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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