license	licence	naval	navel
explaining	explaning	hickory	heckory	licorice	licarice	necessary	necesary
extension	extention	history	hestory	lieutenant	lieutenent	negative	negatuve
extremely	extremley	holocaust	holocust	lightning	leightning	negligent	neglagent
eyelids	eyeleds	hominy	hominay	likelihood	likelyhood	nemesis	neumesis
facsimile	faximile	honorific	honorifec	likewise	lekewise	neurology	neurolagy
factor	facter	hooligan	hoiligan	lilac	leilac	neutron	nutron
fallacy	falacy	hopeful	hopefull	limousine	limosine	nibbling	niebbling
familiar	familliar	horizon	horezon	liquid	lequid	ninety	ninty
fanatic	fanaitic	human	huiman	loneliness	loneliniss	nirvana	nirvena
farewell	farewill	humorous	humerous	lottery	lattery	nonsense	nensense
fathom	faethom	hundredth	handredth	loveliest	loevliest	normally	normaly
fatigue	fategue	hunger	hungur	lucrative	lucritive	northern	northurn
feathers	faethers	hurricane	hurricene	ludicrous	luducrous	nostalgia	nastalgia
fiasco	fiesco	husband	hasband	mafia	mafiuh	nostril	nastril
fiery	firey	hyacinth	hayacinth	magazine	magizine	notary	notery
filibuster	filibaster	hybrid	haybrid	magically	magicaly	novice	novace
finesse	fineisse	hygiene	hygeine	magnolia	magnalia	nuclear	nuculear
fission	fision	hypocrite	hypocrit	maiden	maidun	nuisance	nuisence
flamboyant	flambayant	iceberg	iceburg	malaria	malauria	obituary	obetuary
flammable	flamable	ideally	idealy	mammoth	maimmoth	obliged	obleged
flounder	floundur	ignorance	ignorence	management	managment	obscene	obsene
flourishes	florishes	iguana	iguona	manicure	menicure	obstacle	obsticle
fluoride	floride	imaginary	immaginary	mannequin	manequin	occasion	ocasion
fluttered	fluttured	immovable	inmovable	marathon	marathin	occurred	occured
foliage	faoliage	immune	imune	marijuana	marijuona	octopus	octupus
forcibly	forcebly	impatient	impetient	marinade	marinede	odyssey	odysey
forecast	forcast	imperial	imperiel	marriage	marrage	official	oficial
foreign	foriegn	implicit	implicet	mascara	mascaera	oncology	onculogy
forfeit	forfit	incense	incinse	masquerade	masqueride	opossum	opposum
forlorn	forlern	incisor	incesor	massage	massoge	opponent	opponant
forsake	forseke	incognito	incognato	matinee	mattinee	opposite	oposite
fortune	furtune	incumbent	imcumbant	mattress	matress	oppress	opress
forty	fourty	indicate	indacate	maverick	mauverick	orange	orenge
fragrant	fregrant	indicted	indited	mayonnaise	mayonaise	orangutan	orangatan
frequently	frequintly	inevitable	inevitible	measles	mesles	orchard	orcherd
frolic	froluc	influence	influince	mechanic	mechenic	oregano	oragano
frustrated	fustrated	influenza	infloenza	medieval	medival	original	originel
fulfill	fufill	innate	inate	mediocre	midiocre	ostracize	ostricize
furlough	fuerlough	innovation	inovation	melancholy	melanchuly	outrageous	outragious
galoshes	guhloshes	innuendo	inuendo	melody	meloday	ovation	ovaotion
garage	garege	insomnia	insoimnia	menace	manace	oxygen	oexygen
garden	gairden	insurance	insurence	mesmerize	mesmeraze	paddling	padling
gathered	gaithered	integer	interger	messiah	messeah	pancake	poncake
gazelle	gazille	intercept	intecept	metaphor	metiphor	papaya	papiya
generally	generaly	interlude	interluode	mileage	milage	paprika	papraika
genesis	geanesis	interpret	interprit	military	milatary	papyrus	papayrus
genius	genious	interrupt	interupt	mimicked	mimiced	paradigm	paradegm
gerbil	gerbel	irrational	irretional	minimum	minamum	paradise	paradase
gingivitis	gingivatis	itinerary	itenerary	mischief	mischeif	paradox	paradax
giraffe	girrafe	ivory	ievory	miser	maiser	parallel	paralel
glamour	glaemour	jaguar	jaiguar	missile	missle	paralyzed	paralized
glittered	gliettered	jasmine	jismine	mistletoe	mistletae	paranoia	paranoa
gloomy	gloamy	jealousy	jealosy	mocking	moucking	paraphrase	pariphrase
gnawing	gnaiwing	jeopardy	jeoperdy	moderate	moderite	parasol	parasoel
gorgeous	gergeous	jewelry	jewerly	modified	modafied	parrot	parret
gospel	goespel	jovial	joivial	monarch	moanarch	particular	particuler
government	goverment	jukebox	juokebox	mongoose	mangoose	passage	paissage
governor	govenor	jungle	juingle	mongrel	moengrel	pastime	pasttime
graceful	grauceful	kangaroo	kangaro	monitor	monitir	patriarch	patriurch
graffiti	grafitti	khaki	kakhi	monsoon	mansoon	pavilion	pavelion
grammar	grammer	kinetic	kinitic	morbid	murbid	pebble	peibble
granite	granate	knapsack	knoapsack	morning	morening	peculiar	peculier
guarantee	guarentee	kneaded	kneadid	morsel	mursel	pedigree	pedigre
guard	gaurd	knowledge	knowlege	mortgage	morgage	penicillin	penicilin
guidance	guidence	koala	koula	mortuary	mortuery	peninsula	penansula
guidelines	guidlines	labeled	labelled	mosquito	mosquato	perceive	percieve
guitar	guitair	laboratory	labratory	mountains	muontains	perilous	pirilous
handsome	hendsome	lackluster	lacklaster	mouthful	muothful	perplex	perplax
happily	happilly	lament	lameint	mulberry	muilberry	persimmon	persemmon
harass	harrass	lantern	laentern	murderous	murderuous	peruse	puruse
petroleum	petreleum	rhinoceros	rhineceros	taxation	taxaution	zenith	zaenith
petunia	petuonia	rhubarb	rhabarb	tenacious	tenecious	zombie	zambie
phoenix	phoenux	rhyme	ryhme	tendency	teandency	zucchini	zucchani
physician	physican	rhythm	rythm	Tennessee	Tennesee		
physique	phisique	ribbon	riebbon	therefore	therefor		
pickle	pickel	ricochet	ricachet	thesaurus	thesairus		

Table A1 (*continued*)

picnic	picnick	ridiculous	rediculous	thespian	thespien
pigeon	piegeon	righteous	rightious	thorough	thurough
pineapple	pinapple	rigorous	rigerous	thousand	thuosand
pinnacle	pennacle	rooster	roostir	threshold	thrishold
pistachio	pistaichio	sabotage	sabotege	tickle	tickel
pistol	pistul	safari	saferi	tidings	teidings
pitiful	pitifull	salami	salomi	tiresome	taresome
placebo	placeubo	salivary	salivery	tobacco	tobocco
pleasure	plaesure	samurai	samarai	tomato	tometo
pocket	pockit	sandal	sandel	tomorrow	tommorrow
poignant	poignent	sapphire	sopphire	tongue	toungue
polka	polkuh	sarcasm	sercasm	tornado	torniedo
popping	poping	satellite	satallite	tournament	tournement
porcelain	percelain	satin	satinn	tradition	tradetion
porch	portch	saxophone	saxophane	tragedy	tradgedy
portfolio	portfalio	scarlet	scaurlet	trajectory	trajactory
possess	posess	scattered	scaittered	tribunal	tribuonal
possible	possable	scenario	scenurio	trigger	triggre
postulate	poustulate	schedule	schedual	trousers	trouisers
potato	potatoe	scolded	scoilded	truncate	trancate
power	poawer	secretary	secratary	tsunami	tsunimi
precedent	preicedent	seizure	saizure	tulip	tulup
precious	pracious	separate	seperate	tundra	tuendra
precocious	precacious	sequin	seuquin	turbulence	turbulance
preferred	perferred	shampoo	shampo	twelfth	twelth
pregnant	pregnent	shepherd	shephard	twenty	tweunty
prejudice	predjudice	shivered	shevered	twittered	twettered
pretended	pretinded	shouldn′t	shoudln′t	typhoon	typhoan
pretzel	pritzel	silver	silvur	tyranny	tyrany
probably	probally	similar	simillar	uglier	uiglier
proceed	procede	simile	similie	umbrella	umbrulla
promenade	promenede	sincerly	sincerely	unity	unitay
prominent	prominant	sinister	senister	usage	usege
protect	protict	skeleton	skeileton	useable	usable
provolone	provolune	slaughter	slaighter	usually	usualy
prudent	pruodent	sleuth	slooth	vaccine	vaccaine
pyramid	payramid	smuggler	smugglir	valuable	vailuable
qualify	qualifay	sobriety	sobraety	vampire	vempire
quality	qualaty	sodium	sodiumn	vanilla	vanella
quartet	quartit	solitaire	soilitaire	velocity	velacity
quinine	quanine	sophomore	sophmore	velvet	vealvet
quiver	quiever	soprano	sopreno	vendetta	vendatta
quotient	quoitient	sorcerer	surcerer	vernacular	vernaculer
raccoon	raccoan	souvenir	souvener	versatile	versitile
racquet	racquit	spaghetti	spaghatti	vicarious	vicaurious
receipt	reciept	spectrum	spectrim	vigilante	vigilainte
received	recieved	spinach	spenach	village	vilage
reckless	reickless	spiral	speiral	violin	violan
recommend	recomend	splendid	splandid	virtuoso	virtuoiso
reconcile	reconcale	splinter	splintre	visitor	vesitor
reference	refrence	sporadic	sporedic	volcano	volcuno
referred	refered	squalid	squaolid	voracious	vorecious
refurbish	reforbish	standard	staendard	vulnerable	vulnerible
rehearsal	rehersal	stereotype	stireotype	waffle	waffel
rejoiced	rejouced	stiletto	stilitto	wagon	wagun
relevant	relivant	strategy	strutegy	walrus	waolrus
religious	religous	stupendous	stupandous	wardrobe	werdrobe
remember	remimber	subjugate	subjugite	warrant	warrent
remnants	remnents	success	sucess	weird	wierd
renegade	renegode	sultan	sulten	welcome	waelcome
renowned	reknowned	sunshine	sanshine	welfare	wellfare
represent	reprisent	supposed	suposed	whimsical	whemsical
reservoir	resevoir	surgery	sergery	wicked	wiecked
resilient	risilient	surprise	suprise	wicker	wickur
response	responce	suspension	suspention	wiggle	wiggel
restaurant	restarant	swallow	swaillow	windshield	windsheild
restored	restuored	synonymous	synonomous	withered	withured
reviewing	reveiwing	synthesis	synthasis	womanly	womenly
revival	reveval	syringe	syrange	wounded	wuonded
revolution	revalution	tangerine	tangerane	yacht	yaght
rhapsody	rapsody	tantalize	tantaleize	zealous	zaelous
rheumatism	reumatism	tarantula	tarontula	zebra	zibra

Table B1
Target and foil pairs used as experimental stimuli in Experiment 2.

Phonology-preserving							
absence	absense	rhyme	ryhme	excellent	excelent	exhale	exhail
acquire	aquire	secretary	secratary	exertion	exhertion	flounder	floundur
adjacent	ajacent	silver	silvur	factor	facter	galoshes	guhloshes
afraid	affraid	similar	simillar	familiar	familliar	gerbil	gerbel
ambulance	ambulence	speedy	speady	fiery	firey	honorific	honorifec
anorexia	annorexia	steam	steem	flavor	flaver	hypocrite	hypocrit
apparent	apparant	stranger	strainger	forcibly	forcebly	icicle	icecle
aqueduct	aquaduct	supposed	suposed	forecast	forcast	indicted	indited
attention	atention	surgery	sergery	forfeit	forfit	orangutan	orangatan
audible	audable	synthesis	synthasis	glory	glorey	people	peeple
benefit	benifit	Tennessee	Tennesee	group	groop	skate	skaite
bleachers	bleechers	terrible	terrable	guarantee	guarentee	sultan	sulten
blister	blistur	therefore	therefor	guidance	guidence	surprise	suprise
ceiling	ceilling	tomorrow	tommorrow	happily	happilly	address	adress
collision	colision	torch	tortch	hunger	hungur	aortic	ayortic
cologne	colone	vegetable	vegetible	ignorance	ignorence	appendix	apendix
compare	compair	versatile	versitile	immune	imune	argument	arguement
concede	conceed	warrant	warrent	implicit	implicet	arsenal	arsinal
defense	deffense	welfare	wellfare	industry	indistry	belief	beleif
donkey	donky	wiggle	wiggel	interrupt	interupt	blizzard	blizard
easel	easle	abdomen	abdomin	knowledge	knowlege	budget	budgit
elegance	elagance	accessory	accesory	loyal	loyel	bundle	bundel
embassy	embussy	acclaim	aclaim	magazine	magizine	caliber	calaber
emergency	emergancy	accompany	acompany	maiden	maidun	campus	campis
encourage	encurage	across	accross	marriage	marrage	career	carreer
extension	extention	adjourn	adjurn	military	milatary	careless	careliss
fluoride	floride	admiral	admirel	missile	missle	chemistry	chemastry
forever	fourever	aesthetic	asthetic	modified	modafied	chief	cheif
forty	fourty	aggravate	aggrivate	mortgage	morgage	colony	colany
furniture	furnature	algebra	algibra	motor	moter	column	colomn
gallery	gallary	anatomy	anatamy	negligent	neglagent	committed	commited
giraffe	girrafe	antenna	antennuh	neutron	nutron	conscious	concious
governor	govenor	apprehend	aprehend	northern	northurn	customer	custamer
grammar	grammer	ascend	accend	notary	notery	daily	dayly
guardian	gardian	audience	audiance	nuisance	nuisence	decibel	decible
harass	harrass	balloon	baloon	obscene	obsene	defiance	defience
health	helth	bargain	bargan	occasion	ocasion	descend	decend
helpful	helpfull	bazooka	bazookuh	opponent	opponant	destroy	distroy
hopeful	hopefull	beaker	beakur	orchard	orcherd	doesn′t	dosen′t
humorous	humerous	beginning	begining	original	originel	domineer	domaneer
increase	increese	blame	blaime	paddling	padling	dowry	dowery
influence	influince	boycott	boycot	pardon	pardan	ecstasy	extasy
insurance	insurence	bribery	bribary	peculiar	peculier	ecstatic	ecstatec
khaki	kakhi	cactus	cactas	physique	phisique	elixir	elexir
leather	lether	category	catagory	pocket	pockit	exercise	excercise
license	licence	channel	channal	possible	possable	famous	famos
limousine	limosine	chauffeur	chaufeur	potato	potatoe	flammable	flamable
locket	lockit	checkmate	chekmate	pregnant	pregnent	fluttered	fluttured
lucrative	lucritive	cipher	ciphur	prominent	prominant	funeral	funural
mafia	mafiuh	committee	commitee	receipt	reciept	general	genaral
mattress	matress	component	cumponent	relevant	relivant	genius	genious
murmur	murmer	confirm	conferm	reservoir	resevoir	heavily	heavaly
neurology	neurolagy	consistent	consistint	response	responce	imperial	imperiel
octopus	octupus	constant	constent	rhythm	rythm	indicate	indacate
opposite	oposite	courteous	curteous	rigorous	rigerous	innuendo	inuendo
orange	orenge	criticize	critisize	royal	royel	interpret	interprit
ostracize	ostricize	currency	currancy	satellite	satallite	jealousy	jealosy
paralyzed	paralized	decorator	decarator	schedule	schedual	kitchen	kichen
pistol	pistul	delivery	delivary	scream	screem	labeled	labelled
pitiful	pitifull	deodorant	deoderant	square	squaire	lawyer	lauyer
poison	poisen	dependent	dependant	thespian	thespien	legacy	legicy
polka	polkuh	dirty	dirtey	thorough	thurough	mannequin	manequin
porch	portch	dominant	dominent	tickle	tickel	marijuana	marijuona
possess	posess	element	elament	waffle	waffel	market	markit
proceed	procede	embellish	embelish	wagon	wagun	matinee	mattinee
range	rainge	equipment	equipmant	wicker	wickur	mediocre	midiocre
received	recieved	equipped	equiped	yacht	yaght	metal	metel
rehearsal	rehersal	eradicate	eradacate	answer	anser	mileage	milage
remnants	remnents	errand	errend	celibacy	celabacy	mortuary	mortuery
rhapsody	rapsody	exceed	excede	disguise	disgise	mystique	mysteque
necessary	necesary	carrot	carrit	occurred	occured	circuit	circut
normally	normaly	dissident	dissadent	oppress	opress	cupboard	cuboard
obstacle	obsticle	dissonant	dissonent	papyrus	papayrus	eighth	eigth
odyssey	odysey	everyone	evryone	pedigree	pedigre	establish	establush
official	oficial	extremely	extremley	religious	religous	evidently	evidantly
papaya	papiya	fallacy	falacy	righteous	rightious	fatigue	fategue

Table B1 (*continued*)

parallel	paralel	incense	incinse	samurai	samarai	freeze	freze
parrot	parret	jeopardy	jeoperdy	satin	satinn	furlough	fuerlough
pastime	pasttime	mascara	mascaera	shepherd	shephard	image	imege
perceive	percieve	minimum	minamum	simile	similie	kangaroo	kangaro
pickle	pickel	reviewing	reveiwing	splinter	splintre	language	lenguage
picnic	picnick	ricochet	ricachet	trigger	triggre	massage	massoge
poignant	poignent	rooster	roostir	vanilla	vanella	medieval	medival
quality	qualaty	salami	salomi	biscuit	biscut	mischief	mischeif
railway	railwey	weird	wierd	competent	compatent	monarch	moanarch
recommend	recomend	abnormal	abnormel	deficits	defacits	paradigm	paradegm
reference	refrence	acoustic	acustic	eligible	eligable	position	pusition
referred	refered	anchor	ancor	fission	fision	pretended	pretinded
renowned	reknowned	annual	annuel	ludicrous	luducrous	represent	reprisent
sophomore	sophmore	balance	ballance	popping	poping	sandal	sandel
spectrum	spectrim	brunette	brunnette	preschool	prescool	scarlet	scaurlet
tenacious	tenecious	bureau	buereau	sleeve	sleve	sinister	senister
tragedy	tradgedy	coffin	couffin	success	sucess	sleuth	slooth
tulip	tulup	crimson	cremson	alchemy	alchemay	smuggler	smugglir
twelfth	twelth	critical	critacal	alcohol	alchohol	target	targat
tyranny	tyrany	dollar	doller	algorithm	algorethm	tradition	tradetion
usage	usege	eccentric	eccentrec	armature	armiture	trouble	truble
village	vilage	etiquette	etiquitte	avoid	avoyd	womanly	womenly
withered	withured	facsimile	faximile	believe	beleive	zebra	zibra
abundance	abundence	hyacinth	hayacinth	boomerang	bomerang		
amber	ambur	hygiene	hygeine	cathedral	cathidral		
aware	awaire	innate	inate	cauldron	culdron		
Phonology-altering							
another	anoether	negative	negatuve	children	cheldren	nostril	nastril
baseball	basball	ninety	ninty	coffee	coeffee	paranoia	paranoa
cabbage	cabboge	novice	novace	colonel	colonell	peninsula	penansula
cherub	chirub	obituary	obetuary	confetti	confatti	perhaps	perheps
debacle	debecle	paradox	paradax	corrupt	corruopt	perplex	perplax
lilac	leilac	pavilion	pavelion	courage	cuorage	physician	physican
mechanic	mechenic	perilous	pirilous	denture	dinture	pigeon	piegeon
promenade	promenede	shampoo	shampo	devoured	devuored	pleasure	plaesure
quinine	quanine	sodium	sodiumn	document	documnet	popcorn	papcorn
resilient	risilient	spaghetti	spaghatti	dreadful	draedful	portfolio	portfalio
shrimp	shremp	tidings	teidings	dyslexia	dyslixia	professor	profassor
unhappy	unhaeppy	tribunal	tribuonal	ebony	ebonay	pyramid	payramid
walrus	waolrus	twenty	tweunty	eggnog	eggnag	qualify	qualifay
wicked	wiecked	virtuoso	virtuoiso	elegant	eilegant	quiver	quiever
abolition	abulition	visiting	visating	eternal	etarnal	quotient	quoitient
arena	areuna	welcome	waelcome	exhaust	exhast	reckless	reickless
bequeath	bequeth	wonder	wondar	explode	exploide	regular	regalar
blossom	blassom	beneath	beneth	eyelids	eyeleds	remember	remimber
breakfast	brakfast	capsize	cepsize	fanatic	fanaitic	restored	restuored
cajole	cajule	cattle	caettle	forsake	forseke	ribbon	riebbon
cashew	cashoew	chimney	chemney	fragrant	fregrant	scenario	scenurio
chocolate	chacolate	cleanser	claenser	garage	garege	souvenir	souvener
cinnamon	ciennamon	exist	exest	gathered	gaithered	spiral	speiral
crescent	creascent	finesse	fineisse	goldfish	goldfesh	standard	staendard
decayed	decuyed	nausea	naseua	grapefruit	grapefrit	strategy	strutegy
entice	entaice	nostalgia	nastalgia	grateful	gratful	thirsty	tharsty
equinox	equinax	provolone	provolune	guitar	guitair	threshold	thrishold
exactly	exatly	station	stetion	handsome	hendsome	tobacco	tobocco
glamour	glaemour	unity	unitay	hazard	haizard	tomato	tometo
guideline	guidline	vacant	vecant	hesitate	heisitate	treatment	tretment
harpoon	harpoin	zealous	zaelous	hickory	heckory	trousers	trouisers
impatient	impetient	zipper	zippar	horizon	horezon	valuable	vailuable
incumbent	imcumbant	advice	advaice	household	househald	vampire	vempire
integer	interger	alarm	alairm	human	huiman	vendetta	vendatta
ivory	ievory	alligator	alligetor	immovable	inmovable	violin	violan
jaguar	jaiguar	amputate	ampuitate	incisor	incesor	voracious	vorecious
kinetic	kinitic	apartment	apertment	insomnia	insoimnia	wounded	wuonded
lantern	laentern	apricot	apricut	intercept	intecept	zombie	zambie
loveliest	loevliest	asteroid	asteruid	koala	koula	aardvark	aardvirk
marinade	marinede	balcony	bailcony	leotard	leotord	ballerina	ballerana
melody	meloday	bayou	bauyou	menace	manace	blatant	bletant
mongoose	mangoose	broccoli	broccole	mongrel	moengrel	bludgeon	bladgeon
monsoon	mansoon	burning	buerning	museum	muesum	cougar	cuogar
morning	morening	century	centiry	nirvana	nirvena	coyote	coyoute
delicate	deilicate	hundredth	handredth	mosquito	mosquato	naughty	nughty
detriment	ditriment	jewelry	jewerly	mouthful	muothful	nemesis	neumesis
entertain	entertan	jovial	joivial	myself	mysilf	nibbling	niebbling
gnawing	gnaiwing	jukebox	juokebox	nonsense	nensense	oatmeal	oatmel
graceful	grauceful	leisure	liesure	reconcile	reconcale	obliged	obleged
gravey	gravay	library	libary	refurbish	reforbish	paradise	paradase

Table B1 (*continued*)

hooligan	hoiligan	malaria	malauria	renegade	renegode	petroleum	petreleum
income	incume	maverick	mauverick	seashore	seashare	plastic	plestic
influenza	infloenza	mesmerize	mesmeraze	thousand	thuosand	pretzel	pritzel
kidnap	kidnep	messiah	messeah	umbrella	umbrulla	pronounce	pronunce
lottery	lattery	mimicked	mimiced	vacation	vacotion	recover	recaver
magnolia	magnalia	oncology	onculogy	velvet	vealvet	revival	reveval
mailbox	mailbax	oregano	oragano	almost	almoist	sapphire	sopphire
manicure	menicure	ovation	ovaotion	amnesia	amnasia	saxophone	saxophane
medicine	midicine	patriarch	patriurch	anchovy	anchavy	seizure	saizure
midnight	midneght	pillow	pilluw	banana	banuna	sideways	sidewuys
morsel	mursel	pineapple	pinapple	banjo	bainjo	slaughter	slaighter
parasol	parasoel	placebo	placeubo	bankrupt	binkrupt	soprano	sopreno
pebble	peibble	popular	papular	business	buisiness	subjugate	subjugite
petunia	petuonia	power	poawer	cafeteria	cafetaria	swallow	swaillow
porcelain	percelain	precious	pracious	caravan	caraven	syringe	syrange
quartet	quartit	probably	probally	carpenter	corpenter	taxation	taxaution
shallow	shellow	prudent	pruodent	cautious	catious	truncate	trancate
shivered	shevered	raccoon	raccoan	cobweb	cobwib	tundra	tuendra
smoke	smoike	rainstorm	rainsturm	cotton	coutton	vaccine	vaccaine
sobriety	sobraety	rejoiced	rejouced	crocodile	crucodile	voyage	vayage
squalid	squaolid	return	retarn	drowsy	drawsy	airplane	airplone
turkey	turkay	sabotage	sabotege	embargo	embergo	alcove	alcuove
zenith	zaenith	sarcasm	sercasm	embrace	embroce	artichoke	artichake
alfalfa	alfelfa	scolded	scoilded	enzyme	eunzyme	barbecue	barbecoe
apron	aupron	shouldn′t	shoudln′t	escape	escepe	caribou	coaribou
astonish	astanish	skeleton	skeileton	farewell	farewill	creature	craeture
autumn	atumn	splendid	splandid	garbage	gerbage	damage	demage
bachelor	bauchelor	sporadic	sporedic	haircut	haircat	daughter	dughter
bonanza	boninza	stiletto	stilitto	halfway	halfwoy	daylight	dauylight
caboose	caboase	subject	subjact	heavenly	haevenly	elbow	elbaw
cannibal	cannibel	sunshine	sanshine	history	hestory	holocaust	holocust
ceremony	ceremany	tarantula	tarontula	hurricane	hurricene	ignore	ignare
clarity	claority	tendency	teandency	husband	hasband	jungle	juingle
comfort	camfort	tiresome	taresome	hybrid	haybrid	knapsack	knoapsack
dazzling	daizzling	tornado	torniedo	hydrant	haydrant	mistletoe	mistletae
debit	deabit	twittered	twettered	incognito	incognato	pancake	poncake
devotion	devoition	typhoon	typhoan	jasmine	jismine	paprika	papraika
dinosaur	dinosar	underdog	underdag	jellyfish	jillyfish	protect	protict
diploma	diplama	velocity	velacity	lament	lameint	quicksand	quicksond
fathom	faethom	visitor	vesitor	lemon	leamon	remark	remerk
feathers	faethers	volcano	volcuno	likewise	lekewise	rhubarb	rhabarb
fiasco	fiesco	wardrobe	werdrobe	liquid	lequid	safari	saferi
forlorn	forlern	adobe	aduobe	mammoth	maimmoth	scarecrow	scarecraw
fortune	furtune	beetle	betle	marathon	marathin	sequin	seuquin
garden	gairden	dishonest	dishanest	moderate	moderite	support	suppart
genesis	geanesis	gazelle	gazille	Monday	Mondoy	tsunami	tsunimi
gloomy	gloamy	invent	invint	morbid	murbid	uglier	uiglier
gorgeous	gergeous	junction	juntion	mountains	muontains	underwear	underwar
gospel	goespel	monkey	mankey	mulberry	muilberry	zucchini	zucchani
Even splits							
awkward	akward	granite	granate				
enough	enogh	guard	gaurd				
frolic	froluc	harmonica	harmanica				
itinerary	itenerary	helmet	helmat				
lasagna	lasanga	heretic	heratic				
licorice	licarice	journal	jornal				
phoenix	phoenux	metaphor	metiphor				
pinnacle	pennacle	monitor	monitir				
racquet	racquit	nuclear	nuculear				
tongue	toungue	oxygen	oexygen				
whimsical	whemsical	preferred	perferred				
almanac	almunac	shoulder	shulder				
alphabet	alphabat	spinach	spenach				
apples	aepples	thesaurus	thesairus				
avenue	avunue	whatever	whataver				
buffalo	buffalao						
cheetah	chetah						
elephant	ealephant						
evenness	eveness						
foreign	foriegn						
fulfill	fufill						

Appendix B

See Table B1.

Appendix C. Supporting information

Supplementary data associated with this article can be found in the online version at: http://dx.doi.org/10.1016/j.neuropsychologia.2013.12.007.

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