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Word and pseudoword superiority effects reflected in the ERP waveform

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Abstract

A variant of the Reicher-Wheeler task was used to determine when in the event-related potential (ERP) waveform indices of word and pseudoword superiority effects might be present, and whether ERP measures of superiority effects correlated with standardized behavioral measures of orthographic fluency and single word reading. ERPs were recorded to briefly presented, masked letter strings that included real words (DARK/PARK), pseudowords (DARL/PARL), nonwords (RDKA/RPKA), and letter-in-xs (DXXX, PXXX) stimuli. Participants decided which of two letters occurred at a given position in the string (here, forced-choice alternatives D and P). Behaviorally, both word (more accurate choices for letters in words than in baseline nonwords or letter-in-xs) and pseudoword (more accurate choices for letters in pseudowords than in baseline conditions) superiority effects were observed. Electrophysiologically, effects of orthographic regularity and familiarity were apparent as early as the P150 time window (100–160 ms), an effect of lexicality was observed as early as the N200 time window (160–200 ms), and peak amplitude of the N300 and N400 also differentiated word and pseudoword as compared to baseline stimuli. Further, the size of the P150 and N400 ERP word superiority effects was related to standardized behavioral measures of fluency and reading. Results suggest that orthographic fluency is reflected in both lower-level, sublexical, perceptual processing and higher-level, lexical processing in fluently reading adults.

Keywords

event-related potentials (ERPs); reading; orthographic processing; word superiority effect; pseudoword superiority effect

1. INTRODUCTION

In alphabetic languages such as English, written words are comprised of letters arranged in sequences according to combinatorial rules that specify the orthography of the language (for a recent review of orthographic processing, see Grainger, 2008). Although it is difficult to isolate the effects of orthography given the highly interactive nature of the reading system (e.g., Adams, 1990; Cunningham et al., 2001; Manis et al., 1999; Olson et al., 1994; Vellutino et al., 1994; Wile and Borowsky, 2004), the results of behavioral studies investigating the word superiority effect have indicated that printed words appear to have a

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special orthographic status in fluent, expert readers beyond their basic properties and features as visual percepts (e.g., Reicher, 1969; Wheeler, 1970). Electrophysiologically, just a handful of studies have investigated the automatic orthographic processing of words in fluent readers in paradigms investigating the word superiority effect (e.g., Martin et al., 2006; Proverbio et al., 2008; Ziegler et al., 1997). Here, we expanded on those studies by using standardized behavioral measures of fluency and reading, accuracy in a modified Reicher-Wheeler paradigm, and event-related potentials (ERPs) recorded during the modified Reicher-Wheeler paradigm to investigate orthographic processing in fluently reading adults. Our goals were to determine when in the ERP waveform word and pseudoword superiority effects might be indexed and whether those ERP indices would correlate with behavioral measures of orthographic fluency and single word reading.

1.1. The Word Superiority Effect

A large body of behavioral literature confirms a word superiority effect in adult fluent readers. In the classic Reicher-Wheeler paradigm designed to index the word superiority effect, a string of letters is briefly presented and masked, then participants are given a forced choice task in which they decide which of two presented letters occurred at a given position in the string (Reicher, 1969; Wheeler, 1970). In the classic paradigm and across many variations, participants are more accurate at identifying the correct letter when the briefly presented string is a word (e.g., *frog*) than if it is a pronounceable pseudoword (e.g., *thap*) or an unpronounceable nonword (e.g., *yibg*) (e.g., Adams, 1979; Estes and Brunn, 1987; Ferraro and Chastain, 1993; Ferraro and Chastain, 1997; Grainger and Jacobs, 1994; Johnston and McClelland, 1974; Juola et al., 1974; Krueger, 1992; Lukatela et al., 1981; Prinzmetal, 1992; Prinzmetal and Silvers, 1994; Solman, 1988; Williams et al., 1985). Interestingly, there have also been reports of a pseudoword superiority effect in adults, such that accuracy is higher for letters embedded in pseudowords than for letters embedded in nonwords (e.g., Chase and Tallal, 1990; Estes and Brunn, 1987; Grainger and Jacobs, 1994; Grainger et al., 2003; Grainger and Jacobs, 2005). The pseudoword superiority effect may be due to the word-likeness of pseudowords and some have suggested that it may be due to misperception of pseudowords as words (e.g., Grainger and Jacobs, 2005); others have suggested that this finding indicates that word superiority effects are prelexical and generalizable (e.g., McCandliss et al., 2003). Recently, an “acronym superiority effect” also has been reported, such that letters in familiar acronyms are identified more accurately than the same letters in illegal, unfamiliar strings; this pattern of findings suggests that the word superiority effect may be influenced more by orthographic familiarity than regularity (Laszlo and Federmeier, 2007).

Traditionally, the superiority effects observed in the Reicher-Wheeler paradigm are thought to index processing in terms of top-down influences of lexical representations on letter identification (e.g., Laszlo and Federmeier, 2007; Martin et al., 2006); both word superiority and pronounceable pseudoword superiority effects have been modeled as such (McClelland and Rumelhart, 1981). In this view, the match between an orthographic stimulus and a known lexical item facilitates the identification of the letters comprising the orthographic stimulus through top-down (lexical-level) interaction with lower (letter) level processing (McClelland and Rumelhart, 1981). Another possibility that does not depend on such interaction is that the word superiority effect reflects greater activation at the whole word level than the letter level accompanied by read-out from whole word orthographic representations in long-term memory, which allows for correct identification of the individual letters comprising the word; that is, rather than letters being identified directly at the level of letter representations, letters are determined on the basis of word read-out, at the lexical level (Grainger and Jacobs, 1994; Grainger, 2008, p. 3).

Regardless of the mechanism of the effects, the use of the Reicher-Wheeler paradigm in behavioral studies is inherently limited in terms of investigating automatic orthographic processing: Although the letter strings are presented briefly and masked (thus potentially accessing automatic processing), the findings are limited to a delayed behavioral response and can provide virtually no information about the on-line processing of orthographic information at the letter level or the word level. Instead, the automaticity of processing must be inferred from the accuracy of what is essentially a controlled response. Converging evidence from neuroscience provides more information about orthographic processing in real time.

1.2. Automaticity and Orthography: The Visual Word Form

The results of behavioral studies have suggested a special status for word-like orthographic forms and prompted hypotheses about the existence of an abstract mental representation of words, termed the visual word form (Warrington and Shallice, 1980). According to the visual word form hypothesis, letter strings at an early level of processing are specified according to their orthographic properties – in terms of abstract linguistic information beyond lower level, featural visual characteristics. Investigations of the visual word form hypothesis at the neural level have suggested that a specific region within the left fusiform gyrus, predictably referred to as the visual word form area, is particularly tuned to the detection of orthographic regularity and familiarity (for reviews, see Cohen and Dehaene, 2004; McCandliss et al., 2003) and may play a causal role in reading (e.g., Gaillard et al., 2006), although the specificity of processing in this region is under debate (e.g., Kronbichler et al., 2004; Polk and Farah, 2002; Price and Devlin, 2004).

Studies using more temporally sensitive methods have shown that processing in this region is sensitive to orthographic properties of stimuli within 250 ms of stimulus presentation (e.g., Nobre et al., 1994). Indeed, several event-related potential and magnetoencephalography studies have reported that negative-going components peaking at about 200 ms (specifically, a M or N170 and N200) are sensitive to orthography (e.g., Bentin et al., 1999; Compton et al., 1991; Kramer and Donchin, 1987; McCandliss et al., 1997; Simon et al., 2004; Tarkiainen et al., 1999). For example, Compton et al. (1991) described an early negativity (~ 200 ms) that was larger to consonant strings than to words across passive reading, feature detection, and letter detection tasks, but the effect was reversed in a lexical decision task. McCandliss et al. (1997) also reported an N1 (peak at 170–230 ms) greater to consonant strings than to English words and thus inversely sensitive to orthographic regularity; this component was not reportedly sensitive to familiarity of the string. In contrast, Bentin et al. (1999) described a left temporo-occipital N170 larger to orthographic (words, pseudowords, and consonant strings) than nonorthographic (symbols and forms) stimuli in an oddball font-size discrimination task, but the amplitude of the N170 did not differ across the three types of orthographic stimuli. Similarly, Sauseng and colleagues (2004) reported an occipital N160 greater for standard strings (e.g., *taxi*) than altered strings (e.g., *taXi* or *taksi*); the authors concluded that “at this time [N160], the letter input came in contact with memory representations” (p. 531). Recently, using a speeded lexical decision task, Hauk et al. (2006b) reported ERP orthographic typicality effects at about 100 ms (words and pseudowords with atypical orthography elicited more activity than those with typical spelling patterns) and lexicality effects at about 200 ms (pseudowords elicited more activity than words). Overall, these studies suggest that these components in this latency range of about 200 ms are sensitive to orthography – that is, letter representations and combinations – and may index prelexical processing likely to be modulated by top-down lexical effects in a Reicher-Wheeler paradigm (Martin et al., 2006, p. 154).

Across many of these ERP studies neural systems indexed by an early component peaking at about 200 ms were activated not only by orthographically legal stimuli such as words and pseudowords, but also by illegal strings of letters. It is likely that differences in stimuli, task, and attentional demands contributed to these various findings (e.g., see discussion in Grossi and Coch, 2005). Thus, such studies do not adequately address the issue of specificity in orthographic processing as indexed by the components peaking at about 200 ms, or the issue of the automaticity of orthographic processing in fluent adult readers. Using a masked priming paradigm designed to investigate these issues specifically, Grossi and Coch (2005) reported both an N200 under masked conditions (implying that the N200 reflects automatic processing) and a refractory N200 sensitive to orthography in a graded manner (maximal with word-like stimuli and relatively reduced with illegal letter string stimuli). In concordance, activation patterns in left occipitotemporal cortex (consistent with the putative visual word form area) in positron emission tomography and functional magnetic resonance imaging studies also tend to show a linear increase with increasing word-likeness of the stimuli (e.g., Petersen et al., 1990; Price et al., 1996; Tagamets et al., 2000).

Only a handful of ERP studies have used a variant of the Reicher-Wheeler paradigm or similar paradigm to investigate automatic orthographic processing. In one study, the authors reported a typical word superiority effect behaviorally and a modulation of an N1 component (mean peak latency 210 ms) by lexical status for stimuli presented at a 66 ms (but not a 50 ms) duration: 5-letter, high frequency French words elicited a larger N1 than nonwords over occipital regions (Martin et al., 2006). A P1 peaking on average at 99 ms was not sensitive to lexicality, but waves in the 200–300 ms epoch were more negative over left temporoparietal regions for words than for nonwords (Martin et al., 2006). The authors concluded that “visual word form representations can constrain letter identification at a prelexical stage – i.e., during the extraction of letter shape information, within the first 200 ms poststimulus” (p. 158). This study using a masked Reicher-Wheeler paradigm did not investigate other time periods in the ERP waveform when word superiority effects might be reflected, and did not explore a pseudoword superiority effect.

In another recent ERP study that used a different kind of letter identification task that might be considered a variant of the Reicher-Wheeler task (in which participants were asked to indicate if unmasked stimuli presented for 250 ms contained a given target letter), there was evidence of both a behavioral word superiority effect (faster reaction times to letters in words than pseudowords) and an ERP word superiority effect: an N240 was larger to high frequency words than low frequency words or pseudowords (Proverbio et al., 2008). One source of the N2 was localized to left fusiform gyrus (Proverbio et al., 2008). A previous study using a similar letter search task reported similar behavioral results, but an N350 that was smallest to nonwords and larger to words and pseudowords (Experiment 1); in a delayed letter search task (Experiment 2), words and pseudowords again elicited larger N350s than nonwords (Ziegler et al., 1997).

1.3. Automaticity and the N400 Component

The N400 component of the ERP waveform has also been associated with lexicality. The N400 is elicited traditionally by semantically incongruent words in sentence contexts (e.g., Kutas and Hillyard, 1980). An N400 can also be elicited in the context of words presented in pairs and by single words presented in lists (e.g., Bentin et al., 1985; Bentin, 1987; Coch et al., 2002; Harbin et al., 1984; Holcomb, 1988; Nobre and McCarthy, 1994; Noldy et al., 1990; Rugg, 1985). One theory is that the N400 reflects a high-level integrative process (e.g., Brown and Hagoort, 1993; Doyle et al., 1996; Holcomb, 1993; Osterhout and Holcomb, 1995; Rugg, 1990). According to this theory, N400 amplitude reflects the ease of integration: the more difficult the integration process, the larger the N400 (e.g., Holcomb, 1993).

In adults, unpronounceable nonwords do not elicit an N400 while pronounceable pseudowords do (e.g., Bentin et al., 1985; Bentin, 1987; Holcomb, 1988; Holcomb, 1993; Kounios and Holcomb, 1994; Nobre and McCarthy, 1994; Rugg, 1984; Rugg, 1987; Swick and Knight, 1997). This pattern is consistent with the hypothesis that the N400 reflects a higher-level process that builds upon the products of lower-order processes (Holcomb, 1988) because lower-level orthographic and phonological processing cannot be completed with nonwords (thus no integration is possible) while integration of lower-level orthographic and phonological information may be attempted with pseudowords although semantic processes may be only partially activated (e.g., Holcomb et al., 2002). Thus, the N400 may be a “default response to words” or potential words (Kutas and Van Petten, 1994, p. 104). However, to our knowledge, despite its potential utility as an index of word processing, no previous studies have investigated the N400 in the context of a Reicher-Wheeler paradigm. If the context of a word or pseudoword as compared to a nonword facilitates letter processing, the N400 would seem a likely component in terms of which to observe such specialized processing.

1.4. Orthographic Automaticity, Integration, and Fluency: Brain and Behavior Connections

Theoretically, fluent readers have mastered a number of subskills at an automatic level and have made their integration automatic as well (e.g., LaBerge and Samuels, 1974). The development of automaticity is critical because it frees cognitive resources to allow for integrated comprehension of the semantic meaning of the text in context – it allows for truly fluent reading (Adams, 1990; Fletcher, 1981; Stanovich, 1980; Wolf and Katzir-Cohen, 2001). Automaticity of lower-level orthographic processing is key to fluency (Reitsma, 1983; Wolf and Katzir-Cohen, 2001); indeed, “prelexical processing of orthographic information appears to be the component most related to reading skill” (Perfetti and Bolger, 2004, p. 297). Traditionally, fluency has been measured by timed oral reading tests (e.g., Torgesen et al., 1999) or rapid automatized naming tasks (e.g., Denckla and Rudel, 1974) although standardized measures of single word fluency for expert readers are sparse. Functional magnetic resonance imaging research with fluent readers has confirmed that simple rapid automatized naming tasks engage multiple brain regions known to be involved in reading (Misra et al., 2004). To our knowledge, there have been no previous ERP studies exploring possible connections between electrophysiological measures of orthographic automaticity in a Reicher-Wheeler paradigm and standardized behavioral measures of fluency and reading.

1.5. The Present Study

Previous ERP studies using a Reicher-Wheeler paradigm have focused only on a word superiority effect (using only word and nonword stimuli), have reported only on the first 300 ms of the waveform, and have not considered possible brain-behavior correlations with standardized measures (e.g., Martin et al., 2006). Here, we addressed each of these gaps in the literature. We used multiple measures – standardized behavioral measures, button-press responses in a modified Reicher-Wheeler paradigm, and ERP recordings during the modified Reicher-Wheeler paradigm – to investigate automatic orthographic processing in fluent readers. We used word, pseudoword, and nonword stimuli in order to investigate both word and pseudoword superiority effects for both behavioral and ERP measures. We also considered an alternate baseline to nonwords, a letter-in-xs stimulus (e.g., DXXX). Grainger and Jacobs (2005, see their footnote 6) discussed the utility of nonwords as a baseline condition; we used the letter-in-xs stimulus in order to investigate a baseline that further reduced orthographic information at the letter level. In addition, we considered both early (e.g., N200) and late (e.g., N400) components elicited by these various stimuli. Our primary research questions concerned when in the ERP waveform word and pseudoword superiority effects might be reflected, and whether or not the ERP measures would correlate with the behavioral measures.

2. RESULTS

2.1. Standardized Behavioral Tests

Raw, standard, and percentile rank scores on the behavioral tests are summarized in Table 1. Scores on the Letters and Numbers RAN/RAS Tests (Wolf and Denckla, 2005) indicated that participants had above-average naming speed and fluency.[1] Scores on the Sight Word subtest of the TOWRE (Torgesen et al., 1999) indicated average performance, while mean percentile rank on the Phonemic Decoding Efficiency subtest of the TOWRE was higher. Scores on the Word Identification subtest from the WRMT-R (Woodcock, 1987) were also above average. Overall, the standardized behavioral test scores confirmed that participants had average or above-average orthographic fluency, decoding, and single word reading skills.

2.2. ERP Task Behavioral Accuracy

Behavioral accuracy on the ERP letter identification task across the four stimulus conditions is summarized in Figure 1 in terms of percent correct. Participants correctly identified letters in masked words (raw mean 74.6, *SD* 6.8) more often than letters in masked nonwords (raw mean 69.7, *SD* 8.0; $t(23) = 3.6$, $p < .01$), the typical word superiority effect. A typical pseudoword superiority effect was also observed: Participants correctly identified letters in masked pseudowords (raw mean 73.9, *SD* 6.2) more often than letters in masked nonwords ($t(23) = 4.4$, $p < .001$). This pattern replicates the behavioral results with adults reported in Chase and Tallal (1990) using the same stimuli. Using the letter-in-xs stimuli (raw mean 65.0, *SD* 9.0) as an alternate baseline to nonwords, both a word superiority effect ($t(23) = 6.6$, $p < .001$) and a pseudoword superiority effect ($t(23) = 7.2$, $p < .001$) were observed.

2.3. ERP Waveforms

2.3.1. P150 (100–160 ms)—An omnibus ANOVA revealed a main effect of condition on peak amplitude of the P150 such that nonwords elicited the largest P150, followed by letter-in-xs, pseudoword, and word stimuli ($F(3, 69) = 3.57$, $p < .05$; see Figures 2 and 3). Planned comparisons indicated a larger P150 to nonwords than to words ($F(1, 23) = 32.28$, $p < .001$) or to pseudowords ($F(1, 23) = 4.70$, $p < .05$). There were no significant differences between the peak amplitude of the P150 to word or pseudoword as compared to letter-in-xs stimuli.

2.3.2. N200 (160–220 ms)—An omnibus ANOVA revealed that the effect of condition on N200 peak amplitude varied across the scalp (condition × anterior/posterior, $F(3, 69) = 5.35$, $p < .01$; condition × anterior/posterior × lateral/medial, $F(3, 69) = 3.52$, $p < .05$; see Figures 2 and 3). Planned comparisons indicated a larger N200 to words than nonwords, particularly at medial occipital sites (condition × anterior/posterior, $F(1, 23) = 7.46$, $p < .05$; condition × anterior/posterior × lateral/medial, $F(1, 23) = 5.52$, $p < .05$), but no significant difference in the peak amplitude of the N200 to pseudowords and nonwords. In comparison to the alternate baseline letter-in-xs condition, there was no significant difference in N200 peak amplitude to words but pseudowords elicited a larger N200 than letter-in-xs stimuli at medial parietal sites while the reverse pattern was observed at medial occipital sites (condition × anterior/posterior, $F(1, 23) = 8.60$, $p < .01$; condition × anterior/posterior × lateral/medial, $F(1, 23) = 6.58$, $p < .05$).

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[1] Normalized scores were based on age norms for 18;0–18;11, the oldest normed age group for these RAN/RAS tests.

2.3.3. N300 (250–350 ms)—An omnibus ANOVA revealed that the effect of condition on N300 peak amplitude varied across the scalp (condition, $F(3, 69) = 3.11$, $p < .05$; condition × hemisphere, $F(3, 69) = 6.74$, $p < .001$; condition × anterior/posterior, $F(15, 345) = 13.50$, $p < .001$; condition × hemisphere × anterior/posterior, $F(15, 345) = 2.97$, $p < .01$; condition × anterior/posterior × lateral/medial, $F(15, 345) = 3.10$, $p < .01$; see Figures 3 and 4). A planned comparison of the word and nonword conditions showed that nonwords elicited a larger N300 particularly at medial sites anterior to the occipital sites (condition, $F(1, 23) = 4.92$, $p < .05$; condition × anterior/posterior, $F(5, 115) = 13.02$, $p < .001$; condition × anterior/posterior × lateral/medial, $F(5, 115) = 3.49$, $p < .05$). Pseudowords elicited a larger N300 than nonwords at posterior sites over the left hemisphere and across the right hemisphere (condition × hemisphere, $F(1, 23) = 7.59$, $p < .05$; condition × anterior/posterior, $F(5, 115) = 4.67$, $p < .01$; condition × hemisphere × anterior/posterior, $F(5, 115) = 4.66$, $p < .01$).

Similar planned comparisons with the alternate baseline letter-in-xs stimuli showed that these stimuli elicited a larger N300 than words across the right hemisphere and over the left hemisphere at sites anterior to the occipital and parietal sites (condition, $F(1, 23) = 7.26$, $p < .05$; condition × hemisphere, $F(1, 23) = 9.84$, $p < .01$; condition × anterior/posterior, $F(5, 115) = 31.84$, $p < .001$; condition × hemisphere × anterior/posterior, $F(5, 115) = 3.89$, $p < .05$), particularly medial parietal and lateral and medial occipital sites (condition × anterior/posterior × lateral/medial, $F(5, 115) = 5.54$, $p < .01$). Comparison of the pseudoword and letter-in-xs conditions showed a similar pattern: The letter-in-xs stimuli elicited a larger N300 than pseudowords across the right hemisphere except at occipital sites and across the left hemisphere except at parietal and occipital sites, particularly medial parietal and lateral and medial occipital sites (condition × anterior/posterior, $F(5, 115) = 20.69$, $p < .001$; condition × hemisphere × anterior/posterior, $F(5, 115) = 5.04$, $p < .01$; condition × anterior/posterior × lateral/medial, $F(5, 115) = 4.17$, $p < .05$).

2.3.4. N400 (350–450 ms)—An omnibus ANOVA revealed a main effect of condition on N400 peak amplitude such that pseudowords elicited the largest N400, followed by words, nonwords, and letter-in-xs stimuli ($F(3, 69) = 9.64$, $p < .001$; see Figures 3 and 4). Planned comparisons indicated that words elicited a larger N400 than nonwords, particularly at more posterior and lateral sites (condition × anterior/posterior, $F(2, 46) = 4.292$, $p < .05$; condition × lateral/medial, $F(1, 23) = 6.65$, $p < .05$). Pseudowords also elicited a larger N400 than nonwords, particularly at more posterior sites (condition, $F(1, 23) = 8.06$, $p < .01$; condition × anterior/posterior, $F(2, 46) = 10.65$, $p < .001$). In comparison to the letter-in-xs baseline, words elicited a larger N400 (condition, $F(1, 23) = 15.31$, $p < .01$; condition × hemisphere × anterior/posterior × lateral/medial, $F(2, 46) = 3.63$, $p < .05$), as did pseudowords, particularly at medial, posterior sites (condition, $F(1, 23) = 24.86$, $p < .001$; condition × anterior/posterior × lateral/medial, $F(2, 46) = 4.95$, $p < .05$).

2.4. Correlations Among ERP Task Behavioral Performance, Standardized Test Scores, and ERP Measures

2.4.1. ERP task performance and standardized test scores—Raw scores on the RAN Numbers subtest were correlated with accuracy in the pseudoword ($r = -.446$, $p < .05$) and letter-in-xs ($r = -.424$, $p < .05$) conditions. Raw scores on the TOWRE Phonemic Decoding subtest were correlated with accuracy in the word ($r = .462$, $p < .05$), pseudoword ($r = .462$, $p < .05$), and nonword ($r = .554$, $p < .01$) conditions. Raw scores on the Woodcock Word Identification test were also correlated with accuracy in the word ($r = .640$, $p < .001$), pseudoword ($r = .652$, $p < .001$), and nonword ($r = .568$, $p < .01$) conditions, as well as in the letter-in-xs condition ($r = .458$, $p < .05$).

2.4.2. ERP task performance and ERP measures—The average peak amplitudes of the P150, N200, N300, and N400 to words, pseudowords, nonwords, and letter-in-xs stimuli were not correlated with accuracy on the ERP task in the word, pseudoword, nonword, or letter-in-xs conditions. The size of the ERP word and pseudoword superiority effects were not correlated with accuracy except in the case of the size of the P150 word superiority effect, which was positively correlated with accuracy in the pseudoword ($r = .439$, $p < .05$) and letter-in-xs ($r = .416$, $p < .05$) conditions.

2.4.3. Standardized test scores and ERP measures—A measure of the average P150 peak amplitude at parietal and occipital sites did not correlate with raw scores on any of the standardized behavioral tests. A measure of N200 peak amplitude at sites O1 and O2 (medial occipital sites at which a word superiority effect was observed) also did not correlate with raw scores on any of the standardized behavioral tests. Similarly, a measure of average N300 peak amplitude at parietal and occipital sites did not correlate with any behavioral test raw scores. A measure of average N400 peak amplitude at central, parietal, and occipital sites for word stimuli was moderately correlated ($r = .418$, $p < .05$) with TOWRE Sight Word raw scores.

A measure of the average peak amplitude of the P150 word superiority effect at parietal and occipital sites (words – nonwords) was moderately correlated with TOWRE Sight Word ($r = .538$, $p < .01$) and Woodcock Word Identification ($r = .559$, $p < .01$) scores. Similar measures of the N200 and N300 word and pseudoword superiority effects were not correlated with any of the behavioral test scores. However, a measure of the average peak amplitude of the N400 word superiority effect was correlated with scores on the RAN Numbers ($r = -.419$, $p < .05$) and TOWRE Sight Word ($r = .405$, $p < .05$) tests.

3. DISCUSSION

In a modified Reicher-Wheeler paradigm (Reicher, 1969; Wheeler, 1970) designed to index traditional word and pseudoword superiority effects through both behavioral and electrophysiological measures, we replicated both word and pseudoword superiority effects behaviorally (Chase and Tallal, 1990) and found a posterior P150, a posterior N200, a widespread N300, and a posterior N400 that were differentially sensitive to words and pseudowords as compared to nonwords and letter-in-xs stimuli. Behaviorally, letter identification was more accurate in words and pseudowords as compared to nonwords and letter-in-xs stimuli, and effects of orthographic regularity and familiarity were apparent in the ERP waveform as early as the P150 time window (100–160 ms), while an effect of lexicality was apparent as early as the N200 time window (160–220 ms). ERP measures of the word superiority effect for the P150 and N400 were correlated with behavioral measures of orthographic fluency and single word reading. Thus, with respect to our primary research questions, we found that word and pseudoword superiority effects in the masked Reicher-Wheeler ERP paradigm were reflected both early and late in the ERP waveform, in the P150, N200, N300 and N400. We also found that some of these ERP measures were correlated with standardized behavioral measures. These findings, discussed below, extend the ERP literature on fluent orthographic processing in the Reicher-Wheeler paradigm and contribute to our understanding of early and late ERP effects associated with word perception.

3.1. P150

Nonwords elicited a larger P150 than either words or pseudowords, reflecting an early effect of orthographic regularity and familiarity; that is, orthographically irregular and unfamiliar strings of letters (nonwords) elicited a greater P150 than orthographically regular strings (words and pseudowords). Previous reports of orthographic and lexicality effects on a P1 have been inconsistent. For example, Sereno et al. (1998) found that consonant strings elicited a larger P1 than words, as did pseudowords, while Proverbio et al. (2004) reported the opposite: a P150 larger to words and pseudowords than letter strings. Also supporting the orthographic sensitivity of the P150, Hauk et al. (2006b) reported that effects of orthographic typicality and lexicality interacted at about 160 ms in a speeded lexical decision task, while lexicality effects were first observed at 160 ms in another lexical decision task (Hauk et al., 2006a). However, Nobre and colleagues (1994) found that P1 amplitude differentiated among types of nonwords, but words did not differ from pseudowords or nonwords in terms of P1 amplitude, while Carreiras et al. (2008) found no lexicality effects on a P150 for words and pseudowords but a sensitivity to the delayed presence of both vowels and consonants in these strings. And in an ERP word superiority effect paradigm using only word and nonword stimuli, Martin et al. (2006) reported a P1 (peaking at about 100 ms) that was not sensitive to stimulus condition. This P1 effect was earlier than the P150 observed here, there were only two stimulus conditions presented, duration of stimulus presentation was manipulated, stimuli were five letters in length (as compared to four here), nonwords were consonant strings (as compared to including vowels here), each stimulus was presented six times (as compared to once here), and stimuli were in French (as compared to English here); any one of these factors or a combination of these factors and other methodological variances might account for the observed differences between the findings of Martin et al. and the present study.

Modulation of P150 amplitude by stimulus condition in the present paradigm – reflecting both a word superiority effect and a pseudoword superiority effect – might suggest an early time course for lexical processing (e.g., Grainger and Jacobs, 2005) but is also consistent with a prelexical interpretation of these effects (e.g., McCandliss et al., 2003). If superiority effects in the Reicher-Wheeler paradigm are considered an index of the top-down influences of lexical representations on letter identification (e.g., Laszlo and Federmeier, 2007; Martin et al., 2006; McClelland and Rumelhart, 1981), these findings indicate that the early processing indexed by the P150 is influenced by lexical-level knowledge of orthographic regularity or familiarity; others have reported on sublexical-lexical interactions within a later (175–300 ms) time window (e.g., Holcomb and Grainger, 2006). Interestingly, previous studies have indicated that the P150 indexes activation of feature-level, location-specific letter detectors during an “initial phase of sublexical orthographic processing” (Chauncey et al., 2008; Dufau et al., 2008; Holcomb and Grainger, 2006, p. 1639) or “perceptual fluency for more common letter forms” (Dien, 2009, p. 14), consistent with the demands of the Reicher-Wheeler task and this interpretation of the P150 findings.

However, this interpretation is tempered by comparison with the alternate baseline stimuli used in the present study: There were no differences in the peak amplitude of the P150 to words or pseudowords as compared to letter-in-xs stimuli. Perhaps a string of Xs with one other letter is perceived and processed as more regular or familiar than a string of jumbled letters (nonwords), but the similarity of the P150 peak amplitude across these orthographically legal and illegal stimuli suggests that the letter-in-xs stimuli may not be an appropriate baseline for elicitation of word and pseudoword superiority effects at the neural level, at least in terms of the processing indexed by the P150. Indeed, if the P150 does index feature-level, location-specific letter detectors (Chauncey et al., 2008; Dufau et al., 2008), the repetitive nature of the letter-in-xs stimuli (by definition consisting of a string of identical Xs and one other letter) may not be well suited to comparison on these terms. Interestingly, comparison of words and pseudowords with the letter-in-xs stimuli did result in both a word and pseudoword superiority effect behaviorally in terms of percent correct in the letter identification task, but participants were least accurate in the letter-in-xs condition.

Overall, the inconsistent findings regarding the P150 indicate that further research designed specifically to address the orthographic sensitivity of this component is needed. The pattern of present findings in combination with findings in the literature suggests that future studies of the orthographic sensitivity of the P150 should systematically manipulate task and stimulus characteristics, as well as carefully considering baseline comparisons. Here, under masked conditions with four types of stimuli varying in orthographic regularity and familiarity in a letter identification task, P150 peak amplitude did provide an index of orthographic processing, but only with respect to the nonword baseline. Nonword and letter-in-xs stimuli differed on a number of orthographic parameters including N, constrained and unconstrained bigram frequency, and constrained and unconstrained trigram frequency (see Table 2). Which of these factors (or others) might influence the orthographic sensitivity of the P150 remains for future investigation.

3.2. N200

Only words (not pseudowords) elicited a larger N200 than nonwords at medial occipital sites, reflecting a word superiority effect for N200 peak amplitude. Martin and colleagues (2006) also reported an N1 (peaking at about 210 ms) with larger amplitude to words than nonwords in their 66 ms duration condition. In combination with the P150 findings in the present study, this pattern of results suggests an increasingly selective processing of legal, orthographically familiar and regular stimuli within the timeframe encompassing these two components: In comparison to nonwords, both pseudowords and words elicited a smaller P150 but only words elicited a larger N200 than nonwords. It would seem that, like the P150, N200 peak amplitude in this paradigm may be influenced by top-down lexical-level knowledge of orthographic regularity or familiarity but is also influenced by top-down information regarding lexicality.

These N200 results are consistent with the behavioral acronym findings suggesting that the word superiority effect may be influenced more by orthographic familiarity than regularity (Laszlo and Federmeier, 2007), given that both words and pseudowords were regular according to grapheme-to-phoneme correspondence rules here, but only words were orthographically familiar and only a word superiority effect was observed for N200 peak amplitude. They are also consistent with other reports of negativities peaking at about 200 ms sensitive to lexicality (e.g., Grossi and Coch, 2005; Hauk et al., 2006b; Maurer et al., 2005; Maurer et al., 2008; Sauseng et al., 2004). Sauseng and colleagues (2004, p. 531) proposed that a negativity in this latency indexed interaction between letter input and memory, consonant with our interpretation of the present word, pseudoword, and nonword N200 findings in a Reicher-Wheeler paradigm as indexing top-down influences of lexical memory.

But once again in the case of the N200, the letter-in-xs stimuli used as an alternate baseline to nonwords did not serve to clarify neural processing related to the word and pseudoword superiority effects. In comparison to the letter-in-xs stimuli, only pseudowords elicited a larger N200, at medial parietal sites. Again, it is difficult to interpret the similar processing of words and letter-in-xs stimuli in terms of the letter identification task; perhaps orthographic regularity and familiarity apply in similar ways to these different stimulus types (as discussed above), while there is no apparent explanation at the level of lexicality. In their behavioral comparison of pseudowords and letter-in-xs stimuli in a Reicher-Wheeler paradigm, Grainger and Jacobs (2005, pp. 315–316) also reported an effect of sublexical orthographic regularity, but not at the level of bigram or trigram frequency, suggesting that “other measures of orthotactic constraints need to be specified and tested.” The similarity of the N200 elicited by words and letter-in-xs stimuli here is difficult to explain in terms of either the non-interactive word read-out model (e.g., Grainger and Jacobs, 1994; Grainger, 2008), as word stimuli should facilitate read-out while letter-in-xs stimuli should not, or the interactive top-down lexical interaction model (McClelland and Rumelhart, 1981), as words should facilitate top-down influence but letter-in-xs stimuli, having no lexical entries, should not.

Overall, the N200 findings with words, pseudowords, and nonwords are consistent with previous work suggesting that the N200 may be an index of orthographic familiarity and lexical access. The results from the letter-in-xs condition call this interpretation into question. By definition, the word superiority effect reflects the facilitatory effects of the word context on the perception of component letters. The behavioral results from the ERP letter identification task show a word superiority effect for the comparison between word and letter-in-xs stimuli – at the level of forced choice between letters, the word context facilitates. The electrophysiological results from the same ERP task suggest that this facilitation may not be happening entirely at the level of the N200. This N200 finding reinforces the importance of systematically investigating various task and stimulus parameters, including baseline comparisons, in determining where and when in the ERP waveform superiority effects might be indexed.

3.3. N300

Words elicited a larger N300 than nonwords only at the most posterior, medial sites; pseudowords also elicited a larger N300 than nonwords, particularly at posterior, right hemisphere and medial sites. In comparison to letter-in-xs stimuli, words elicited a larger N300 only at the most posterior sites, with a similar pattern for pseudowords. The most striking aspect of the N300 component was its large amplitude to the letter-in-xs stimuli at anterior sites (particularly in comparison to word stimuli), a reversal of the pattern observed at the most posterior sites.

Previous reports of an N300 in word processing paradigms have been sparse (e.g., Dien, 2009). Some reports have related an N300 to an N400, and suggested that the N300 is an index of semantic fit (e.g., Dien et al., 2000); others have reported a lexical processing negativity in the N300 time window sensitive to lexicosemantic properties and number of orthographic neighbors (Proverbio and Adorni, 2008); still others have related an N300 to phonological processing (e.g., Bentin et al., 1999; Proverbio and Adorni, 2008; Simon et al., 2004; Simon et al., 2006). For example, in a rhyming task, Bentin and colleagues (1999) reported a mid-temporal, bilateral N320 larger over the left hemisphere elicited by pronounceable (but not unpronounceable) stimuli. Simon and colleagues (2004; 2006) have also suggested that an N320 indexes phonological processing modulated by orthography, in particular, phonological processing related to grapheme-to-phoneme correspondence rules. Similarly, Proverbio and colleagues recently reported an occipito-temporal N300 sensitive to orthographic familiarity and a temporo-parietal N300 sensitive to phonology, localized to, among other regions, the left angular gyrus known to be involved in grapheme-to-phoneme conversions (Proverbio and Adorni, 2008). Dien (2009) also reported an N300 sensitive to phonological familiarity, although other work from this group has suggested that the process(es) indexed by the N300 might be less specific (O’Hare et al., 2008). The word and pseudoword superiority effects observed here at the most posterior electrode sites are consistent with the pronounceability of these stimuli as compared to nonwords. Hypothetically, the marked reversal of these effects at more anterior sites could be related to a greater effort to phonologically analyze the orthographic information presented in the nonword and letter-in-xs stimuli or the illegal mismatch between orthography and phonology characterizing these stimuli. If so, this might suggest obligatory phonological analysis of letter strings in fluent adult readers, as the letter identification task was wholly dependent on orthography. There are numerous reports in the literature of obligatory phonological analysis in fluent readers reading for meaning (e.g., Van Orden, Johnston, and Hale, 1988). In turn, this might suggest that some part of the superiority effects observed in

Reicher-Wheeler paradigms – the facilitatory context of words and pseudowords as compared to nonwords (or letter-in-xs stimuli) in terms of the forced-choice letter identification task – is phonological.

3.4. N400

Both words and pseudowords elicited a larger N400 than nonwords at posterior sites, consistent with previous findings outside of a Reicher-Wheeler paradigm (e.g., Bentin et al., 1985; Bentin, 1987; Holcomb, 1988; Holcomb, 1993; Kounios and Holcomb, 1994; Nobre and McCarthy, 1994; Rugg, 1984; Rugg, 1987; Swick and Knight, 1997; Ziegler et al., 1997). A similar pattern was apparent for words and pseudowords as compared to letter-in-xs stimuli. These findings are consistent with an interpretation of the N400 as an index of a higher-level integration process (e.g., Holcomb, 1988; Holcomb et al., 2002): hypothetically, because lower-level orthographic and phonological processing could not be completed with the nonword and letter-in-xs stimuli, there was little indication of any integration of the products of those processes (smaller N400s); because lower-level orthographic and phonological processing could be conducted with word and pseudoword stimuli, there was evidence for the attempted integration of this information (larger N400s). This pattern is compatible with an interpretation of the N400 as reflecting a higher-level superiority effect for words and legally word-like stimuli, perhaps at the level of a “form-meaning interface” (Holcomb and Grainger, 2006, p. 1641). Theoretically, such a lexical-level effect would contrast with the sublexical-lexical interaction effects (McClelland and Rumelhart, 1981) reflected in the earlier (P150, N200) components.

While we have discussed each of these components in a sequential fashion, it is important to note that the data do not necessarily support a serial processing view of reading. For example, our speculation regarding sublexical-lexical interaction effects as reflected in the early P150 and N200 components is consistent with other recent data indicating interactive and dynamic neural systems for reading with “early interactions between the visual and language domains” (Cornelissen, Kringelbach, Ellis, Whitney, Holliday, and Hansen, 2009, e5359, p. 1). As discussed above, it is difficult to isolate the effects of orthography given the highly interactive nature of the reading system (e.g., Adams, 1990; Cunningham et al., 2001; Manis et al., 1999; Olson et al., 1994; Vellutino et al., 1994; Wile and Borowsky, 2004), and a Reicher-Wheeler type paradigm is just one potentially useful tool in this endeavor.

3.5. Electrophysiological and Behavioral Measures of Orthographic Fluency

Our standardized behavioral measures of orthographic fluency – traditional, timed rapid automatized naming and reading tasks [subtests of the RAN/RAS (Wolf and Denckla, 2005) and TOWRE (Torgesen et al., 1999)] – not only confirmed that participants were at least averagely fluent readers, but also were, in some cases, correlated with our electrophysiological measures. Correlations indicated an association between orthographic familiarity and fluency as measured behaviorally by the TOWRE Sight Word subtest and the size of the electrophysiological word superiority effects for the P150 and N400. Single word reading skill as measured by the Woodcock Word Identification task was also correlated with the size of the P150 word superiority effect, suggesting that this early ERP effect specific to words is reflective of behavioral facility with words. The size of the N400 word superiority effect was also negatively correlated with RAN Numbers scores, suggesting that the N400 effect may be more closely related to fluency in terms of speed, since longer times on the RAN Numbers task and more sight words read in the allotted time on the TOWRE were both correlated with this ERP effect. Overall, this pattern of findings suggests that the word superiority effects reflected in the ERP waveform on the P150 and N400 might be indexing, in part, processing within the same or similar systems used in the standardized behavioral tasks. Interestingly, almost none of the correlation analyses between P150, N200, N300, and N400 amplitude to words, pseudowords, nonwords, and letter-in-xs stimuli separately and the behavioral test scores were significant; rather, it was the difference between conditions – the superiority effect – that was correlated with the behavioral measures. To our knowledge, this is the first report of such brain-behavior correlations.

In contrast, the size of the ERP superiority effects was not, for the most part, correlated with accuracy on the ERP task; only the size of the P150 word superiority effect was associated with accuracy. However, there was stronger evidence of an association between scores on some of the timed standardized measures and accuracy on the ERP task. Accuracy in each of the four conditions was correlated with scores on at least one of the timed tests. This pattern of findings suggests that the standardized behavioral measures and ERP task performance were more closely associated than either the behavioral measures or task performance and the ERP waveforms. This might not be surprising given that the ERP waveforms were recorded not to the two-alternatives forced-choice letter stimuli but instead to the masked letter string stimuli; thus, the ERPs reflect the processes that lead to the differences observed in the task rather than task performance directly. Overall, these are intriguing associations that deserve further investigation beyond this initial exploratory study, as they do indicate that specific brain-behavior relationships can be indexed by ERPs in a Reicher-Wheeler paradigm and standardized behavioral measures.

All three types of our measures – the standardized reading tests, the ERPs to letter strings, and the behavioral accuracy data in the forced-choice task – capture aspects of the same reading skill, so it was expected that they would be related, as suggested by the correlation analyses. This overlap provides confirmation for each as a measure of orthographic fluency. However, despite these associations, the overall pattern of correlation results seems to indicate that the electrophysiological measures of word and pseudoword superiority effects may index different aspects of orthographic fluency than the standardized behavioral measures and performance on the Reicher-Wheeler letter identification task. Given the complexity of the concept of fluency (e.g., Wolf and Katzir-Cohen, 2001) and the apparent early (within 150 ms) and automatic (likely, although not certain, under backward masked conditions and 46 ms presentation duration) nature of the orthographic fluency indexed by the ERP word and pseudoword superiority effects, it is not surprising that the behavioral tasks might not index the same aspects of fluency as on-line processing measures.

This is not to say that reading can be parceled into potentially different processes for the standardized tests, the ERPs, and the behavioral data from the forced-choice task, but that each of these measures might provide both shared (as indicated by the correlation analyses) and unique (as indicated by the lack of perfect correlations) information. In order to refine an understanding of orthographic fluency, it would seem necessary to consider the evidence from both neural and behavioral sources. The neural and behavioral measures can help to mutually constrain interpretations of each other and provide a more multidimensional view of orthographic fluency. For example, the standardized behavioral tests employed here, and others like them, are typically used in education to measure aspects of reading fluency across development. The pattern of findings from the present study suggests that scores on these measures alone might not provide a full picture of developing fluency. Perhaps such measures in combination with temporally sensitive electrophysiological measures can provide more or better information about the development of orthographic fluency. Indeed, ERP studies using the modified Reicher-Wheeler paradigm described here are currently under way with elementary school children in order to investigate this question.

3.6. An Alternative Interpretation

Our primary research question concerned when in the ERP waveform word and pseudoword superiority effects might be reflected. We operationally defined such effects as they are typically defined in a Reicher-Wheeler task: a difference in performance between words and a baseline (here, nonwords or letter-in-xs stimuli) and a difference in performance between pseudowords and a baseline, respectively. In the behavioral letter identification task during ERP recording, performance was measured in terms of accuracy between conditions, while in the ERP waveforms, performance was measured in terms of peak amplitude between conditions. The facilitation found for accuracy is relatively straightforward, but it could be argued that the same does not have to be the case for the ERP effects, which could be just showing the processing of different letter strings independently of the letter recognition task. [2]

While it is the case that the ERP effects by condition reported above are for the most part consistent with previous word recognition studies in which participants performed tasks other than a Reicher-Wheeler task, we would expect nothing less in a study involving word processing. So are the ERPs simply reflective of letter string processing regardless of task, or are they a potential index of superiority effects in the Reicher-Wheeler task? It is probably not even fair to differentiate the two possibilities: the differential processing of letter strings leads to the superiority effects. The only measure we have of the actual letter identification task is behavioral (letter choice accuracy), and accuracy was not correlated with any of the ERP measures except the size of the P150 word superiority effect (which, in itself, is suggestive). However, there was not a lot of variance in the accuracy scores and only ERPs to trials with correct responses were included in the average waveforms, both of which would reduce the power of the correlation analyses. Correlations between the ERP superiority effects and the standardized behavioral test scores also cannot disentangle what in the ERPs is differential processing of types of letter strings and what is a reflection of word and pseudoword superiority effects in a Reicher-Wheeler task.

The accuracy of subsequent letter identification was robustly different by condition, which strongly suggests that the letter strings in each condition must have been processed differently. The ERPs confirm this differential processing, but cannot definitively determine whether it is due to standard letter string processing or the demands of the Reicher-Wheeler task or both. Future studies could further investigate these possibilities by having participants perform a different task with the same stimuli. Past studies have interpreted such effects in the Reicher-Wheeler context as an index of the constraint of visual word form representations on letter identification at a prelexical stage (Martin et al., 2006, p. 158). For our purposes here, the ERP results are consistent with traditional word and pseudoword superiority effects such that the word context and the pseudoword context, respectively, were associated with improved perception of component letters. Although this is not the only possible interpretation of the pattern of findings, it does address our primary research question of when in the ERP waveform reflections of a word and pseudoword superiority effect, as operationally defined, can be found.

3.7. Summary

Our electrophysiological measure in a modified Reicher-Wheeler paradigm indicated both word and pseudoword superiority effects reflected both early in the ERP waveform, as early as the peak amplitude of the P150, and late in the waveform, in terms of the peak amplitude of the N400. These findings are consistent with other ERP findings indicating both early (e.g., Sereno et al., 1998) and late (e.g., Bentin et al., 1999) effects of lexical processing in various paradigms, but simultaneously reveal both for the first time, to our knowledge, in the context of the modified Reicher-Wheeler paradigm theoretically indexing lexical-level effects on orthographic processing (McClelland and Rumelhart, 1981). This pattern of

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[2] We thank a Reviewer for this suggestion.

findings suggests that orthographic fluency is reflected in both lower-level, sublexical, perceptual processing and higher-level, lexical processing in fluently reading adults and contributes to an understanding of ERP effects associated with word and letter processing.

Moreover, the size of the P150 and N400 ERP word superiority effects was related to standardized measures of fluency and single word reading, indicating brain-behavior associations perhaps as common resources were drawn upon by these tasks. In addition to this overlap, there was evidence that the ERP measures, performance on the letter identification task in the ERP paradigm, and scores on the standardized measures provided unique, non-overlapping indices of orthographic fluency. Therefore, it seems most useful to employ multiple measures, including both behavioral and neural measures, in concert in order to fully and systematically investigate orthographic fluency in letter string processing.

4. EXPERIMENTAL PROCEDURE

4.1. Participants

The final sample of participants included 24 undergraduate students (12 female), average age 19.4 years, *SD* 1.1. All participants were right-handed (Edinburgh Handedness Inventory, Oldfield, 1971), monolingual English speakers with no history of neurological, speech, language, or reading disorders and normal or corrected-to-normal visual acuity. Participants were screened for binocular visual acuity using the standard kindergarten Snellen chart. All participants were volunteers paid for their participation.

4.2. Behavioral Testing Materials

The Letters and Numbers subtests from the Rapid Automatized Naming and Rapid Alternating Stimulus Tests (RAN/RAS, Wolf and Denckla, 2005), the Sight Word and Phonemic Decoding Efficiency subtests of the Test of Word Reading Efficiency (TOWRE, Torgesen et al., 1999), and the Word Identification subtest from the Woodcock Reading Mastery Tests - Revised (WRMT-R, Woodcock, 1987) were administered. The RAN tests provided a measure of naming speed and fluency, the Sight Word subtest of the TOWRE served as a measure of orthographic fluency, the Phonemic Decoding subtest of the TOWRE measured orthographic-to-phonemic correspondence knowledge and fluency, and the Word Identification subtest of the WRMT-R was a general measure of sight word vocabulary.

4.3. Stimuli

The stimuli for the ERP experiment were the same as those used by Chase and Tallal (1990) in a previous behavioral study of the word superiority effect (see also Rumelhart and McClelland, 1982). Chase and Tallal (1990, pp. 455–456) noted that their list of 80 four-letter words included only words that were rated as having a frequency of 12 or more per million according to an adult corpus (Kucera and Francis, 1967) and were also rated as high frequency according to a corpus for children in grades 3 through 5; frequency statistics for the stimuli are summarized in Table 2. As required by the Reicher-Wheeler paradigm, Chase and Tallal (1990, pp. 455–456) selected words as pairs that differed only by a single letter position (target). The forced-choice alternatives were the two target letters for each pair. Target letters were equally distributed across the four letter positions (i.e., 10 pairs differed by first letter, 10 pairs by second, 10 pairs by third, and 10 pairs by fourth letter; thus, the position of the target letter was counterbalanced across all pairs). Matched pseudowords and nonwords were constructed based on the 40 word pairs. Nonwords were constructed by rearranging the order of the letters according to a 3142 scheme. Pseudowords, used to control for familiarity, were constructed by changing the letter most distant from the target letter to produce a pronounceable string; note that replacing only one letter of a word to create a pseudoword may result in higher orthographic familiarity for the latter (e.g., Proverbio and Adorni, 2008). So, for example, the word pair *DARK-PARK* was matched with the pseudoword pair *DARL-PARL* and the nonword pair *RDKA-RPKA* and the forced-choice alternatives for each member of the pair were *D-P*.

Grainger and Jacobs (2005) noted that the literature is equivocal regarding whether nonwords are the best baseline condition to which to compare pseudowords; while nonwords are the traditional baseline condition, we included an additional type of control stimulus, the letter-in-xs stimulus, in order to investigate the utility of further reducing orthographic information at the letter level. The letter-in-xs stimuli were matched to the pseudowords, as in *DXXX-PXXX*. All four types of stimuli were presented intermixed, appearing as white uppercase letters on a black background in size 85 Lucida Console font. Stimuli subtended approximately 0.6° of vertical visual angle and all strings of letters fit within the horizontal visual angle of 2.2° subtended by the visual mask.

In the original Chase and Tallal report (1990), half the participants saw one member of each stimulus pair (list 1) and half saw the other member of the pair (list 2) for a total of 40 trials within each condition. Here, in order to increase the number of trials for ERP recording, each participant saw both members of the pair at different times across the experiment, with order of presentation of list 1 and list 2 counterbalanced across participants (in each case, the forced-choice alternatives were the same). The stimuli within each list were presented in pseudorandom but fixed order, with no more than 4 stimuli in the same condition (word, pseudoword, nonword, or letter-in-xs) and no more than 2 target letters in the same position (first, second, third, or fourth letter) in a row. Thus, ERPs were recorded to 80 word, 80 pseudoword, 80 nonword, and 80 letter-in-xs stimuli overall.

4.4. Procedure

All participants were given a brief tour of the lab and an overview of the procedures, and were asked to sign a consent form; the Committee for Protection of Human Subjects at Dartmouth College approved all procedures. Following the behavioral testing (see above), participants were fitted with an electrode cap used for recording ERPs (see below). Participants were then seated in a comfortable armchair in a sound attenuating, electrically shielded booth. Participants were told that they would see four-letter words on the monitor[3] in front of them, some of which they would know and some of which they would not know. They were told that the words would go by very quickly and were instructed to indicate what letters they saw in the words using a simple button-press device. Participants were further instructed to try not to blink or move while anything was on the monitor. Practice trials preceded the actual testing session.

Stimuli were presented using Presentation software (Neurobehavioral Systems). The stimulus presentation procedure was a variant of the typical Reicher-Wheeler paradigm (see Figure 5). Participants viewed an asterisk fixation point on the monitor directly in front of them. Four hundred eighty six ms after presentation of the fixation point, a string of letters was presented for 46 ms. Directly following, a mask consisting of four consecutive hash marks (####) replaced the letter string and remained in view for 500 ms, after which a blank screen replaced the mask for 268 ms.[4] Thus, an answer choice was presented 814 ms from the onset of the prime in the form of a post-mask with a pair of letters, one above and one below the target letter position. Position of the correct letter (presented above or below the hash mark) was randomized for each trial but averaged to 50% above and 50% below across participants. Participants responded with a button press to indicate which of the two letters

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[3] The monitor was an 8U Rackmount 19″ Samsung LCD-TFT, model RP819, with t_r = 1.3 ms (black to white) and t_f = 3.7 ms (white to black); rise and fall times were within the 4 ms sampling rate.

had been presented in that position; the left and right trigger buttons on the response device were counterbalanced for top and bottom responses across participants. The post-mask with two letters remained on the screen until a response was entered. Once a response was entered, a blank screen appeared and pressing either button advanced the program to the next trial starting with the fixation.

ERPs time-locked to the presentation of the letter string stimuli (80 words, 80 pseudowords, 80 nonwords, 80 letter-in-xs) were recorded with customized digitization software using LabView (National Instruments). ERPs to the presentation of the forced-choice letters were not recorded as presentation of the letters was accompanied by substantial eye movements and other sources of artifact (e.g., button presses). The ERP portion of the experiment lasted about 30 minutes, including a break at the halfway point, and the duration of the entire experiment was about 2 hours.

4.5. EEG/ERP Recording and Analysis

Electroencephalogram (EEG) was recorded from 29 tin electrodes mounted in an elastic cap (Electro-Cap International) according to an extended 10–20 configuration (see Figure 6). Electrodes were also placed beneath the right eye and at the outer canthi of the left and right eyes in order to monitor eye movements. In addition, recordings from FP1/2 were used to reject trials contaminated by eyeblink artifacts. On-line recordings were referenced to the right mastoid and recordings were re-referenced to averaged mastoids in the final data averaging. Eye electrode impedances were maintained below 10 KΩ and mastoid and scalp electrodes below 5 KΩ.

The EEG was amplified with SA amplifiers (bandpass 0.01 to 100 Hz) and digitized online (sampling rate 4 ms, 250 Hz). Off-line, separate ERPs to word, pseudoword, nonword, and letter-in-xs targets were averaged for each subject at each electrode site over an 800 ms epoch, using a 200 ms pre-stimulus-onset baseline. Only trials for which participants responded correctly were included. Trials contaminated by eye movements, muscular activity, or electrical noise were not included in analyses (standard artifact rejection parameters were initially employed and data were analyzed subsequently on an individual basis for artifact rejection if necessary). The average number of trials included in the word condition was 69.3 (*SD* 8.6); in the pseudoword condition, 69.0 (*SD* 8.4); in the nonword condition, 65.4 (*SD* 8.9); and in the letter-in-xs condition, 60.2 (*SD* 10.3).

Appropriate time windows of measurement were determined by visual inspection of grand averages and individual participant data. A P150 was measured within the 100–160 ms window, an N200 within the 160–220 ms window, an N300 within the 250–350 ms window, and an N400 within the 350–450 ms window. Local peak amplitude was measured as the most positive or negative data point within each window, such that the two preceding and two following data points were less positive or negative, to avoid local minima. For each time window, an omnibus repeated measures ANOVA was performed with within-subjects factors of condition (4 levels: words, pseudowords, nonwords, letter-in-xs), anterior/posterior [6 possible levels: frontal (F7/8, F3/4), fronto-temporal (FT7/8, FC5/6), temporal (T3/4, C5/6), central (CT5/6, C3/4), parietal (T5/6, P3/4), and occipital (TO1/2, O1/2); the P150 and N200 were observed and measured only at parietal and occipital sites, the N300

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[4] Studies using masked priming are perennially questioned as to whether the primes were truly masked and presented briefly enough to prevent conscious processing, thus indicating that any observed effects are automatic and unconscious. In a previous masked priming study with college students manipulating prime duration to specifically investigate this issue, a 120 ms duration made conscious processing of the prime "relatively easy," an 80 ms duration "more difficult," and a 40 ms duration "nearly impossible" (Holcomb, Reder, Misra, & Grainger, 2005, p. 164). Although these authors also note that it "is impossible to completely eliminate" the possibility of "conscious leakage" (p. 163), within the constraints of the masked priming design, our 46 ms duration primes are likely to have been adequately backward masked for most participants most of the time.

was observed and measured at all sites, and the N400 was observed and measured only at central, parietal, and occipital sites (refer to Figure 6)], lateral/medial (2 levels), and hemisphere (2 levels: left, right). Significant ERP effects involving condition are reported and were followed up with planned comparisons between the word and nonword conditions (word superiority effect), the pseudoword and nonword conditions (pseudoword superiority effect), the word and letter-in-xs conditions (word superiority effect, alternate baseline), and the pseudoword and letter-in-xs conditions (pseudoword superiority effect, alternate baseline) with further ANOVAs. The Huynh-Feldt correction was applied to all within-subjects measures with more than one degree of freedom.

In addition, in order to better visually characterize the distribution of the effects, topographical voltage maps were created based on the mean amplitude of the effects measured from the difference waves (ERPs to nonwords subtracted from ERPs to words, representing the word superiority effect, and ERPs to nonwords subtracted from ERPs to pseudowords, representing the pseudoword superiority effect). An automated spherical spline interpolation (Perrin, Pernier, Bertrand, & Echallier, 1989) was used to interpolate the potential on the surface of an idealized, spherical head based on the mean amplitude voltages at each electrode location within the specified time windows (see Figure 3). Finally, Pearson’s correlations were calculated in order to investigate specific relationships among the standardized behavioral test scores, the behavioral accuracy scores, and the electrophysiological measures [peak amplitude of each component within each condition and the size, in terms of peak amplitude, of the word and pseudoword superiority effects (word-nonword condition, pseudoword-nonword condition) for each component]. All results are significant at the .05 level unless otherwise noted.

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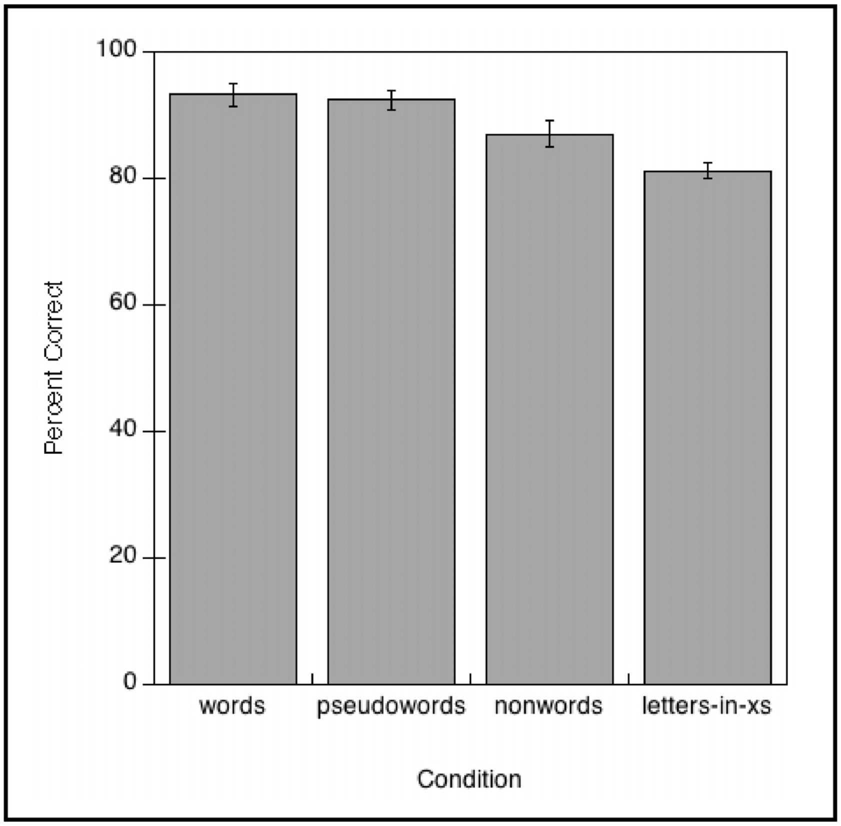

Figure 1.

Behavioral accuracy in the ERP letter identification task across the four conditions. Both a word superiority effect and a pseudoword superiority effect were observed, both with the typical nonword baseline and with the alternate letters-in-xs baseline. Bars indicate standard error.

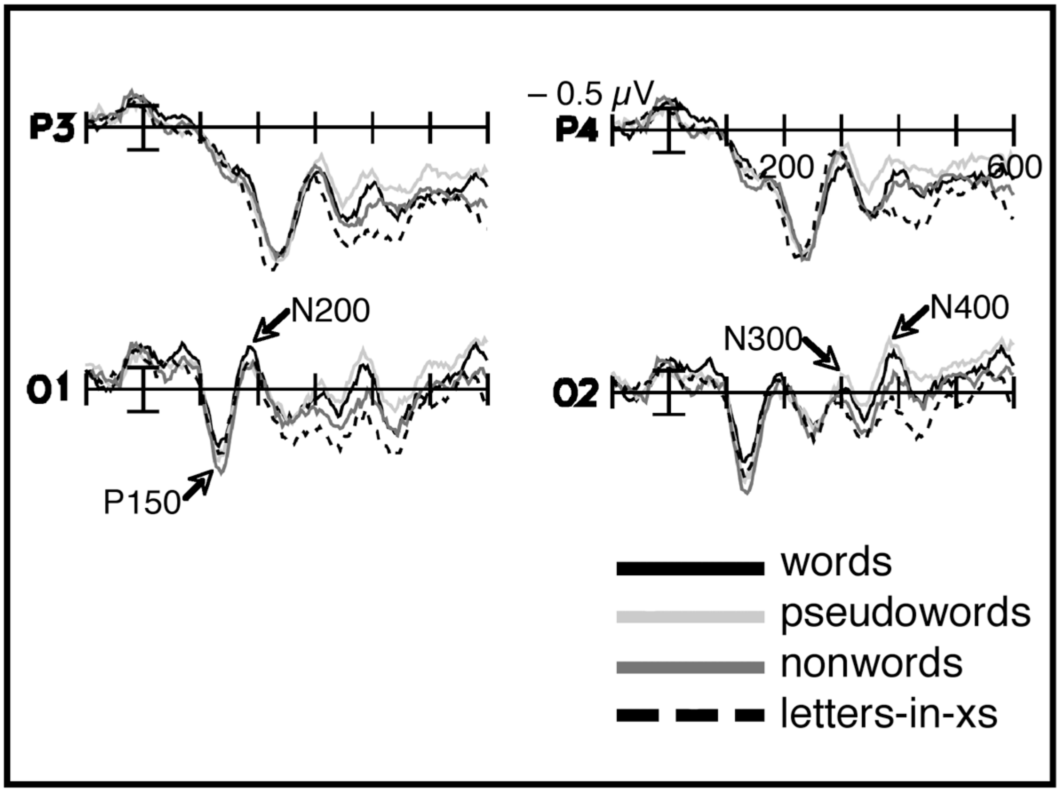

Figure 2.

Grand average ERP waveforms elicited at posterior medial sites by words (solid black line), pseudowords (light gray line), nonwords (dark gray line), and letters-in-xs (dashed line). The P150 and N200 are identified at site O1 and the N300 and N400 are identified at site O2. Each vertical tick marks 100 ms and negative is plotted up. Refer to Figure 6 for full electrode montage. The calibration bar marks 0.5 μV.

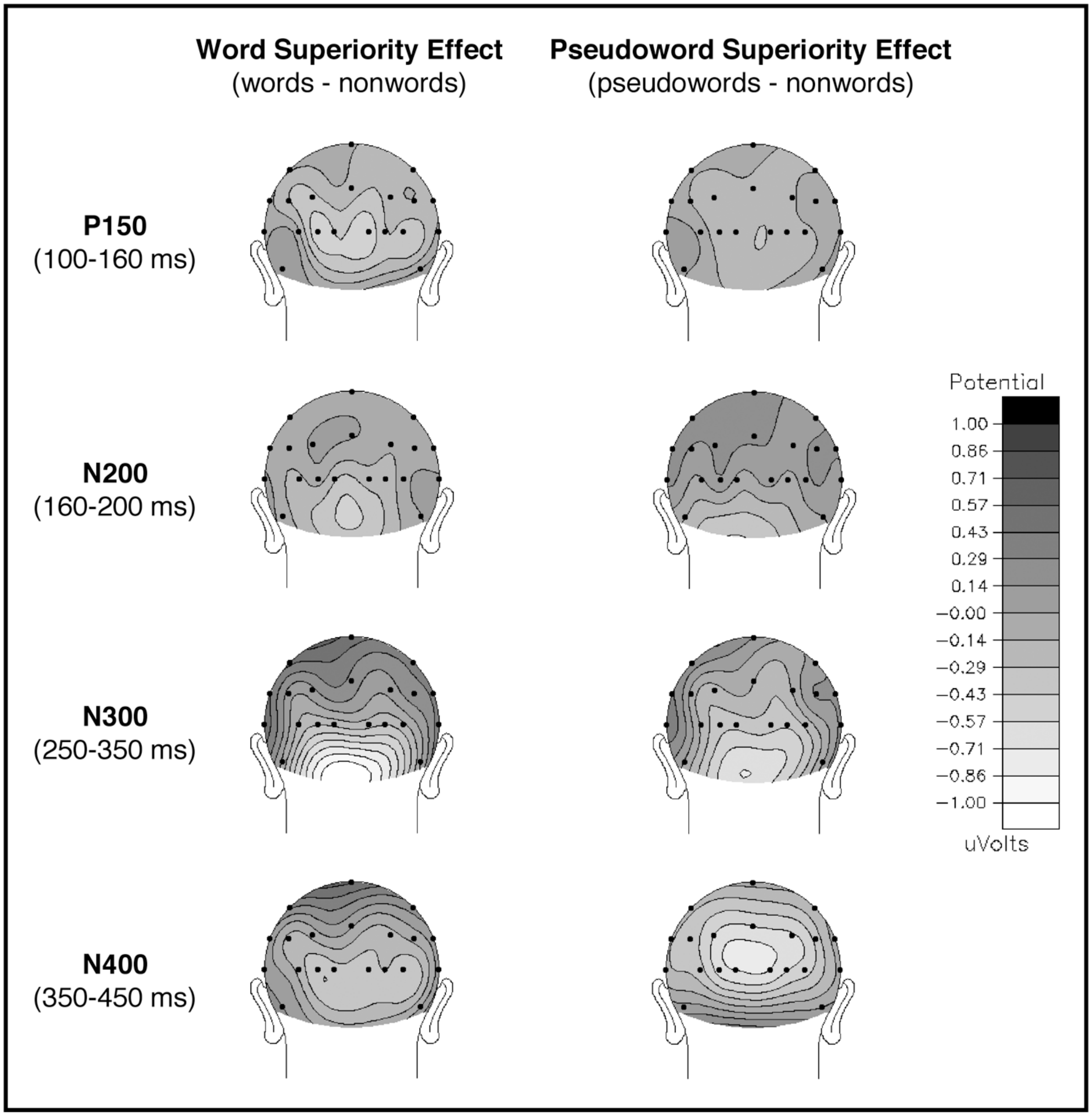

Figure 3.

Topographical voltage maps illustrating the distributions of the word (left column) and pseudoword (right column) superiority effects in each of the four time windows of interest. A spherical spline interpolation (Perrin, Pernier, Bertrand, & Echallier, 1989) was used to interpolate the potential on the surface of an idealized, spherical head based on the mean amplitude voltages measured from the difference waves (ERPs to nonwords subtracted from ERPs to words and pseudowords) at each electrode location within the specified time windows. Peak amplitude measures (reported in the text) revealed word and pseudoword superiority effects (differential processing between words and nonwords or pseudowords and nonwords, respectively) for all components except an N200 pseudoword superiority effect.

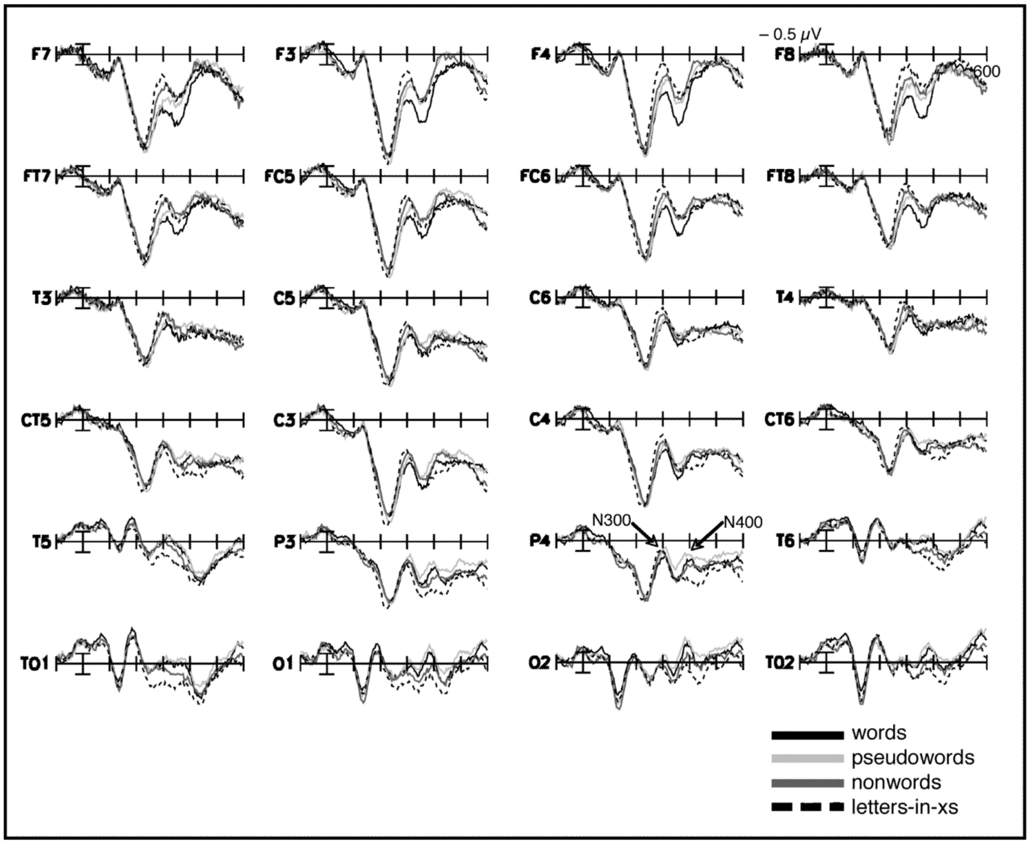

Figure 4.

Grand average ERP waveforms elicited by words (solid black line), pseudowords (light gray line), nonwords (dark gray line), and letters-in-xs (dashed line) across recording sites. Peak amplitude of the N300 was measured at all sites shown while peak amplitude of the N400 was measured at the three most posterior rows (N300 and N400 are identified at site P4). More anterior sites are toward the top of the figure while more posterior sites are toward the bottom; left hemisphere sites are on the left and right hemisphere sites are on the right; lateral sites are toward the outer edges and medial sites are toward the middle of the figure; each vertical tick marks 100 ms and negative is plotted up.

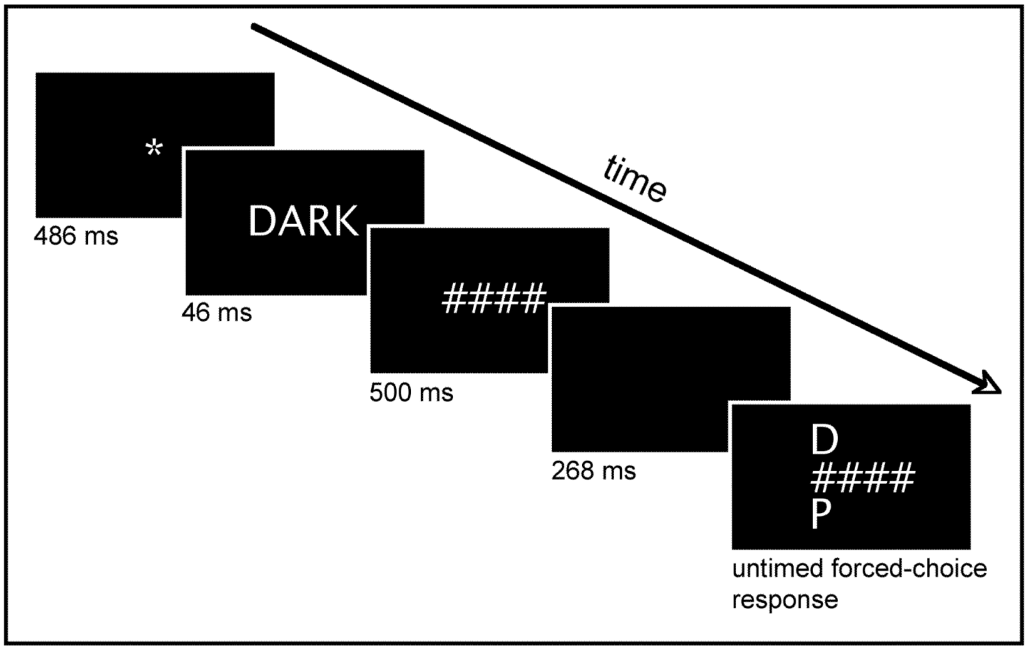

Figure 5.
Illustration of the stimulus presentation sequence in a single trial.

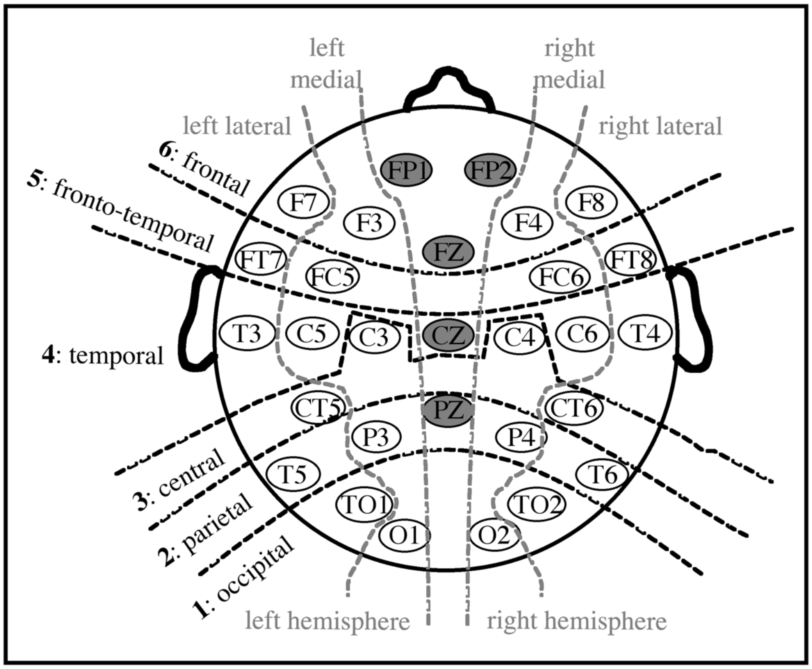

Figure 6.

Schematic representation of the electrode montage and the factors used in analyses. Six levels of the anterior/posterior factor, two levels of the lateral/medial factor, and two levels of the hemisphere factor are indicated. Electrodes in gray were not used in the primary analyses reported in the text.

Table 1

Summary of Standardized Behavioral Test Scores

Subtest	**Raw Score *(SD)***	**Standard Score *(SD)***	**Percentile Rank *(SD)***
RAN/RAS Numbers[a]	14.89 *(2.21)*	116.83 *(5.55)*	85.54 *(6.97)*
RAN/RAS Letters[a]	15.61 *(3.86)*	113.79 *(6.71)*	80.25 *(13.05)*
TOWRE Sight Word[b]	100.54 *(5.66)*	101.09 *(9.89)*	52.45 *(23.49)*
TOWRE Phonemic Decoding[b]	57.83 *(4.39)*	106.41 *(9.46)*	64.23 *(21.12)*
WRMT-R Word Identification[c]	98.83 *(2.78)*	105.46 *(5.28)*	63.29 *(12.74)*

[a] Rapid Automatized Naming and Rapid Alternating Stimulus Tests (RAN/RAS, Wolf and Denckla, 2005)

[b] Test of Word Reading Efficiency (TOWRE, Torgesen et al., 1999)

[c] Woodcock Reading Mastery Tests - Revised (WRMT-R, Woodcock, 1987)

Table 2

Summary of Frequency Statistics for Stimuli

Stimulus Category	**K & F Adult**[a]	**AH 3–5**[b]	**N**[c]	**Constrain Bigram**[d]	**Unconst. Bigram**[e]	**Constrain Trigram**[f]	**Unconst. Trigram**[g]
Words	539.11 *(1161.73)*	545.06 *(1004.82)*	169.65 *(347.33)*	3188.77 *(3113.16)*	24417.77 *(17414.60)*	1151.59 *(2021.22)*	3943.56 *(5836.84)*
Pseudowords	*n/a*	*n/a*	206.92 *(435.76)*	2154.30 *(1920.11)*	20707.10 *(13195.36)*	465.70 *(799.44)*	2352.21 *(3099.63)*
Letter Strings	*n/a*	*n/a*	9.87 *(34.71)*	371.48 *(874.07)*	11053.87 *(11032.97)*	4.16 *(21.28)*	362.86 *(734.72)*
Letter-in-Xs	*n/a*	*n/a*	0	2.89 *(17.68)*	199.82 *(453.56)*	0	0

[a] Adult frequency based on Kucera and Francis (1967) from the original Chase and Tallal (1990) report

[b] Child frequency grades three to five based on the American Heritage ratings from the original Chase and Tallal (1990) report

[c] Orthographic neighborhood, Coltheart’s N (Medler and Binder, 2005)

[d] Constrained bigram frequency (Medler and Binder, 2005)

[e] Unconstrained bigram frequency (Medler and Binder, 2005)

[f] Constrained trigram frequency (Medler and Binder, 2005)

[g] Unconstrained trigram frequency (Medler and Binder, 2005)