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Behavioral and ERP evidence of word and pseudoword superiority effects in 7- and 11-year-olds

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Abstract

In groups of 7-year-olds and 11-year-olds, event-related potentials (ERPs) were recorded to briefly presented, masked letter strings that included real word (DARK/PARK), pronounceable pseudoword (DARL/PARL), unpronounceable nonword (RDKA/RPKA), and letter-in-xs (DXXX, PXXX) stimuli in a variant of the Reicher-Wheeler paradigm. Behaviorally, participants decided which of two letters occurred at a given position in each string (here, forced-choice alternatives D and P). Both groups showed evidence of behavioral 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 nonwords or letter-in-xs) superiority effects. Electrophysiologically, 11-year-olds evidenced superiority effects on P150 and N400 peak amplitude, while 7-year-olds showed effects only on N400 amplitude. These findings suggest that the mechanisms underlying the observed behavioral superiority effects may be lexical in younger children but both sublexical and lexical in older children. These results are consistent with a lengthy developmental time course for automatic sublexical orthographic specialization, extending beyond the age of 11.

Keywords

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

1. Introduction

Learning to recognize and process written words as words – and doing so fluently, effortlessly, and automatically – is fundamental to learning to read (e.g., Adams, 1990). Automaticity is a foundation for fluent reading: Fluent readers have both automatized a number of subskills (like those involved in orthographic and phonological processing) and automatized their integration (e.g., LaBerge and Samuels, 1974). This development of automaticity is key because it frees cognitive resources for comprehension (Adams, 1990; Fletcher, 1981; Stanovich, 1980; Wolf and Katzir-Cohen, 2001). The development of

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automatic orthographic processing, in particular, is critical to fluent reading development (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).

Behavioral studies using tasks such as lexical decision with young children have shown that words, pronounceable pseudowords, and unpronounceable nonwords are processed similarly (letter-by-letter) by kindergarteners and beginning first-graders, who appear insensitive to orthographic patterns and are often unable to determine the word-likeness of letter strings (e.g., Juola et al., 1978; Lefton et al., 1973; Lefton and Spragins, 1974; Rosinski and Wheeler, 1972; Santa, 1976–1977). Sensitivity to orthographic structure appears to develop across the elementary school years with increased exposure to letter sequences and words and concomitant increasing familiarity with orthography; in a variety of behavioral paradigms, words, pseudowords, and nonwords are relatively reliably discriminated in typically developing readers by the fourth grade, by which time reading of most high frequency words is thought to be relatively automatized, effortless, and fluent (e.g., Barron, 1981; Doehring, 1976; Krueger et al., 1974; Lefton and Spragins, 1974; McCaughey et al., 1980; Rosinski and Wheeler, 1972; Stanovich, 1980). At the neural level, relatively little is known about the development of automatic orthographic processing for words. Here, we used a classic masked priming paradigm and event-related potentials (ERPs) to index automatic orthographic processing, in combination with standardized behavioral tests.

1.1 The Reicher-Wheeler Paradigm: Word and Pseudoword Superiority Effects

As children repeatedly encounter and read specific letter strings, over developmental time those strings assume an orthographic identity beyond basic visual percepts and come to be processed automatically as words (e.g., Grainger and Whitney, 2004; LaBerge and Samuels, 1974). Behavioral studies have indicated that printed words have a special orthographic status in fluent readers, which is reflected in the word superiority effect (e.g., Reicher, 1969; Wheeler, 1970). In the classic Reicher-Wheeler paradigm designed to elicit a word superiority effect – originally run with adult participants – a string of letters is presented briefly and masked, then participants are asked to decide which of two presented letters occurred at a given position in the string (Reicher, 1969; Wheeler, 1970). In this paradigm and across variants, participants are more accurate in identifying the correct letter when the briefly presented string is a word (e.g., *DARK*) than if it is a nonword (e.g., RDKA, Adams, 1979; Estes and Brunn, 1987; Ferraro and Chastain, 1993; Johnston and McClelland, 1974; Juola et al., 1974; Krueger, 1992; Prinzmetal, 1992; Williams et al., 1985). A similar pseudoword superiority effect, such that accuracy is higher for letters embedded in pseudowords (e.g., *DARL*) than in nonwords, has also been reported in adults and may be due to the word-likeness of pseudowords (e.g., Estes and Brunn, 1987; Grainger and Jacobs, 1994; Massol et al., 2011; Ozubko and Joordens, 2011). Because the letter strings in Reicher-Wheeler-type paradigms are presented briefly and masked, these sorts of paradigms can be used to index automatic orthographic processing.

The word and pseudoword superiority effects reported in such paradigms may be based on the orthographic regularities of letter strings, such that there are facilitatory effects of orthotactic constraints (e.g., Grainger and Jacobs, 1994; Grainger et al., 2003). According to this "cascaded" view of superiority effects, letters may be determined at the lexical level on the basis of whole word read-out from orthographic representations in long-term memory (Grainger and Jacobs, 1994; Grainger, 2008, p. 3). Alternately, these effects may reflect the top-down influence of lexical representations on letter identification (e.g., Laszlo and Federmeier, 2007; Martin et al., 2006; McClelland and Rumelhart, 1981). According to this interactive view, the match between a presented orthographic stimulus and an already-known lexical item facilitates the identification of letters in the presented stimulus through top-down (lexical level) interaction with lower (letter) level processing; both word and pseudoword superiority effects have been modeled as such (McClelland and Rumelhart, 1981). More specifically, in an interactive activation model, words activate word units that send excitatory feedback to constituent letter units, effectively increasing the perceptibility of the letters and facilitating letter recognition; pseudowords activate word units in terms of shared letter sequences with real words, which similarly send excitatory feedback to constituent letter units; but nonwords, which do not share orthographic sequences with real words, do not activate word units and thus there is no top-down influence on letter processing for nonwords, creating the conditions for word and pseudoword superiority effects.

Although the Reicher-Wheeler paradigm provides a potential avenue for investigating the development of orthographic automaticity, regardless of whether that involves development of sensitivity to orthotactic constraints or top-down influence on letter-level processing or both, few studies have used it developmentally. One behavioral study with 7-year-olds, 11-year-olds, and adults found that both children and adults showed both word and pseudoword superiority effects (in comparison to nonwords, Grainger et al., 2003). An earlier study using the paradigm with the same age groups reported that both children and adults demonstrated a word superiority effect, but the pseudoword superiority effect was larger for adults than children (Chase and Tallal, 1990). Comparisons between typically developing children and those with dyslexia indicate that behavioral superiority effects develop in children as young as seven even in the presence of phonological deficits, suggesting that these effects can be attributed to orthographic processing, even among beginning readers (Grainger et al., 2003; Lété and Ducrot, 2008).

These studies report evidence for sensitivity to orthographic structure and some degree of automaticity in orthographic processing by the second grade. As this is earlier than results from lexical decision-type tasks would indicate, the masked Reicher-Wheeler task might be particularly sensitive to the development of automatic orthographic processing. The letter-by-letter reading of kindergarteners and beginning first-graders (e.g., Juola et al., 1978; Lefton et al., 1973; Lefton and Spragins, 1974; Rosinski and Wheeler, 1972; Santa, 1976–1977) stands in contrast to the automatized reading of high frequency words by fourth graders (e.g., Barron, 1981; Doehring, 1976; Krueger et al., 1974; Lefton and Spragins, 1974; McCaughey et al., 1980; Rosinski and Wheeler, 1972; Stanovich, 1980) and the apparent parallel processing of letters in strings in fluently reading adults (e.g., Adelman et al., 2010). However, all of the studies reviewed above are limited to a behavioral response and can provide virtually no information about the on-line automatic processing of orthographic information.

1.2 ERPs, the Reicher-Wheeler Paradigm, and Orthographic Processing

The recording of ERPs can index such on-line processing. Several ERP studies have reported that negative-going components peaking at about 200 ms (e.g., N170 or N200) are sensitive to orthography in adults (e.g., Bentin et al., 1999; Compton et al., 1991; Grossi and Coch, 2005; Hauk et al., 2006; Maurer et al., 2005a; Maurer et al., 2010; Simon et al., 2004; Tarkiainen et al., 1999). In addition, the later N400 component may index the integration of orthographic and phonological information into lexical or semantic representations (e.g., Brown and Hagoort, 1993; Doyle et al., 1996; Grainger and Holcomb, 2009; Holcomb, 1993; Holcomb and Grainger, 2006; Rugg, 1990). In the first report in the literature, to our knowledge, of the use of an ERP variant of the Reicher-Wheeler paradigm, Martin and colleagues reported a typical behavioral word superiority effect in adults accompanied by a larger N1 component (peak latency 210 ms) for words than nonwords (operationally defined as an ERP word superiority effect, in parallel to the traditional behavioral effect), but did not report on an N400 (Martin et al., 2006).

In a previous report with adult participants, we also explored when indices of word and pseudoword superiority effects were present in the ERP waveform by using a variant of the Reicher-Wheeler paradigm (Coch and Mitra, 2010). In this masking paradigm with a two-alternative forced-choice task, we found that nonwords elicited a larger P150 than words or pseudowords; that words elicited a larger N200 than nonwords, similar to Martin and colleagues (2006); and that both words and pseudowords elicited larger N400s than nonwords in adults. Given this pattern of results, we concluded that orthographic automaticity, as indexed by word and pseudoword superiority effects, is reflected in both lower-level, sublexical processing and higher-level, lexical processing in adults (Coch and Mitra, 2010). Here, we extend this investigation developmentally, employing the same paradigm and stimuli, to include groups of 7-year-olds and 11-year-olds.

Few studies have investigated the typical development of the N200 and N400 components in relation to orthography (e.g., Maurer et al., 2005b; Maurer et al., 2006; Parviainen et al., 2006; Posner and McCandliss, 1999). Maurer and colleagues reported that a larger N1 (peaking at about 200 ms) was elicited for words than symbol strings as children learned to read from kindergarten to second grade (Maurer et al., 2006). Posner and McCandliss (1999) reported that 10-year-olds showed adult-like responses to high frequency words, but not pseudowords, within the 200–300 ms epoch; however, they proposed that this effect was due to familiarity (word-specific encoding) rather than abstract orthographic encoding. An N400 to written words has been shown in children as young as age 7 (e.g., Coch and Holcomb, 2003; Grossi et al., 2001; Weber-Fox et al., 2003); however, a selective response of the N400 to word-like as compared to non-word-like stimuli is seen only among the strongest readers at this age (Coch and Holcomb, 2003). To our knowledge, no previous ERP studies have used a Reicher-Wheeler paradigm to explore the development of automatic orthographic processing.

1.3 The Present Study

The objective of the present research was to investigate behavioral and neural measures of automatic orthographic processing at each end of the elementary school years, from beginning readers (7-year-olds) to theoretically newly fluent readers (11-year-olds). ERPs recorded to word, pseudoword, nonword, and control stimuli in a variant of the Reicher-Wheeler paradigm served as the neural measure; the Reicher-Wheeler paradigm provided a unique perspective on the development of prelexical orthographic processing. Forced-choice letter responses in this paradigm and traditional, timed oral reading and rapid automatized naming tasks served as the behavioral measures (Torgesen et al., 1999; Wolf and Denckla, 2005). As reviewed, the results of a number of behavioral studies suggest that words develop a specialized orthographic status over time; however, behavioral word and pseudoword superiority effects have been reported in Reicher-Wheeler paradigms in children as young as age 7 (e.g., Chase and Tallal, 1990; Grainger et al., 2003). We expected to replicate these behavioral findings such that both groups of children would be more accurate for word and pseudoword stimuli than for nonword stimuli and our alternate letter-in-xs baseline stimuli, which further reduced word-likeness of the letter string. Our primary research question was when in the ERP waveform word and pseudoword superiority effects would be reflected (e.g., Coch and Mitra, 2010; Martin et al., 2006). Operationally defining the superiority effects at the neural level as a difference in ERP (P150, N200, and N400) amplitude to words and pseudowords as compared to nonwords and letter-in-xs stimuli as in previous work (e.g., Coch and Mitra, 2010; Martin et al., 2006), we predicted smaller effects for younger children as a reflection of their relative lack of experience with print but more adult-like responses in older, more fluently reading children (e.g., McCandliss et al., 2003).

2. Results

2.1 Standardized Behavioral Test Scores

Raw, standard, and percentile rank scores on the behavioral tests are summarized in Table 1. Both the 7- and 11-year-old groups scored, on average, above the standardized means on these measures of orthographic fluency, decoding, and single word reading skills. Independent sample t-tests indicated that Woodcock Reading Mastery Test – Revised Word Identification raw scores were significantly higher for the 11-year-old group than the 7-year-old group ($t(46) = -6.74$, $p < .001$), while standardized scores were significantly higher for the 7-year-old group than the 11-year-old group ($t(46) = 4.15$, $p < .001$). Raw scores on the Rapid Automatized Naming Numbers subtest favored 11-year-olds ($t(46) = 4.72$, $p < .001$), but there was no difference between groups on standardized scores ($p = .58$); similarly for the Rapid Automatized Naming Letters subtest raw ($t(46) = 5.50$, $p < .001$) and standardized ($p = .69$) scores. The same pattern was evident for the TOWRE Sight Word (raw, $t(46) = -6.63$, $p < .001$; standard, $p = .27$) and Phonemic Decoding (raw, $t(46) = -6.86$, $p < .001$; standardized, $p = .71$) subtest scores.

2.2 Behavioral Accuracy on the ERP Task

Accuracy on the ERP task for both groups is summarized in Figure 1. An ANOVA with factors group (7-year-olds, 11-year-olds) and condition (words, pseudowords, nonwords, letter-in-xs) yielded significant effects of both group ($F(1, 46) = 26.01$, $p < .001$, partial $\eta^2 = .36$) and condition ($F(3, 138) = 53.22$, $p < .001$, partial $\eta^2 = .54$), but no interaction between the two factors (condition x group, $p = .36$). Eleven-year-olds were more accurate overall than 7-year-olds, and planned simple comparisons indicated both typical word (greater accuracy for words than nonwords, $t(47) = 10.94$, $p = .001$) and pseudoword (greater accuracy for pseudowords than nonwords, $t(47) = 8.24$, $p = .001$) superiority effects. Participants also correctly identified letters in masked words ($t(47) = 7.67$, $p = .001$) and pseudowords ($t(47) = 5.55$, $p = .001$) more often than in masked letter-in-xs stimuli, an alternate baseline condition.

2.3 ERP Waveforms

Grand average ERP waveforms for the 7-year-old group are illustrated in Figure 2A, while ERP waveforms for the 11-year-old group are illustrated in Figure 2B. Three marked components were evident in both groups upon visual inspection; the P150, N200, and N400 are identified at site TO1 in each figure. Figure 3 provides a closer comparative view of the grand average ERP waveforms at site O1 for 7-year-olds and 11-year-olds, and for the adult group analyzed in a previous report (Coch and Mitra, 2010, see their Figure 2).

2.3.1 P150 (100–180 ms)—An omnibus ANOVA on local peak amplitude measures within the P150 time window indicated that the effect of condition varied by group (condition x group, $F(3, 138) = 5.10$, $p < .01$, partial $\eta^2 = .10$). In planned simple comparisons within the 7-year-old group, there was neither a word [P150 amplitude to words did not differ significantly from P150 amplitude to nonwords (condition, $p = .15$) or letter-in-xs (condition, $p = .18$)] nor a pseudoword [P150 amplitude to pseudowords did not differ from P150 amplitude to nonwords (condition, $p = .29$) or letter-in-xs (condition, $p = .11$)] superiority effect. Thus, in 7-year-olds, there were no significant differences between the peak amplitude of the P150 to word or pseudoword as compared to nonword stimuli, or as compared to letter-in-xs stimuli. In the 11-year-olds, there was no word superiority effect for P150 amplitude (condition, $p = .65$ for words compared to nonwords, $p = .32$ for words compared to letter-in-xs), but pseudowords elicited a larger P150 than both nonwords (condition, $F(1, 23) = 7.45$, $p = .012$) and letter-in-xs (condition, $F(1, 23) = 7.99$, $p = .010$), particularly at posterior, medial sites (condition x lateral/medial, $F(1, 23) = 10.67$, $p = .003$;

condition x anterior/posterior x lateral/medial, $F(1, 23) = 8.69$, $p = .007$; see Figures 2 and 3).

2.3.2 N200 (180–280 ms)—An omnibus ANOVA on local peak amplitude measures within the N200 time window yielded no significant effects involving condition and group.

2.3.3 N400 (280–450 ms)—An omnibus ANOVA on peak amplitude measures within the N400 time window yielded a main effect of condition ($F(3, 138) = 15.32$, $p < .001$, partial $\eta^2 = .25$) such that, overall, peak amplitude of the N400 was largest to pseudowords (mean −4.75 μV), then nonwords (mean −4.32 μV), then words (mean −4.09 μV), and smallest to letter-in-xs (mean −2.91 μV) stimuli. This effect varied across the scalp (condition x anterior/posterior, $F(15, 690) = 8.91$, $p < .001$, partial $\eta^2 = .16$; condition x lateral/medial, $F(3, 138) = 3.30$, $p < .05$, partial $\eta^2 = .07$; condition x hemisphere x lateral/medial, $F(3, 138) = 2.73$, $p < .05$, partial $\eta^2 = .06$; condition x anterior/posterior x lateral/medial, $F(15, 690) = 3.57$, $p < .001$, partial $\eta^2 = .07$), and varied by group (condition x hemisphere x lateral/medial x group, $F(3, 138) = 4.00$, $p < .01$, partial $\eta^2 = .08$). Due to the developmental focus of the study, this complex interaction was followed up by analyses by group.[1]

In planned simple comparisons in the 7-year-old group, the N400 was larger to nonwords than words, particularly at medial right hemisphere sites (condition x lateral/medial x hemisphere, $F(1, 23) = 12.15$, $p = .002$); the comparison between words and letter-in-xs did not survive Bonferroni correction (condition, $p = .027$). The N400 was also larger to pseudowords than letter-in-xs, particularly at central and temporoparietal sites (condition, $F(1, 23) = 11.28$, $p = .003$; condition x anterior/posterior, $F(5, 115) = 4.74$, $p = .006$; see Figure 2A), while the peak amplitude of the N400 elicited by pseudowords and nonwords was not significantly different (condition, $p = .864$).

In the 11-year-old group, although there was not a main effect of condition ($p = .46$), there was evidence of a word superiority effect such that words elicited a larger N400 than nonwords, particularly at posterior, lateral sites (condition x anterior/posterior, $F(5, 115) = 23.22$, $p = .001$; condition x anterior/posterior x lateral/medial, $F(5, 115) = 5.03$, $p = .002$), and a larger N400 than letter-in-xs, with a similar distribution (condition, $F(1, 23) = 14.93$, $p = .001$; condition x anterior/posterior, $F(5, 115) = 17.06$, $p = .001$; condition x anterior/posterior x lateral/medial, $F(5, 115) = 6.09$, $p = .001$; see Figure 2B). There was also evidence of a pseudoword superiority effect, with pseudowords eliciting a larger N400 than both nonwords (condition, $F(1, 23) = 12.97$, $p = .002$; condition x anterior/posterior, $F(5, 114) = 8.47$, $p = .001$; condition x anterior/posterior x lateral/medial, $F(5, 115) = 5.36$, $p = .001$) and letter-in-xs (condition, $F(1, 23) = 24.02$, $p = .001$; condition x anterior/posterior, $F(5, 115) = 9.86$, p = .001; condition x lateral/medial, $F(1, 23) = 8.63$, $p =.007$; condition x anterior/posterior x lateral/medial, $F(5, 115) = 6.59$, $p = .001$; see Figure 2B), particularly across posterior lateral sites.

2.4 Electrophysiological and Behavioral Measure Correlations

Overall accuracy on the two-alternative, forced-choice task was correlated with standard scores on the RAN Numbers ($r = .377$, $p < .01$) and Letters ($r = .463$, $p < .001$) tests, as well as scores on the TOWRE Sight Word ($r = .351$, $p < .05$) and Phonemic Decoding ($r = .390$, p

[1]Another approach would be to attempt to isolate a significant condition x group effect in order to conduct follow-up analyses by group only at sites at which the condition x group effect held. Restricting analyses to left hemiphere medial, left hemisphere lateral, right hemisphere medial, and right hemisphere lateral sites yielded no condition x group effects that met conventional levels of significance (all *p*'s > .08). Because the four-way interaction can be interpreted as indicating that an effect of group differed across both conditions and recording sites, and because the primary research questions concerned group differences, analyses by group were undertaken as follow-ups to the signficant four-way interaction.

< .01) subtests. Overall accuracy was also negatively correlated with the average peak amplitude of the P150 ($r = -.309$, $p < .05$), and with the word superiority effect (words compared to nonwords) on P150 peak amplitude ($r = -.311$, $p < .05$); however, partialling the effect of age rendered these correlations nonsignificant. Accuracy was not correlated with average peak amplitude of the N200 or N400, or the size of the N400 word or pseudoword superiority effects, using either the typical baseline or the letter-in-xs baseline. As noted previously (Coch and Mitra, 2010), this may not be surprising given that the ERPs were recorded to the masked letter strings and not the letter choices, and thus likely reflect the processes that led to the behavioral differences observed, not necessarily task performance directly.

The only significant correlation between the ERP measures (average peak amplitude of the P150, N200, and N400, and size of the word and pseudoword superiority effects for the P150 and N400 with each baseline) and the standardized behavioral test measures was a correlation between the average peak amplitude of the N400 and standard scores on the Woodcock Word Identification subtest ($r = -.418$, $p < .01$). Partialling the effect of age rendered this correlation nonsignificant.

3. Discussion

In a modified Reicher-Wheeler paradigm (Reicher, 1969; Wheeler, 1970), two-alternative, forced-choice behavioral responses from 7-year-olds and 11-year-olds showed both word and pseudoword superiority effects, both with the usual nonword baseline and with a letter-in-xs baseline that further reduced letter-level orthographic information. In contrast, in electrophysiological recordings taken simultaneously from the same participants, superiority effects on a P150 were absent in 7-year-olds but present in 11-year-olds, neither group showed superiority effects on N200 amplitude, and each group showed a different pattern of superiority effects on N400 amplitude. Task accuracy was correlated with performance on speeded standardized reading tests, but was not correlated with measures of the ERP superiority effects. Taken together, these findings suggest a shift in the mechanisms underlying the superiority effects across development (from purely lexical to utilizing sublexical), and highlight the importance of using multiple measures at different levels of analysis in developmental investigations of automatic orthographic processing.

3.1 P150

While 7-year-olds showed no significant superiority effects on the peak amplitude of the P150, peak amplitude of this component in 11-year-olds was larger to pseudowords than both nonwords and letter-in-xs stimuli at medial, posterior sites – ERP pseudoword superiority effects. Maurer and colleagues (2006) have reported P1 GFP smaller for words than symbol strings in 8.3-year-olds, but not kindergarteners. This general pattern suggests a developing sensitivity to word-like orthography reflected in the P1 across early elementary school, which is not yet present in kindergartners or first graders. However, while Maurer et al. found *less* P1 processing elicited by words as compared to strings in 8-year-olds in an unmasked paradigm, we found *greater* P1 amplitude to pseudowords than strings in 11-year-olds in a masked paradigm – and no difference in P1 amplitude to words as compared to nonwords or letter-in-xs. Given the paucity of the literature, it is unclear whether these differential findings are due to paradigm or stimulus, developmental, or other differences.

Unfortunately, the adult literature offers little clarification. In our previous study with adults in this paradigm, nonwords elicited a greater P150 than words and pseudowords (reverse superiority effects) across all parietal and occipital sites measured, but the P1 to words and pseudowords did not differ from the P1 to letter-in-xs; the latter findings led us to conclude 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" (Coch and Mitra, 2010, p. 166). Here, in 11-year-olds, the P150 pseudoword superiority effect with the nonword baseline was widespread across the posterior scalp, as with the reverse effect in adults (Coch and Mitra, 2010), but the pseudoword superiority effect with letter-in-xs baseline was more focal, consistent with the notion that the letter-in-xs baseline may serve a different function in terms of the P150. Holding aside the letter-in-xs condition in our masked paradigm, that leaves us with no superiority effects on P150 amplitude in 7-year-olds, a pseudoword superiority effect in 11-year-olds, and reverse word and pseudoword superiority effects in adults. Interestingly, within the adult literature outside of the Reicher-Wheeler paradigm, there are also conflicting reports of a P1 larger (e.g., Sereno et al., 1998) or smaller (e.g., Proverbio et al., 2004) to nonwords than to words or pseudowords. Overall, this sparse literature and the general pattern of P150 findings here suggest that P150 amplitude in a masked paradigm is sensitive at least partly to orthography in adults and 11-year-olds, but not yet in 7-year-olds.

In previous ERP masked priming studies, an N/P150 has been identified in adults and associated with processing at the level of visual features, specifically "the mapping of visual features onto location-specific letter representations," as it is particularly sensitive to featural overlap between prime and target (e.g., Grainger and Holcomb, 2009, pp. 136–137). More generally, the N/P150 has been related to 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; Mitra and Coch, 2009), consistent with the demands of the Reicher-Wheeler task. Similarly, others have reported a P150 indexing "perceptual fluency for more common letter forms" (Dien, 2009, p. 14). If our P150 is the N/P150 previously reported, our results suggest that early stages of letter detection in sublexical orthographic processing are not sensitive to lexical status in 7-year-olds but are in 11-year-olds and adults, although differentially so. Why and how a pseudoword superiority effect on P150 peak amplitude becomes reversed and a reverse word superiority effect emerges between age 11 and adulthood remains for future research; one might make conjectures about greater sublexical resources spent on very low frequency or uncommon features/letter combinations in nonwords in adult readers as compared to less familiar or less common features/letter combinations in pseudowords in 11-year-olds, but this would be pure speculation. Another speculative possibility is that visual span or visual attention might play a role in the P150 effects, given that visual span is likely smaller in 7-year-olds than 11-year-olds; although the P150, to our knowledge, has not been associated with visual span previously and all stimuli were presented within 2.2° horizontal visual angle, others have reported on the critical roles of visual span and attention in reading acquisition (e.g., Franceschini et al., in press; Valdois et al., 2004).[2] Overall, the present data cannot address these questions directly – only further research can determine the nature of the processing indexed by this component, its potential relationship with the N/P150, and its developmental course.

3.2 N200

As noted in the Introduction, in studies with adults, negative-going components peaking at about 200 ms (usually N170 or N200) have consistently been associated with orthographic processing (e.g., Bentin et al., 1999; Compton et al., 1991; Hauk et al., 2006; Maurer et al., 2005a; Maurer et al., 2010; Simon et al., 2004; Tarkiainen et al., 1999). In a previous masked priming study with adults, we demonstrated the automatic nature of the graded orthographic processing (largest to word-like stimuli, reduced to illegal letter string stimuli) indexed by the N200 (Grossi and Coch, 2005), and noted the consistency of this pattern with

[2]We thank a Reviewer for this suggestion.

other neuroimaging reports showing the greatest amount of activation to real words and graded levels of activation to word-like stimuli dependent on degree of word-likeness in the putative visual word form area (e.g., Petersen et al., 1990; Price et al., 1996; Tagamets et al., 2000).

Compatible with this interpretation of the N200, previous studies using a modified Reicher-Wheeler paradigm with adults have reported both word and pseudoword superiority effects for this component, suggesting specialized processing for legal word-like stimuli (Coch and Mitra, 2010; Martin et al., 2006). In an unmasked paradigm with children, a negativity peaking at about 200 ms was larger for words than symbol strings as children learned to read across the early elementary grades (Maurer et al., 2006). In marked contrast, here, in a masked paradigm, we found neither word nor pseudoword superiority effects on the N200 in either 7-year-olds or 11-year-olds. This pattern of findings suggests a remarkably long developmental time course for prelexical automatic orthographic processing, consistent with a recent fMRI report of age-related increases in cortical sensitivity to words in left occipito-temporal sulcus across childhood (Ben-Shachar et al., 2011). This is all the more remarkable because visual word form area specialization is thought to develop with experience with words (e.g., McCandliss et al., 2003) and the children here were, on average, at or above grade level in reading on the standardized measures.

3.3 N400

Word and pseudoword superiority effects were not evident in the waveforms of both 7-year-olds and 11-year-olds until the lexical-level processing of the N400. Overall, as in adults (Coch and Mitra, 2010), pseudowords elicited the largest N400, followed by words, nonwords, and letter-in-xs. Even for the N400, though, there was evidence of developmental change. The 7-year-olds demonstrated a reversed word superiority effect, with a larger N400 to nonwords than words, particularly at right hemisphere medial sites, and a pseudoword superiority effect at temporoparietal sites only with the letter-in-xs baseline. The 11-year-olds demonstrated both word and pseudoword superiority effects with both the nonword and letter-in-xs baselines, particularly at posterior lateral sites, similar to the effects observed in our study with adults (Coch and Mitra, 2010). Thus, both the superiority effects and the distribution of those effects differed between the 7-year-olds and the 11-year-olds, strongly suggesting differential N400 processing between groups. Although N400 amplitude in adults is typically larger to words and pseudowords (e.g., Bentin et al., 1999; Coch and Mitra, 2010), it has been reported that N400 amplitude does not differentiate amongst word types in 6- and 7-year-olds in a word list semantic categorization task (Coch and Holcomb, 2003).

One theory of the N400 is that it reflects a higher-level integrative process that builds from the cascaded products of lower-order processes, including orthographic processing (e.g., Holcomb et al., 2002), representations that provide the basis for comprehension (e.g., Coch and Holcomb, 2003; Holcomb, 1988; Laszlo and Federmeier, 2011). If the amplitude of the N400 reflects the ease or amount of effort required to integrate or link orthographic, phonological, and semantic information in lexical processing (e.g., Grainger and Holcomb, 2009; Holcomb, 1988), the current findings with 7-year-olds might be interpreted as indicating less efficient word processing, with more resources (i.e., effortful – yet futile – attempts at integration) spent on letter strings that cannot be words in English (nonwords) than real words, and more resources spent on word-like stimuli (pseudowords) only in comparison to more clearly not-word-like stimuli (letter-in-xs). In contrast, the N400 word and pseudoword superiority effects for 11-year-olds might be interpreted as indicating comparatively more efficient word processing in the sense that integration resources were not “wasted” and “useless” integration effort was not spent on strings that could not be integrated (nonwords and letter-in-xs) in comparison to strings that could, at least in part, be integrated (words and pseudowords).

At first glance, this general interpretation might appear to be contradicted by the moderate negative correlation ($r = -.418$) between N400 amplitude and standardized scores on the Woodcock Word Identification subtest indicating a tendency for higher reading scores to be associated with larger N400s. However, standardized scores on this subtest were significantly higher for the 7-year-old group than the 11-year-old group, which indicates “better” single word reading behaviorally for their age in the 7-year-old group, but not necessarily more efficient or less effortful reading than in the 11-year-olds. Indeed, holding the effects of age constant nullified the correlation finding. Another relevant factor, perhaps related to the Word Identification findings, might be lexical network size; 7-year-olds were able to read fewer single words accurately than 11-year-olds, consistent with fewer lexical representations in the younger age group. However, we did not use a more direct measure of lexical network size (e.g., a standardized test of vocabulary). If superiority effects reflect the top-down influence of lexical knowledge on letter identification (e.g., McClelland and Rumelhart, 1981), fewer lexical representations in 7-year-olds might have contributed to different superiority effects. Although all the word stimuli used here were considered high frequency in an elementary school corpus, we cannot rule out the possibility of an effect of lexical network size on the appearance of lexical-level superiority effects.

Overall, the N400 here may serve as an indirect measure of the automaticity of orthographic processing (as such processing is but one contributor to the N400); the lack of an adult-like pattern in 7-year-olds with respect to words, pseudowords, and nonwords suggests that the integration process – perhaps due to orthography (which is consistent with the lack of superiority effects earlier in the waveform) or some other factor – is not yet fully developed at age 7. In contrast, some products of lower-level processes, including orthography, appear to be available and integrated in an adult-like fashion in 11-year-old readers – despite the lower-level processes themselves (as indexed here by the P150 and N200 findings) not being fully adult-like.

3.4 Developmental Patterns

Overall, the pattern of findings across these three components sensitive to word and pseudoword superiority effects in adults (e.g., Coch and Mitra, 2010; Martin et al., 2006), and measured here in 7- and 11-year-olds, suggests continued fine-tuning for word processing over developmental time at least through age 11. This lengthy developmental time course is consistent with other recent ERP studies on the development of the word processing system not focusing on superiority effects (e.g., Brem et al., 2006; Froyen et al., 2009). For example, Froyen and colleagues (2009) reported that mismatched letters and speech sounds do not elicit an ERP mismatch negativity effect in readers with one year of reading experience, but do in readers with four years’ experience – but the timing of this effect is still not adult-like, even after four years’ reading experience. Further, in a study of word and symbol string processing, Brem and colleagues (2006) reported even later developmental changes – some following adolescence – in the amplitude and latency of an N1 and P1. In turn, this sort of evidence is consistent with the view that the developing word recognition system is adaptive and dynamic, loosely specified early in development but modified over time to become more specific and efficient at processing words (e.g., Castles et al., 2003, p. 357).

At the level of theory, these developmental findings may help to distinguish between the possibilities of a cascaded effect or top-down effect as underlying mechanisms for superiority effects (e.g., Grainger and Jacobs, 1994; Grainger, 2008; Laszlo and Federmeier, 2007; Martin et al., 2006; McClelland and Rumelhart, 1981), although this study was not designed to address this issue specifically. Speculatively, because the most robust superiority effects were found on the N400 amplitude, at the lexical level, our findings appear more consistent with the notion of lexical read-out from long-term memory as a mechanism for letter identification in the two-alternative, forced-choice task in children. Particularly for 7-year-olds, who performed the task relatively well behaviorally (although not as well as 11-year-olds), there was little evidence for early top-down influences on letter identification, as there were no superiority effects in the ERP waveform prior to the N400. This contrasts with the findings from adults in ERP versions of Reicher-Wheeler tasks which indicate 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" (Martin et al., 2006, p. 158) and that orthographic automaticity is reflected in both lower-level, sublexical processing and high-level, lexical processing (Coch and Mitra, 2010). Given the behavioral evidence for significant word and pseudoword superiority effects in both 7-year-olds and 11-year-olds (replicating previous studies, e.g., Chase and Tallal, 1990; Grainger et al., 2003), overall, this pattern of findings raises the possibility that the mechanisms underlying superiority effects may shift over developmental time (from lexical to sublexical, or from lexical to both lexical and sublexical). These data are consistent with the hypothesis that orthographic processing is not automatic or efficient enough in 7-year-olds to allow for top-down or other highly specialized processing within an early time window, while sublexical and lexical processing in fluent readers occur more in parallel, affording top-down effects on early automatic orthographic processing. That the ERP and behavioral measures were taken within the same task and participants – and that the former show clear evidence for developmental change while the latter appear more adult-like – emphasizes the importance of using multiple measures at different levels of analysis to explore development.

3.5 Multiple Measures

Providing further support for these points, the only significant correlation between the electrophysiological measures and the standardized behavioral test scores was a moderate relationship between average N400 peak amplitude and Woodcock Word Identification scores (Woodcock, 1987), although partialling for age nullified this effect, as discussed above. First, this suggests a connection between lexical-level processing and the N400 consistent with the extant literature as reviewed above, and consistent with the interpretation of the superiority effects on the N400 as at the lexical level. Second, this highlights the need for multiple measures at different levels of analysis – the electrophysiological data reveal only part of the story about developing orthographic skills, and the behavioral tests can provide another part of that story. As noted previously (Coch and Mitra, 2010), this is not to suggest that reading can be divided into separate processes in terms of the standardized tests, ERPs, and task accuracy, but that each of these measures can provide complementary information, which can help to constrain interpretation at other levels, regarding the development of automatic orthographic processing.

Finally, accuracy on the two-alternative, forced-choice task was correlated with standard scores on both the RAN Letters and Numbers tests (RAN/RAS, Wolf and Denckla, 2005) and the TOWRE Sight Words and Phonemic Decoding subtests (TOWRE, Torgesen et al., 1999), similarly to adults (Coch and Mitra, 2010). This suggests that behavioral tests emphasizing speeded processing (one component of fluency) might in part draw on the same resources required by the Reicher-Wheeler task. In addition, both the average peak amplitude of the P150 and the size of the P150 word superiority effect (the difference between P150 peak amplitude to words and nonwords) were correlated with accuracy. Here, this was a negative correlation indicating that a smaller amplitude and smaller difference were associated with better accuracy; these effects appear to be confounded with age, however, as partialling the effect of age rendered these correlations nonsignificant. Interestingly, the size of the P150 word superiority effect was positively correlated with task accuracy in adults (Coch and Mitra, 2010). Because the N/P150 has been associated with sublexical orthographic processing (Chauncey et al., 2008; Dufau et al., 2008; Holcomb and Grainger, 2006, p. 1639) and differential processing related to superiority effects at this level appears to be lacking in beginning but not practiced readers, it will be important to further investigate this relationship over developmental time across the school years.

Overall, the pattern of findings across our multiple measures seems consistent with the notion of a more loosely specified word processing system that becomes more efficient over time (e.g., Castles et al., 2003), with that efficiency including increasing top-down influence of lexical representations on early orthographic processing (e.g., Laszlo and Federmeier, 2007; Martin et al., 2006; McClelland and Rumelhart, 1981) and concomitant strengthening relations across various measures of orthographic processing and reading.

3.6 Conclusion

In conclusion, using an ERP variant of a Reicher-Wheeler paradigm can be useful for charting the developmental course of automatic orthographic processing and specialization within the word processing system. In one of the first masked priming ERP studies with children, our findings indicate that the time course of this development extends beyond the age of 11. Further, our findings suggest that the mechanism underlying the observed behavioral word and pseudoword superiority effects in young children may be lexical, while automatic orthographic processing is reflected both lexically and sublexically in older children and adults (Coch and Mitra, 2010; Martin et al., 2006). Thus, our results are consistent with a lengthy developmental time course for sublexical orthographic specialization, for which, it has recently been postulated, there may be multiple types of codes (e.g., Grainger and Ziegler, 2011).

4. Experimental Procedure

4.1 Participants

Participants included 24 7-year-olds [13 female, average age 89.2 months (*SD* 3.9)] and 24 11-year-olds [12 female, average age 137.0 months (*SD* 3.5)]. All participants were right-handed (Edinburgh Handedness Inventory, Oldfield, 1971), monolingual English speakers with no history of neurological, speech, language, or reading disorders. Participants had normal or corrected-to-normal binocular visual acuity (20/30 or better), screened with the standard kindergarten Snellen chart. Participants were recruited through letters sent home through local schools, posters posted in public places frequented by families, and word-of-mouth. All participants were volunteers paid for their participation.

4.2 Standardized Behavioral Tests

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

4.3 ERP Paradigm 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 and pseudoword superiority effects (see also Rumelhart and McClelland, 1982) and by Coch and Mitra (2010) in a previous ERP study with adults. The master list of 80 four-letter words included only items that were rated as having a frequency of 12 or more per million in an adult corpus (Kucera and Francis, 1967) and as high frequency according to a corpus for children in grades 3 through 5 (Chase and Tallal, 1990). 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, etc.). 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. Altogether, then, four types of stimuli were used here in a variation of the classic Reicher-Wheeler paradigm: real words, pseudowords, nonwords, and a letter within a string of Xs. For example, the word pair *DARK-PARK* was matched with the pseudoword pair *DARL-PARL*, the nonword pair *RDKA-RPKA*, and the letter-in-xs pair *DXXX-PXXX*, and the forced-choice alternatives for each member of the pair were *D-P.* We considered the letter-in-xs stimuli an alternate baseline to nonwords that further reduced letter-level orthographic information (see Grainger and Jacobs, 2005, for a discussion about the utility of nonwords as a baseline).

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. Each participant saw both members of a pair at different times across the experiment (list 1, list 2), with order of list presentation counterbalanced across participants. 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. Overall, ERPs were recorded to 80 word, 80 pseudoword, 80 nonword, and 80 letter-in-xs stimuli.

4.4 Procedure

All participants and their parents or guardians were given a brief tour of the lab and an overview of the procedures. Parents were asked to sign a consent form while children signed an assent form; the Committee for Protection of Human Subjects at Dartmouth College reviewed all procedures. Following administration of the standardized behavioral tests, participants were fitted with an electrode cap used for recording ERPs. Participants were then seated in a comfortable armchair in a sound attenuating, electrically shielded booth, with an experimenter seated on a stool next to them. An illustrative trial sequence is presented in Figure 4. Participants were told that they would see four-letter words on the monitor 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 by verbal response when the forced-choice stimulus appeared on the screen; the experimenter seated next to the child in the booth entered the child's answers on a button-press device. This procedure prevented both contamination of the ERP waveforms by vigorous button pressing by the children, and incorrect responses due to confusion about which button to press. Stimuli were presented using Presentation software (Neurobehavioral Systems). Position of the correct letter (presented above or below the hash mark) in the forced-choice stimulus was randomized for each trial but averaged to 50% above and 50% below 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 the experimenter in the booth could then advance the program to the next trial starting with the fixation when the child was ready. A closed circuit video camera, an intercom system, and an in-ear microphone system connected the experimenter in the booth with the experimenter viewing the incoming EEG data; the experimenter outside the booth could also advise the experimenter inside the booth with the child when to advance to the next trial given the quality of the incoming EEG data.

In previous behavioral masked priming reports of word and pseudoword superiority effects in children of the same ages, it was necessary to vary the duration of stimulus presentation by age in order to avoid floor and ceiling effects (e.g., Chase and Tallal, 1990; Grainger et al., 2003). Remarkably similar durations were used: Chase and Tallal (1990) reported a critical stimulus duration of 223.8 (98.5) ms in 7-year-olds and 85.4 (26.1) ms in 11-year-olds, while Grainger et al. (2003) used a 200 ms duration with 7-year-olds and a 100 ms duration with 11-year-olds. Here, stimuli were presented for 212 ms for 7-year-olds and 112 ms for 11-year-olds; duration of the blank screen following presentation of the mask was such that 500 ms elapsed from presentation of the stimulus to presentation of the forced-choice letters for each age group, controlling both for total processing time across groups and preventing contamination of the first 500 ms of the ERP response to the stimuli by the response to the forced-choice letters (refer to Figure 4). Thus, the between-groups manipulation of duration used here was based squarely on previous developmental work involving masking thresholds.

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 substantial eye movements and other sources of artifact (e.g., verbal responses) accompanied the presentation of the letters. A brief practice session preceded the experimental session; none of the stimuli used in the practice session were used in the actual experiment.

4.5 EEG/ERP Recording and Analysis

EEG was recorded from 29 tin electrodes mounted in an elastic cap (Electro-Cap International) according to an extended 10–20 configuration, including sites F3, F4, F7, F8, FC5, FC6, FT7, FT8, C3, C4, C5, C6, CT5, CT6, T3, T4, T5, T6, P3, P4, TO1, TO2, O1, O2, Fz, Cz, and Pz (see Figure 6, Coch and Mitra, 2010). Data from FP1/2 were used only to measure eye blinks, and data from Fz, Pz, and Cz are not reported here. 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 and blinks. 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 stimuli were averaged for each subject at each electrode sites over an 800 ms epoch using a 200 ms pre-stimulus-onset baseline. Only trials for which participants responded correctly were used in ERP averages. Trials contaminated by eye movements or blinks, muscular activity, or electrical noise were not included in analyses. Standard artifact rejection parameters were employed initially and data were analyzed subsequently on an individual basis for artifact rejection if necessary. For 7-year-olds, the average number of correct trials included in the word condition was 48.4 (*SE* 2.7); in the pseudoword condition, 46.9 (*SE* 2.8); in the nonword condition, 42.6 (*SE* 2.1); and in the letter-in-xs condition, 41.1 (*SE* 2.4). For 11-year-olds, the average number of correct trials included in the word condition was 63.6 (*SE* 1.8); in the pseudoword condition, 61.2 (*SE* 1.8); in the nonword condition, 55.4 (*SE* 1.9); and in the letter-in-xs condition, 55.5 (*SE* 2.2).

The analysis approach was the same as in the companion study with adults (Coch and Mitra, 2010). Time windows for measurement were determined by visual inspection of grand averages and individual participant data; windows that best fit both the 7-year-old and 11-year-old data were used. A P150 was measured within the 100–180 ms window, an N200 within the 180–280 ms window, and an N400 within the 280–450 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. An omnibus repeated measures ANOVA was performed with the between-subjects factor group (2 levels: 7-year-olds, 11-year-olds) and 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 occipital and parietal sites, while an N400 was observed and measured at all sites], lateral/medial (2 levels), and hemisphere (2 levels: left, right). Significant ERP effects involving condition were followed up with simple 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 a Bonferroni-corrected *p* value of .0125 (.05/4). Partial eta squared values are reported as estimates of effect size for primary analyses. The Huynh-Feldt correction was applied to all within-subjects measures with more than one degree of freedom. Finally, Pearson's correlations were calculated to investigate specific relations among the behavioral accuracy scores on the ERP task, the standardized behavioral test scores, and the electrophysiological measures. A conventional significance level of .05 was used for all primary analyses.

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Research Highlights

- Used an ERP variant of the Reicher-Wheeler paradigm with 7-year-olds and 11-year-olds
- Both 7- and 11-year-olds showed behavioral word and pseudoword superiority effects
- 7-year-olds showed ERP superiority effects only on N400 amplitude
- 11-year-olds showed ERP superiority effects on P150 and N400 amplitude
- Lengthy developmental time course for neural automatic orthographic processing

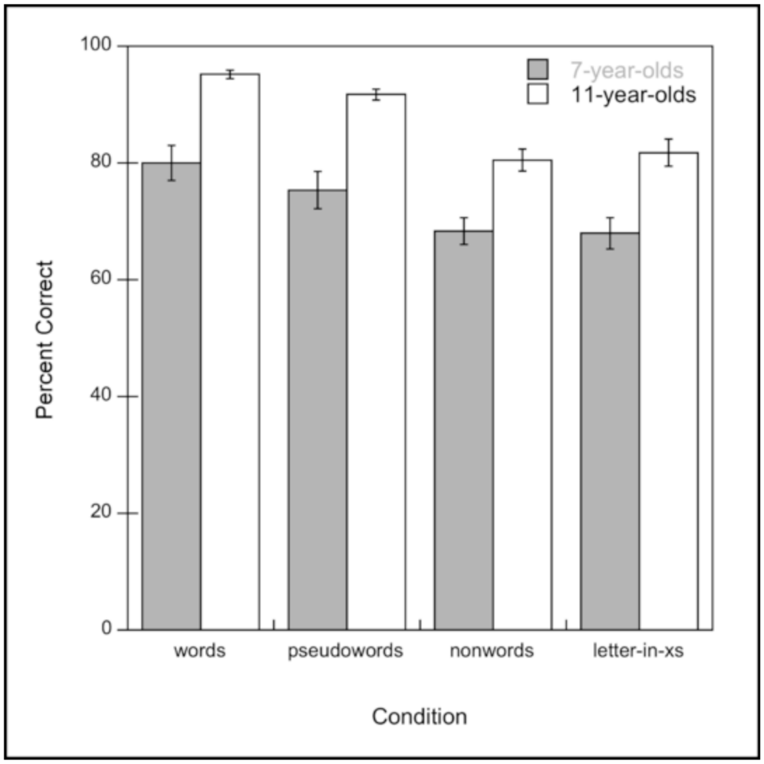

Figure 1.
Behavioral accuracy in the ERP letter identification task across the four conditions for 7-year-olds (gray bars) and 11-year-olds (white bars). The 11-year-olds were more accurate overall than the 7-year-olds, but both groups showed behavioral word and pseudoword superiority effects, both with the typical nonword baseline and with the alternate letter-in-xs baseline. Bars indicate standard error.

Figure 2A

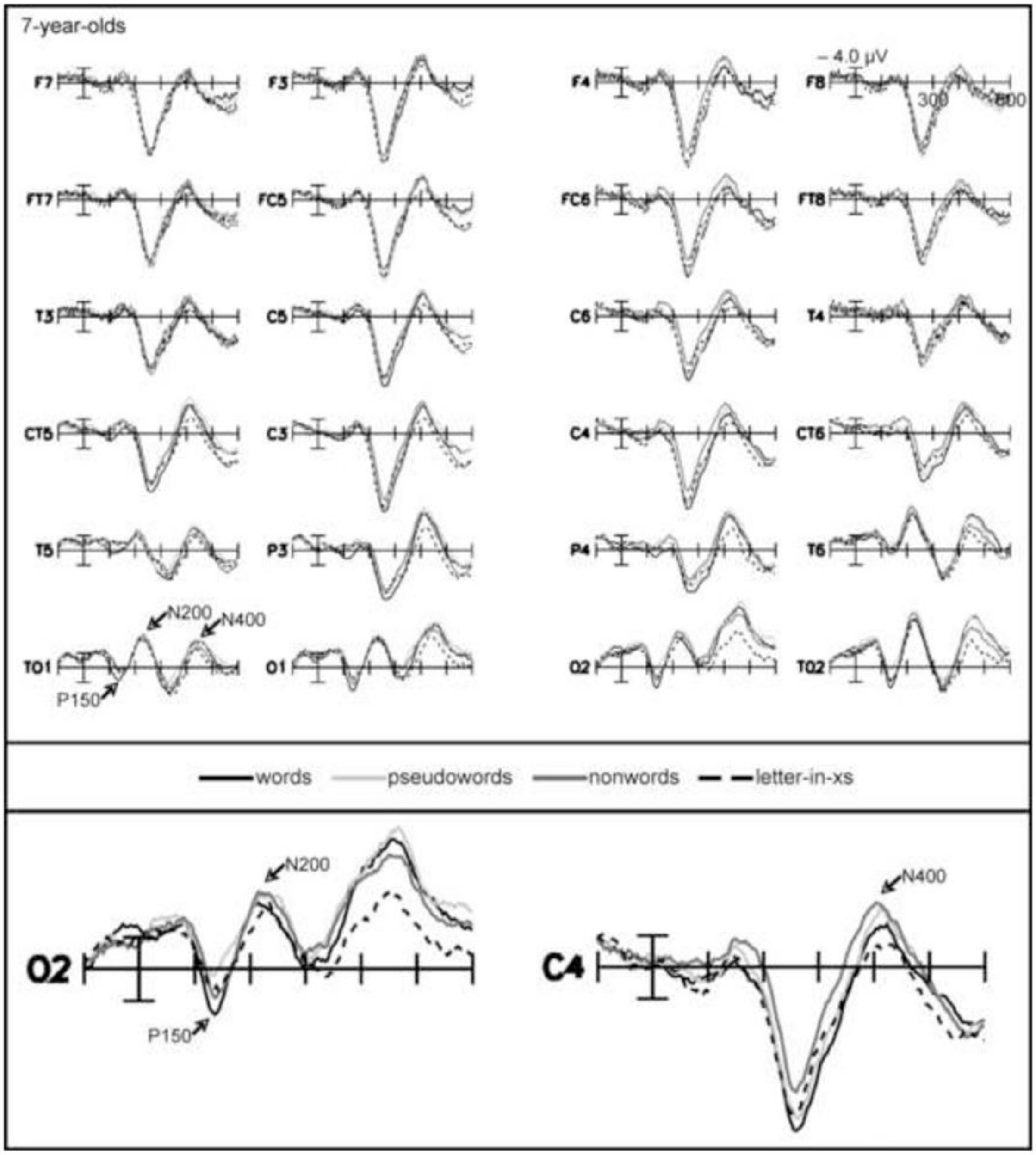
7-year-olds
– 4.0 μV
300
600
F7
F3
F4
F8
FT7
FC5
FC6
FT8
T3
C5
C6
T4
CT5
C3
C4
CT6
T5
P3
P4
T6
TO1
O1
O2
TO2
N200
N400
P150
words
pseudowords
nonwords
letter-in-xs
O2
C4
N200
P150
N400

Figure 2B

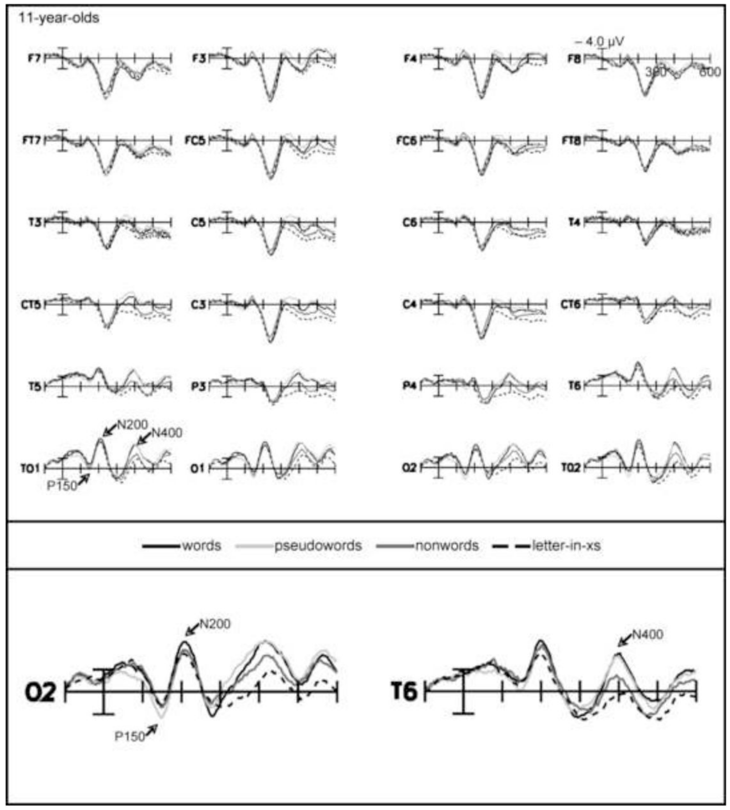

Figure 2.

Grand average ERP waveforms elicited by word (solid black line), pseudoword (light gray line), nonword (dark gray line), and letter-in-xs (dashed line) stimuli for (**A**) 7-year-olds and (**B**) 11-year-olds. Components of interest are identified in the top panels, and enlarged views of selected electrode sites more clearly illustrate the effects in the bottom panels of each figure. (**A**) Seven-year-olds showed no superiority effects for P150 or N200 amplitude (O2 example), a reversed word superiority effect such that nonwords elicited a larger N400 than words at medial right hemisphere sites (C4 example), and a pseudoword superiority effect for N400 amplitude with the letter-in-xs baseline at central and temporoparietal sites (C4 example). (**B**) Eleven-year-olds showed a pseudoword superiority effect for P150 amplitude with both nonword and letter-in-xs baselines, particularly at posterior medial sites (O2 example), no superiority effects on N200 amplitude (O2 example), and both word and pseudoword superiority effects on N400 amplitude with both nonword and letter-in-xs baselines at lateral posterior sites (T6 example). In the top panels, more anterior sites are toward the top 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. Each vertical tick marks 100 ms and negative is plotted up. The calibration bar marks 4.0 μV.

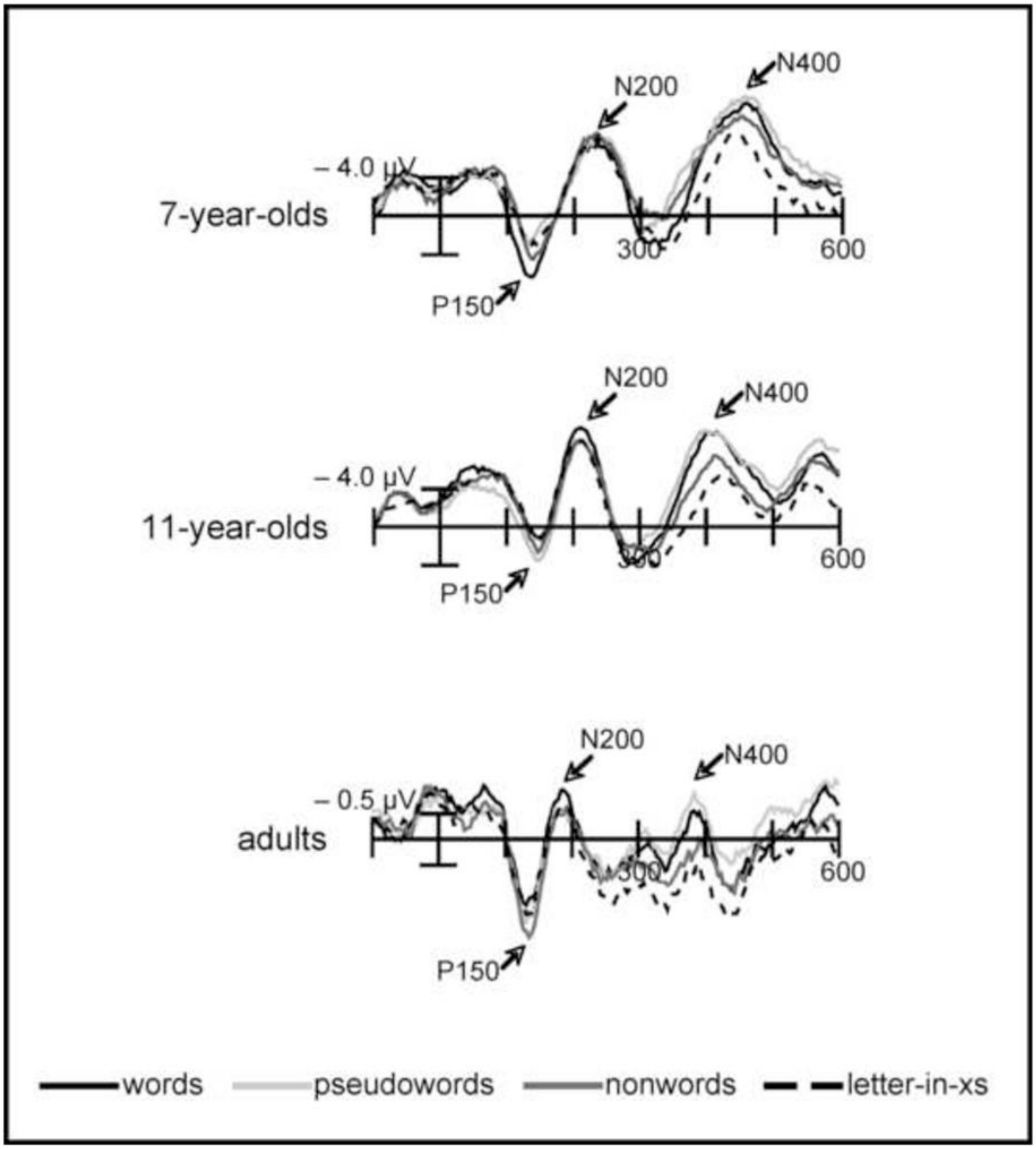

Figure 3.
Grand average ERP waveforms elicited at posterior, medial site O1 by word (solid black line), pseudoword (light gray line), nonword (dark gray line), and letter-in-xs (dashed line) stimuli for the 7-year-old group (top trace), the 11-year-old group (middle trace), and the adult group [bottom trace; from a previous report using the same paradigm (Coch & Mitra, 2010, adapted from their Figure 2)]. The three components of interest are identified in each trace. Each vertical tick marks 100 ms and negative is plotted up. The calibration bar marks 4.0 μV for the child groups and 0.5 μV for the adult group.

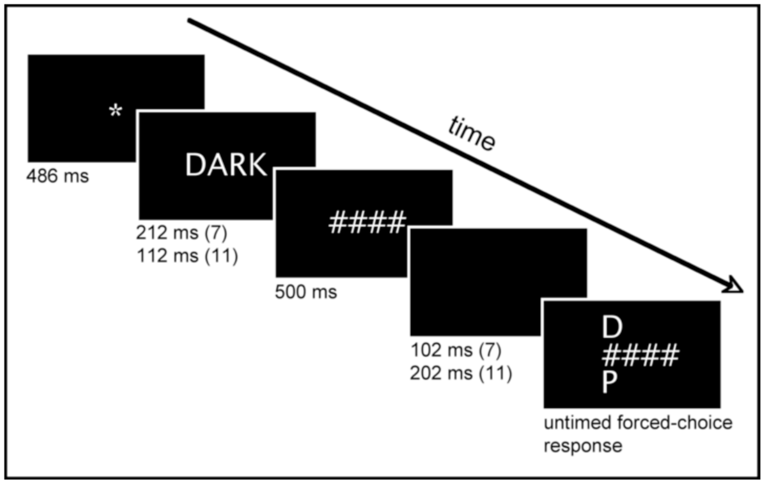

Figure 4.
Illustration of the stimulus presentation sequence in a single trial.

Table 1

Summary of Standardized Behavioral Test Scores

	7-year-olds			11-year-olds		
Subtest	**Raw Score *(SD)***	**Standard Score *(SD)***	**Percentile Rank *(SD)***	**Raw Score *(SD)***	**Standard Score *(SD)***	**Percentile Rank *(SD)***
RAN/RAS Numbers[a]	34.15 *(8.21)*	105.92 *(12.39)*	62.33 *(26.16)*	23.37 *(7.61)*	107.92 *(12.76)*	67.13 *(26.11)*
RAN/RAS Letters[a]	31.45 *(7.63)*	108.92 *(10.72)*	69.21 *(20.85)*	21.73 *(4.11)*	110.21 *(11.68)*	70.58 *(22.66)*
TOWRE Sight Word[b]	52.04 *(18.08)*	113.33 *(14.98)*	73.79 *(26.83)*	79.17 *(8.66)*	109.17 *(10.76)*	68.83 *(22.60)*
TOWRE Phonemic Decoding[b]	24.33 *(11.29)*	108.96 *(12.10)*	67.92 *(23.59)*	43.58 *(7.86)*	107.71 *(11.09)*	65.38 *(22.80)*
WRMT-R Word Identification[c]	55.33 *(17.45)*	118.04 *(12.26)*	82.33 *(19.13)*	81.29 *(7.15)*	105.54 *(8.25)*	62.42 *(18.25)*

[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)