Electrophysiological Dynamics of the Development of Automatic Reading

A thesis

submitted by

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Abstract

Previous ERP studies have mapped the time course of automatic visual word recognition in adults (e.g., Holcomb & Grainger, 2006) and recent work extends this research to children (Eddy, Grainger, Holcomb, Mitra, & Gabrieli, submitted). In an ERP masked priming paradigm, we investigated sublexical and lexico-semantic processing as indexed by the N250 and N400 repetition priming effects, respectively. We then used multiple regression models of reading abilities to predict the size of these priming effects. Children showed similar N250 and N400 priming effects to those seen in adults, but the N250 priming effect started somewhat later in developing readers. Somewhat surprisingly, developing readers did not show overall differences in the amplitude of the N250 and N400 priming effects across age groups. However, the size of these priming effects was predicted by reading skill. Adults' N400 effects were related to their reading fluency. In children, orthographic skills predicted the size of their early and late N250 priming effects and lexical/semantic knowledge predicted the size of their N400 effect. This suggests that the changes in the component processes of word reading indexed by the ERP waveform are more closely tied to the development of reading ability than to maturation.

For those of us who spend our days reading journal articles, the process of understanding the meaning of written words, quickly and accurately, is critical to our professional success. Yet this process of fluent reading is simultaneously trivial for most of us because of the ease with which we do it. Research with adults highlights how the brain develops the ability to process text so efficiently that it becomes automatic – even to the point where reading can take place without conscious effort (Cohen, et al., 2000; Davis, 2003; Dehaene, 2009; Grainger & Holcomb, 2009; McCandliss, Cohen, & Dehaene, 2003). However, we know far less about how this ability develops in young children and how it relates to an individual's proficiency in the various subskills involved in fluent reading.

Young children must learn the basic building blocks of reading – graphemes and phonemes (letters and their associated sounds). They then must learn how these sublexical units combine to make words (Treiman, 2000). And yet, developing expertise in reading implies more than just accuracy in identifying written words. Expert reading must also be fluent, that is, relatively fast and effortless (Samuels, 1997; Wolf, 2001). Children's ability to quickly and accurately utilize letter and sound information to efficiently identify written words is critical to fluent and automatic reading of single words and, ultimately, of connected text (Gorsuch & Taguchi, 2010; Goswami & Ziegler, 2006; Wolf & Katzir-Cohen, 2001). Thus, understanding the processes that go into single word reading for young children provides us with important information about the development of the expert reading abilities we see in adults.

One difficulty in studying reading is the inherent complexity of the system. Orthographic, phonological, morphological, lexical, semantic, syntactic, and comprehension skills must all work in concert to produce the end result of reading text from a page (Adams, 1990). As we study reading in a laboratory setting, we can break reading into these component parts in order to better understand each subskill independently and to help formulate models of how the reading system functions as a whole (Bigsby, 1988; Grainger & Holcomb, 2009; Grainger, Kiyonaga, & Holcomb, 2006; Seidenberg & McClelland, 1989; Shaywitz, Mody, & Shaywitz, 2006; Wolf, 1991). The bi-modal interactive activation model (BIAM) provides a description, based on the most recent behavioral and neuroscience findings on word recognition, of how the adult brain takes low-level visual and auditory inputs and maps them onto our higher-level representations of word meaning (Grainger & Holcomb, 2009). Single word reading can be conceptually broken down into two key stages of processing that are critical to understanding how the reading brain develops. First the reader must process the visual form of the word, mapping sublexical orthographic (visual form/letters) and phonological (sound/phoneme) units onto whole-word lexical representations. Then the reader must map these whole-word form representations onto semantic (meaning) representations.

For adults, both sublexical and lexical processing occur automatically in typical readers (Grainger, et al., 2006; Tanenhaus, Flanigan, & Seidenberg, 1980). However, it is often difficult to separate these early, automatic processes from effects of the many different reading strategies consciously employed by experienced readers. A masked priming design in turn allows us to separate out truly automatic processing as the participants are not consciously aware that they have perceived the masked word (Davis, 2003; Forster, Mohan, & Hector, 2003; Grainger & Holcomb, 2009; Holcomb & Grainger, 2006; Holcomb, Reder, Misra, & Grainger, 2005; Mitra & Coch, 2009), and thus cannot engage some of the strategies that may be engaged in other tasks that have been used to investigate automaticity (Erickson, et al., 2008). In masked priming a rapid sequence of critical stimuli (e.g., words) and perceptual masking stimuli (e.g., ####) are presented. The first critical event is a briefly presented prime, which is quickly masked below recognition threshold by an immediately following mask and then a clearly visible target stimulus. Priming effects are interpreted to reflect automatic activation of representations shared by prime and target because presentation parameters are such that participants are generally unaware that they have even seen the prime (Forster & Davis, 1984; Forster, et al., 2003; Grainger & Jacobs, 1999). Despite not consciously being able to read the prime, neural responses to targets are modulated by orthographic, lexical, and semantic overlap between primes and targets (Grainger & Holcomb, 2009; Holcomb & Grainger, 2006; Kinoshita, 2003; Misra & Holcomb, 2003).

Unfortunately, behavioral masked priming paradigms are limited to measuring priming effects in terms of reaction times (and sometimes accuracy) hundreds of milliseconds after initial processing of both form and meaning have already taken place. Thus these measures are limited in their ability to distinguish and inform our understanding of these online processes. Entirely different patterns of neural processing could produce these same results. In contrast, event-related potentials (ERPs) provide real-time information on the order of milliseconds. This temporal sensitivity is essential when investigating the rapid sequence of neural events involved in automatic word reading. The addition of ERPs as a measure of the timing of form and meaning processing in combination with masked priming has further provided additional detail to our understanding of sublexical and lexico-semantic processing as they unfold over time during word recognition. Priming a target word with an identical word (repetition priming) should reduce the cognitive resources necessary to process the subsequent target (Horn & Manis, 1987; Immordino-Yang & Deacon, 2007; Perfetti, 1985), resulting in facilitation at the neural level as seen in reduced ERP component amplitude to repeated prime-target pairs as compared to unrelated pairs (Grainger & Holcomb, 2009; Holcomb & Grainger, 2006; Luck, 2005). The use of masked primes in an ERP paradigm allows for isolating short-lived orthographic and phonological effects, as well as later lexico-semantic effects, which cannot be adequately differentiated by unmasked priming or behavioral paradigms.

Two ERP components of particular interest for the current study are the N250 and N400, negative-going peaks in the waveform that peak around 250 and 400 ms, respectively, after the presentation of the word. Previous research, mapping the BIAM onto the online processes, shows that the N250 seems to reflect the mapping of sub-lexical orthographic and, slightly delayed, phonological information onto whole-word representations (Grainger, et al., 2006). At this point, targets that overlap orthographically or phonologically with the preceding prime produce a less negative response than targets that have less overlap (Grainger & Holcomb, 2009; Grainger, et al., 2006; Holcomb & Grainger, 2006).

The later N400 priming effect has been shown to be sensitive to both the lexicality of a word-like stimulus as well as the semantic-relatedness of word pairs. In single word processing, the BIAM proposes that the N400 represents a ‘form-meaning interface’ (Grainger & Holcomb, 2009; Holcomb & Grainger, 2006), indexing integrative processing that builds upon earlier sublexical representations to access higher level lexical and semantic representations (Grainger & Holcomb, 2009; Holcomb & Grainger, 2006, 2007; Kiyonaga, Grainger, Midgley, & Holcomb, 2007; Kreher, Holcomb, & Kuperberg, 2006; Misra & Holcomb, 2003).

Comparatively little is known about how this automaticity develops in children. Previous behavioral masked priming research with developing readers can provide some insight, but these studies have produced somewhat conflicting results as to the age at which the automatic masked priming effects elicited in adults develop in children (Acha & Perea, 2008; Castles, Davis, Cavalot, & Forster, 2007; Castles, Davis, & Forster, 2003; Castles, Davis, & Letcher, 1999;

Davis, Castles, & Iakovidis, 1998; Mussolin & Noël, 2008; Pratarelli, Perry, & Galloway, 1994; Schiff, Raveh, & Kahta, 2008). Evidence of masked identity priming in fourth graders has been used to suggest that the automatic processes underlying these effects are already similar to those seen in adults (Davis, et al., 1998; Pratarelli, et al., 1994). This finding is in keeping with traditional education philosophy that automaticity comes with the fourth grade shift from "learning to read" to "reading to learn" (Chall, Jacobs, & Baldwin, 1990). However, other studies have provided evidence that masked priming effects continue to develop beyond this point. For instance, while both third and seventh grade children showed morphological masked priming effects in Hebrew, they relied more heavily on the overlap of surface form than did adult readers (Schiff, et al., 2008). Results from English and Spanish also show evidence of masked priming effects in children as young as 7 years old, but orthographic factors such as word length, letter substitutions, transposed letters, and orthographic legality of the letter string continue to influence masked priming effects, in ways that differ from adults, beyond the fifth grade and perhaps well into adolescence (Acha & Perea, 2008; Castles, et al., 2007; Castles, et al., 1999). Letter substitution and transposed letter masked priming effects developed even later in French, not appearing until fifth grade, with possible further delays for children with phonological deficits (Lété & Fayol, 2013).

This seeming discrepancy again highlights the fact that it is important to define what we mean when we attempt to identify adult-like or automatic reading in children. Specifically, different reading subskills such as phonology, orthography, morphology and lexical access may become automatic at different points. Further complicating our understanding of how masked priming effects develop, Davis and colleagues (1998) failed to find evidence of phonological masked priming effects in fourth graders or adults despite both behavioral and electrophysiological evidence of phonological effects in other masked priming studies with adults (Grainger, Diependaele, Spinelli, Ferrand, & Farioli, 2003; Grainger, et al., 2006). Additionally, Davis et al. (1998) suggest that the presence or absence of phonological masked priming effects may be related to reading ability, as a subset of their developing readers did show evidence of phonological priming effects. Perhaps then, behavioral measures may not be sensitive enough to reliably identify changes in automatic word recognition as these abilities develop incrementally, especially if some of these effects are sensitive to reading skills rather than simply chronological age.

Another possibility is that the masking procedures may be inappropriate for some of the children in the developmental sample. In order to achieve similar levels of behavioral performance and masking in studies of the word superiority effect, previous research has utilized longer presentation durations of at least 100 ms for young children (Chase & Tallal, 1990; Grainger, Bouttevin, Truc, Bastien, & Ziegler, 2003). If we consider that children have necessarily had less experience reading words, then this may relate to ERP masked priming work with adults who are learning a foreign language, and thus also have limited experience and automaticity in reading this second language. When adults do not read fluently in the language that the prime is presented in, N250 and N400 priming effects can be elicited when the prime lasts for 100 ms (Schoonbaert, Holcomb, Grainger, & Hartsuiker, 2010), but shorter primes may not always be sufficient to elicit early priming effects (Midgley, Holcomb, & Grainger, 2009). Even in fluent adult readers, primes that are presented too briefly (below 30 ms) will not reliably elicit priming effects (Holcomb & Grainger, 2007). Longer prime durations elicit larger priming effects, similar to those seen in unmasked priming, but they consistently elicit both N250 and N400 priming effects (Holcomb & Grainger, 2007; Holcomb, et al., 2005).

We have recently expanded our own research to look at ERP masked priming effects in children. In a previous study, we used a masked repetition priming paradigm to compare the time-course of reading single words in children (8-12 years old) and adults (Eddy, et al., submitted). In anticipation of differences in fluency between groups, we used 53, 80, and 107 ms masked primes. Both adults and children showed N250 priming effects, but the amplitude of this effect was larger in children than in adults. An N400 priming effect was seen in both groups and did not differ between the adults and children. The presence of both priming effects in children suggests that by late childhood, typically developing readers have achieved some level of orthographic automaticity, although it is not yet adult-like. In contrast, the similar N400 effect seen in adults and children suggests that lexico-semantic processes for high frequency words may be relatively mature in 8- to 12-year-olds.

This initial study provides valuable insight into the development of automaticity, showing that the ERP masked priming effects elicited in proficiently reading children are similar, but not identical to those seen in adult readers. However, the wide age range of the children in this study does not allow us much specificity in the development of these effects as they relate to maturation or reading ability. Most of the children in this study were at or beyond the third/fourth grade cutoff where children are expected to have mastered the process of learning to read (Chall, et al., 1990). This level of proficiency may mitigate any potential differences that exist between child and adult readers. Furthermore, because the speed of development is more pronounced for children than for adults, the wide age range seen here may disguise a lot of variability within the group of children (Picton, et al., 2000).

Early sublexical processing in particular may undergo extensive changes between 8 and 12 years of age. Previous work has shown that 11-year-olds are sensitive to the lexical status (i.e., word vs. pseudoword vs. consonant string) of masked letter strings at both the P150 (visual feature) and N400 stages of processing, while 7-year-olds only showed N400 effects of lexicality (Coch, Mitra, & George, 2012). However, this contrasts with previous findings in which early orthographic specialization for words by around 200 ms in 6-year-olds (Maurer, Brem, Bucher, & Brandeis, 2005). Although the masking procedure seen in the first study likely contributes to this difference in early processing, another possible source comes from the variability of the participants themselves. Maurer and colleagues (2005) found that children with better knowledge showed more specialization for words within the first 270 ms of processing. The amplitude of the N400 component has also been shown to be related to reading skill. For instance, the N400 has been shown to be less selective in processing word-like stimuli in first grade readers, while N400 effects of repetition in particular were seen in only the more proficient readers (Coch & Holcomb, 2003). The amplitude of the N400 has also been shown to correlate with pseudoword decoding ability and N400 effects of semantic congruency are related to the listening comprehension abilities of 8- to 10-year-old children (Henderson, Baseler, Clarke, Watson, & Snowling, 2011).

The current study expands upon our previous work in which we showed that an ERP masked priming paradigm can be effectively used to study the automaticity of sublexial and lexico-semantic processing in children (Eddy, et al., submitted). Here we use the same priming paradigm to further investigate the effects of age and reading ability on ERP masked priming effects, using multiple regression models of standardized reading and language tests to predict ERP priming effects.

Experiment 1

In Experiment 1, we investigate the ERP effects in adults elicited across three different prime durations (53, 80, and 107 ms) by repetition primes compared to unrelated primes and how the size of the repetition effect relates to individuals' reading proficiency as measured by standardized behavioral measures of reading and language ability. We predict that adults would show both a small N250 priming effect and an N400 priming effect to pairs of high frequency words as previous studies have demonstrated that with longer prime-target SOAs, the N250 to high frequency words is reduced (Grainger, Lopez, Eddy, Dufau, & Holcomb, 2012). We expected priming in the early N250 time window to be related to standardized tests of orthographic ability, the late N250 to be related to phonological ability, and the N400 to be related to both lexico-semantic ability and reading fluency (Grainger, et al., 2006). However, as adults are highly fluent readers, we expect the orthographic, phonological, and lexico-semantic abilities will predict a comparatively small amount of the variance seen in the priming effect sizes, while the higher-level measure of reading fluency should relate more strongly to the N400 priming effect as this ability may continue to develop well into adulthood.

Methods

Participants. Participants included 18 young adults (10 female, 8 male) ages 19-25 (*M* = 22.05, *SD* = 2.2 years). All participants were native English speakers who did not report fluency in any other languages. Participants were right-handed with normal or corrected to normal vision and had no history of language, reading, or neurological disorders. All volunteers provided informed consent and received cash compensation for their participation.

Behavioral testing. Standardized behavioral tests of language and reading were administered and scores were divided into four clusters, constrained by the competencies that they measured. The four clusters were: orthographic, phonological, lexical/semantic, and fluency. The tests included in each cluster are described below.

Orthographic. The Word Choice subtest of the Test of Orthographic Competence (TOC; Mather, Roberts, Hammill, & Allen, 2008) measured participants' ability to differentiate between phonologically identical letter-strings to choose the correct orthographic form of a real word. The Sight Spelling subtest of the TOC was used to measure participants ability to produce the correct spelling of a word, given incomplete orthographic information (Mather, et al., 2008). Fluency of orthographic word reading ability was measured with the Sight Word Efficiency subtest of the Test of Word Reading Efficiency (TOWRE; Torgesen, Wagner, & Rashotte, 1999). The number and letter RAN from the Rapid Automatized Naming and Rapid Alternating Stimulus Tests (RAN/RAS) were also used to measure participants' proficiency with letters and numbers (Wolf & Denckla, 2005), which has been linked with efficiency of orthographic recognition (O'Brien, Wolf, Miller, Lovett, & Morris, 2011).

Phonological. The Word Attack subtests of the Woodcock Reading Mastery Test—Revised (WRMT; Woodcock, 1987) and the Phonemic Decoding Efficiency subtest of the TOWRE (Torgesen, et al., 1999) were used to measure word decoding (i.e., employing grapheme to phoneme correspondence rules to read an unknown letter-string) accuracy and efficiency, respectively. From the Comprehensive Test of Phonological Processing (CTOPP), the Elision and Blending subtests were used to measure phonological awareness and the Memory for Digits and Nonword Repetition subtests were used to measure phonological memory (Wagner, Torgesen, & Rashotte, 1999).

Lexical/Semantic. Receptive vocabulary was investigated with the Peabody Picture Vocabulary Test, Fourth Edition (PPVT; Dunn & Dunn, 2007). The Word Identification subtest of the WRMT-R (Woodcock, 1987) was used to measure sight word recognition and word reading ability. The Sight Spelling and Homophone Choice or Word Choice subtests of the TOC were included as an index of knowledge of visual wordforms (see above). The letter and number RAN were also used as an index of lexical access for alphanumeric characters (see above).

Fluency. Single-word level fluency for both word and nonword reading were measured with the Sight Word Efficiency and Phonemic Decoding Efficiency subtests of the TOWRE, respectively (Torgesen, et al., 1999). A higher (sentence) level measure of fluency was obtained with the Reading fluency subtest of the Woodcock Johnson III (WJIII) Tests of Achievement with Normative Update (Woodcock, McGrew, & Mather, 2007).

ERP stimuli. Stimuli were identical to those used by Eddy et al. (submitted), and consisted of 360 three- to five-letter, open-class, English words with a mean frequency of 418 occurrences per million (Zeno, Ivens, Millard, & Duvvuri, 1995). Words were presented in prime-target pairs, with the prime presented in lowercase letters and the target in uppercase. In half of the critical trials the same word was presented in the prime and target positions of the trial (repeated condition) and in half of the trials pairs were comprised of words that were phonologically, orthographically, and semantically unrelated (unrelated condition). Each word was viewed in only one trial by each participant, but words were presented in both the prime and target position for each prime duration condition and counterbalanced across participants. An additional set of 60 animal names paired with 60 additional unrelated high frequency words, provided probe items for a semantic categorization task. Half of the semantic probe trials contained an animal name in the prime position (equally distributed among the three prime durations) and a filler word in the target position, while the other half had an animal name target and non-animal prime.

Procedure. All procedures were explained to participants before the actual test session, and any questions addressed before the start of the experiment. Participants were fitted with an elastic cap (Electro-Cap Inc.) and seated in a sound attenuated darkened room. Visual stimuli were presented in the center of a 19-in. monitor set to a refresh rate of 75 Hz and located directly in front of the participant. Words were presented in white letters on a black background in Verdana font (40 pixels tall by 20 pixels wide). Each trial began with a forward mask of seven hash marks (#######) presented for 500 ms. The forward mask was replaced lowercase prime for 53, 80 or 107 ms. The prime was then immediately replaced by a backward mask (#######). The backward mask remained on the screen until 120 ms has elapsed from the onset of the prime (67, 40, or 13 ms, depending on the duration of the prime) and was be immediately replaced by the visual target in uppercase letters for a duration of 500 ms. To minimize contamination of trials due to blink artifact, all target words were be followed by a 700 ms blank screen before the 2000 ms presentation of a stimulus indicating that participants could blink and another 500 ms in which no stimuli are presented on the screen preceded the beginning of the next trial (see Figure 1). Participants were asked to refrain from blinking and moving their eyes except when the blink stimulus appears between trials and a short practice preceded the actual test session. The ERP task was broken into 5 blocks of approximately 4 minutes each with short breaks between each block.

Participants performed a go/no go semantic categorization task to ensure sustained attention and a deep level of semantic processing and to assess the extent of prime visibility (in cases where the animal name is presented as the prime word). They were instructed to press a button on a response device whenever one of the words presented is an animal name and told not to press for non-animal items, to minimize motor responses to critical trials.

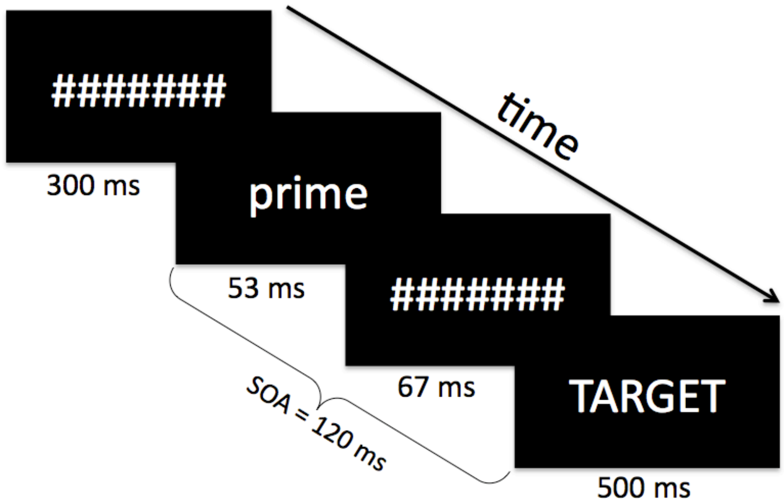

Figure 1. A sample trial denoting the sequence and timing of events presented on the screen. Although duration of the prime and backward mask varied, the stimulus onset asynchrony (SOA) was held constant.

EEG Recording. EEG was recorded from 32 scalp sites (10-20 system positioning; see Figure 2), a vertical eye channel for detecting blinks, a horizontal eye channel to monitor for saccades, and two additional electrodes affixed the mastoid bone. EEG was acquired with the Active Two Biosemi system using active Ag-AgCl electrodes mounted on an elastic cap (Electro-Cap Inc.). Channels were referenced offline to an average of the mastoids. The EEG was recorded at 512 Hz sampling rate and filtered offline (bandpass 0.16-20 Hz). Trials with blinks, eye movements, and muscle artifact were rejected prior to averaging.

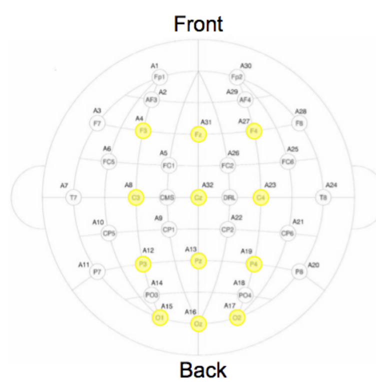

Figure 2. Electrode montage used for adults. Sites marked in yellow were used to analyze ERP effects across the scalp.

Data Analysis. Averaged ERPs were formed off-line from trials free of ocular and muscular artifact. ERPs were calculated by averaging the EEG time locked to a point 100 ms before the onset of the target and lasting for 900 ms. The 100 ms pre-stimulus onset period serves as a baseline. ERPs were measured separately for the repeated and unrelated conditions at 12 sites (O1, Oz, O2, P3, Pz, P4, C3, Cz, C4, F3, Fz, F4) used in previous masked priming studies in adults (Eddy et al., submitted). Mean amplitude measurements were taken between 150-250 ms (early N250 epoch), 250-350 ms (late N250 epoch) and 350-500 ms (N400 epoch). The mean amplitude measurements from these epochs were entered into a repeated measures ANOVA including the within-subjects factors of priming (2 levels: repeated, unrelated), prime duration (3 levels: 53 ms, 80 ms, 107 ms), anterior/posterior (4 levels), and hemisphere (3 levels: left, midline, right).

To better characterize the timing of these effects, we also performed a time course analysis by epoching the data into 50 ms segments from 100-600 ms and examining the repetition effects across the electrodes included in the ANOVA allowing us to the examine the onset and distribution of these priming effects. Time course analyses were used to qualitatively compare adults' priming effects with those seen in children, described later. The Geisser Greenhouse correction was applied to all repeated measures with more than one degree of freedom.

Regression Analysis. Multiple regression analysis was used to evaluate the relationship between standardized behavioral tests and the size of the ERP priming effects. The test scores for each behavioral cluster were included as predictor values for the model to determine whether behavioral performance could predict the size of the ERP priming effects. Electrodes Cz and Pz were chosen as a representative site for measuring the priming effect, consistent with effects seen in previous studies (Eddy, Grainger, Holcomb, Del Tufo, & Gabrieli, in prep; Eddy, et al., submitted). Regressions were run to determine the orthographic cluster of test's ability to predict the early N250 effect. Separate regressions were run for both the orthographic and phonological clusters and the late N250 effect. The lexico-semantic and fluency clusters were both included in models of the N400 effects.

Results

ERP Results.

Early N250 epoch (150-250 ms). The mean amplitude of the early N250 showed a typical masked priming effect in which unrelated targets elicited a more negative going waveform than repeated targets in this time window, especially at anterior sites (priming: $F(1, 17) = 6.65$, $p = .020$; priming x anterior/posterior: $F(3, 51) = 5.70$, $p = .008$ – see Figure 3). This early N250 priming effect did not differ by prime duration ($F(2, 34) = .19$, $p = .832$).

Late N250 epoch (250-350 ms). In keeping with the visual observation that the N250 priming effect occurs early in adults especially for high frequency words, the overall ANOVA revealed a trend towards a priming by anterior/posterior interaction ($F(3, 51) = 2.60$, $p = .075$ – see Figure 3) but did not reveal any other priming effects in this time window.

N400 epoch (350-500 ms). The N400 showed a masked priming effect that was largest over centro-parietal sites (priming: $F(1, 17) = 65.93$, $p < .001$; priming x anterior/posterior: $F(3, 51) = 12.55$, $p < .001$ – see Figure 3). The N400 priming effect also did not show a significant interaction with prime duration ($F(2, 34) = 1.03$, $p = .368$).

Task Accuracy. Adults were highly accurate at detecting animal target words, correctly identifying an average of 29.28 out of 30 ($SD = 0.89$), but identified significantly fewer animal probes when they were presented in the prime position ($M = 23.11$ out of 30, $SD = 6.91$; $p =$

.001). Planned t-tests also demonstrated that 53 ms primes were detected (*M* = 6.5 out of 10, *SD* = 2.66) significantly less often than either 80 ms primes (*M* = 8.28 out of 10, *SD* = 2.42; $p <$ .001) or 107 ms primes (*M* = 8.33 out of 10, *SD* = 2.43; $p = .002$). There was no difference in the number of animal probes detected at the two longer prime durations ($p = .854$).

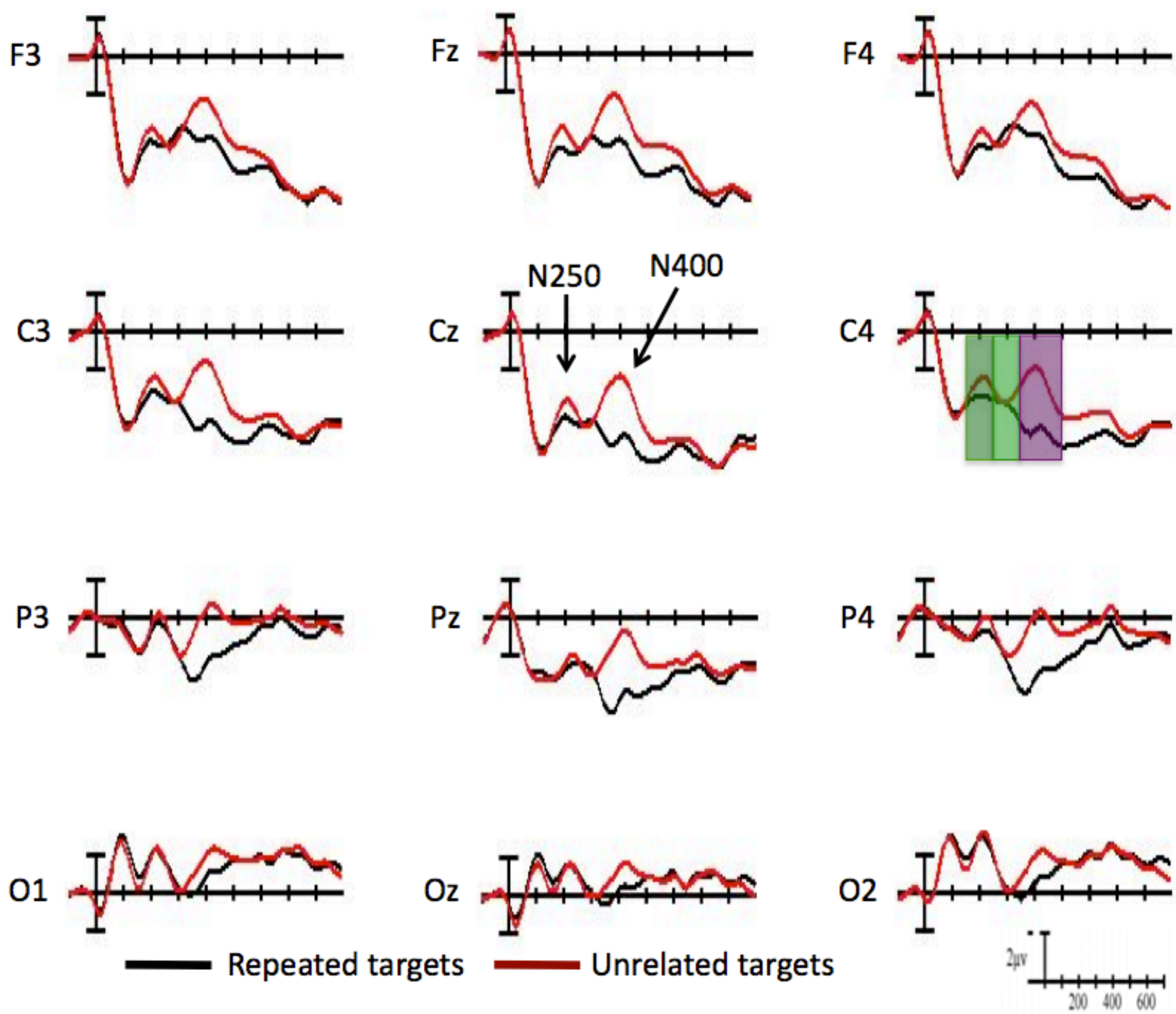

Figure 3. Adult ERPs from 12 electrode sites for repeated (black) and unrelated (red) targets, collapsed across prime durations. Arrows indicate the two ERP components of interest and colored bars at site C4 indicate the time windows used to measure the early N250 (dark green), late N250 (light green), and N400 (purple) effects.

Multiple Regression Results. Multiple regression analysis was used to test if adult participants' performance on tests of orthographic ability significantly predicted the size of their early N250 effect at electrode sites Cz and Pz (150-250 ms – see Figure 4). However, the results of the model were not significant (*p's* > .7). The late N250 priming effect, which has been related to phonological processing, was not predicted by a model of behavioral phonological tests at either site (*p* > .9). We also investigated whether participants' orthographic performance was predictive of their late N250 priming effect, but once again the effect was not significant (*p's* > .3).

The masked priming effect in the N400 window was unrelated to measures of lexical access and semantic knowledge in proficient adult readers (*p's* > .2). However, at the Pz site, the results of the regression indicated the three predictors in the reading fluency model explained 49% of the variance (R^2=.490, $F(3,16) = 4.17$, $p = .028$ – at Cz the model was marginal, $p = .068$). At Pz, sight word reading efficiency significantly contributed to predicting the size of the N400 priming effect (ß = .854, $p = .004$). Pseudoword decoding efficiency ($p = .500$) and sentence reading fluency ($p = .140$) were nonsignificant. Sight word reading ($p = .021$) and sentence reading fluency ($p = .037$) both contributed to the model at Cz. Age and task accuracy did not correlate with masked priming effect size in any of the epochs.

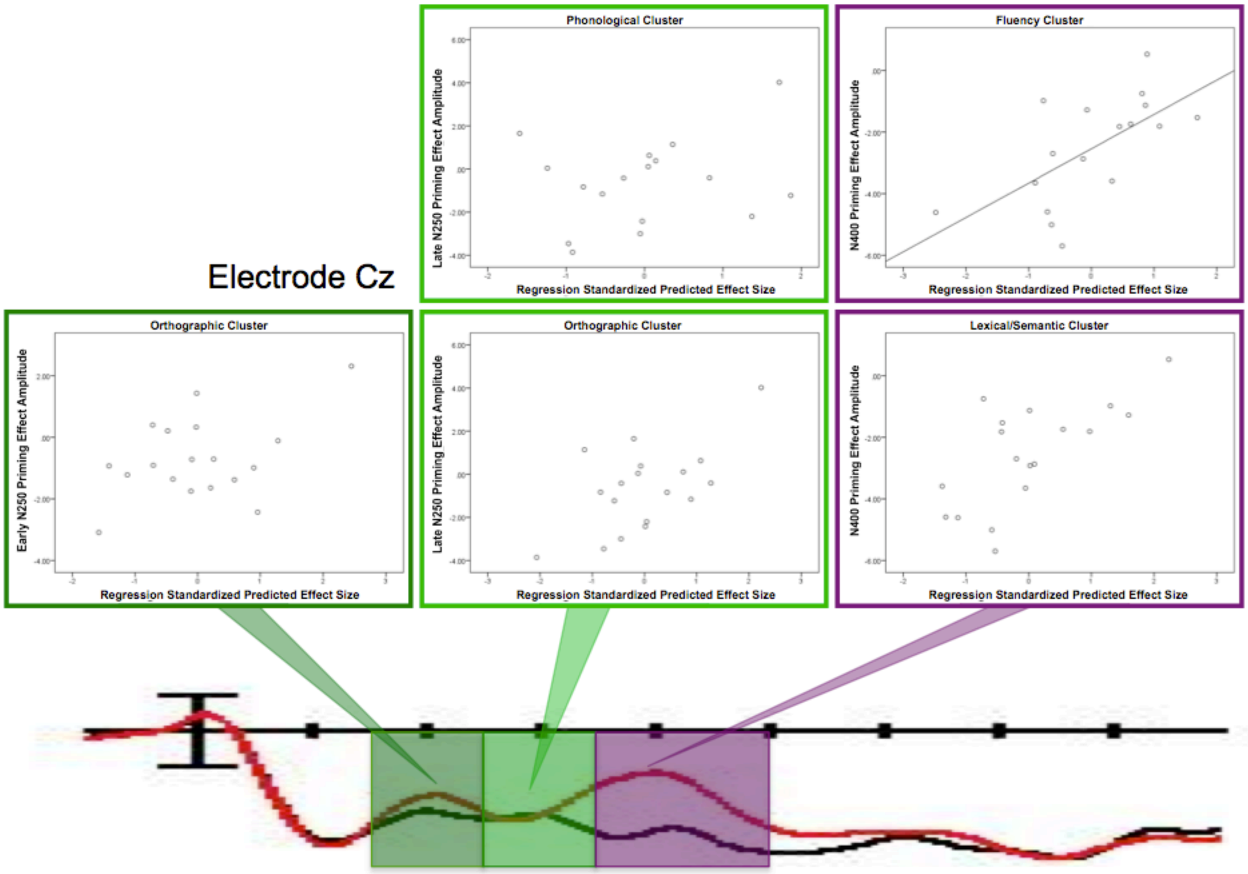

Figure 4. Scatter plots represent the relationship between the regression models' predicted effect size at site Cz and the actual amplitude of the priming effect. Only the reading fluency test cluster was able to significantly predict ERP effect size (in the N400 [purple] time window).

Experiment 2

In Experiment 2, we investigate these same ERP effects in two groups of children – beginning readers (7- to 9-years-old) and newly proficient readers (10- to 12-years-old) to investigate the differences that may occur developmentally during this age range and how these neural measures are related to reading ability across this sample. We predict that children will show both N250 and N400 priming effects, with the N250 effect showing developmental change across these ages, whereas the N400 will be relatively stable across age. We expect priming in the early N250 time window to be related to standardized tests of orthographic ability, the late N250 to be related to phonological ability, and the N400 to be related to lexico-semantic ability and perhaps reading fluency.

Methods

Participants. Seventeen beginning readers (8 female, 9 male) ages 7-9 (*M* = 8.41, *SD* = .86 years) and 18 newly proficient readers (13 female, 5 male) ages 10-12 (*M* = 11.33, *SD* = .83 years) were included in the group analyses of children's ERP repetition priming effects. Participants had normal or corrected to normal vision, and no history of language, reading, or neurological disorders. The TOWRE sight word and phonemic decoding subtests and the WRMT-R word ID and word attack subtests were used to screen participants for severe reading difficulties. Al participants had standard scores above 85 on these tests. Parental reports indicated that all participants were native English speakers who were not fluent in any other languages. All but one participant were right-handed.

To maximize the variability of the sample, 6 additional children were included in the regression analyses. Two of these additional children were 6 years of age and four were between the ages of 8 and 10, but had some history of reading difficulties. All children included in this analysis had a standard score of 85 or higher on at least three of these four subtests. These children included 2 females and 4 males and entire sample of children included in the regression averaged an age of 9.67 years (*SD* = 1.78) and met all of the other screening criteria used for participants in the group analyses.

Parents and children provided informed consent/assent and children received gift cards as compensation for their participation.

Behavioral testing. Children were administered all behavioral tests that were standardized for their age. Tests were not given if they interfered with a child's regular school testing schedule or if the results were not valid because of recent participation in another research study. In these cases, the most recent scores from the previous 6 months were used, if available. In place of the Word choice subtest (ages 13+), the age-appropriate Homophone Choice subtest of the Test of Orthographic Competence (TOC) was administered to all children. Additionally, Sight Spelling was only administered for children above the age of 7. All other behavioral testing procedures were identical to those used in Experiment 1.

ERP stimuli and Procedure. Stimuli, procedures, and experimental task were identical to those used in Experiment 1. Stimuli words were selected to be especially high frequency and easily recognizable to beginning readers, (average first grade frequency of 571 occurrences per million) while still being common in adult corpora. This semantic categorization task has been successfully used with 6-year-olds in previous ERP research (Coch & Holcomb, 2003).

EEG Recording. For the children, EEG was recorded from 61 scalp sites (10-20 system positioning – see Figure 5.), a vertical eye channel for detecting blinks, a horizontal eye channel to monitor for saccades, and two additional electrodes affixed the mastoid bone. Recording procedures were identical to those used for the adults.

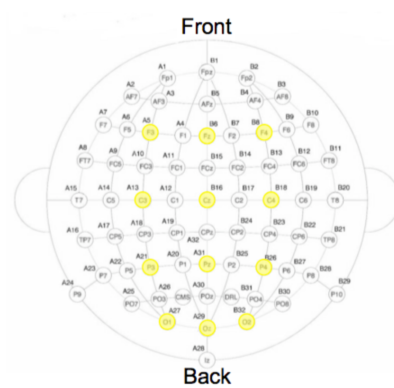

Figure 5. Electrode montage used for children. Sites marked in yellow, corresponding to those measured in adults, were used to analyze ERP effects

Data Analysis. The same 12 sites used in the adult sample were used for all data analyses (F3, Fz, F4, C3, Cz, C4, P3, Pz, P4, O1, Oz, O2). Mixed-model analysis of variance included the same within-subject condition and topographical factors, but also included the between-group factor of age group to compare between younger and older children for each of the three time windows (early N250, late N250, and N400). We followed up on these results with planned repeated measure ANOVAs for each of the two age groups, using the same within-subject factors as the adult analysis. All other analysis procedures were identical to those used in Experiment 1. Time course analyses were used to qualitatively compare the timing of priming effects for each age group, and are presented separately.

Multiple Regression Analysis. Behavioral test clusters were updated to include the age-appropriate tests for all children. Only children who had scores for all tests in a given cluster were included in regression analyses. All other analysis procedures were identical to those in Experiment 1 multiple regression analysis.

Results

ERP Results. Below the ERP results for children for the two ages groups included in this experiment (7-9 and 10-12 years). A mixed-model ANOVA was used to look for group differences between younger and older children in the early N250, late N250, and N400 time windows. Planned follow-up comparisons analyzed the distribution of priming effects for each age group separately.

Early N250 epoch (150-250 ms). The early N250 showed a main effect of priming (F(1,33) = 21.12, p < 001). As can be seen in Figure 6, the priming effect was largest over anterior and right hemisphere sites (priming x anterior posterior: F(3,99) = 9.30, p < .001; priming x anterior/posterior x hemisphere: F(6,198) = 3.02, p = .017). However, the priming effect did not significantly interact with age group (p = .793) or prime duration (p = .409). This was because the pattern of effects was similar for both the younger, 7- to 9-year-old readers (priming: F(1,16) = 6.88, p = 018; priming x anterior posterior: F(3,48) = 6.10, p = .005) and the older, 10- to 12-year-old readers (priming: $F(1,17) = 25.99$, $p < 001$; priming x anterior posterior: $F(3,51) = 3.09$, $p = .060$; priming x anterior/posterior x hemisphere: $F(6,102) = 3.05$, $p = .023$).

Late N250 epoch (250-350 ms). Developing readers also showed a significant priming effect in the late N250 time window, that was largest over anterior sites (priming: $F(1,33) = 34.32$, $p < .001$; priming x anterior/posterior: $F(3,99) = 5.94$, $p = .005$– see Figure 6). The size of the priming effect did not differ by age group ($p = .947$) as both the younger (priming: $F(1,16) = 11.19$, $p = 004$; priming x anterior posterior: $F(3,48) = 4.92$, $p = .015$) and older (priming: $F(1,17) = 34.12$, $p < 001$) readers showed similar priming effects in this time window.

N400 epoch (350-500 ms). The masked priming effect in the N400 time window was largest over centro-parietal sites (priming: $F(1, 33) = 28.60$, $p < .001$; priming x anterior/posterior: $F(3, 99) = 5.36$, $p = .007$– see Figure 6). Once again, the size of the priming effect did not differ by age group ($p = .935$) with both younger children (priming: $F(1,16) = 10.43$, $p = 005$; priming x anterior posterior: $F(3,48) = 3.17$, $p = .055$) and older children (priming: $F(1,17) = 20.85$, $p < 001$; priming x anterior posterior: $F(3,51) = 3.17$, $p = .073$) showing nearly identical distributions of effects across the N400 time window.

Task accuracy. Children detected approximately 3/4 of the animal probe items that were presented in the target position in both the 7- to 9-year-old ($M = 21.29$ out of 30, $SD = 5.90$) and 10- to 12- year old ($M = 24.93$ out of 30, $SD = 5.82$) groups. However, they were far less accurate at identifying animal primes (7-9: $M = 3.35$ out of 10, $SD = 6.77$, $p < .001$; 10-12: $M = 5.50$ out of 10, $SD = 7.59$; $p < .001$).

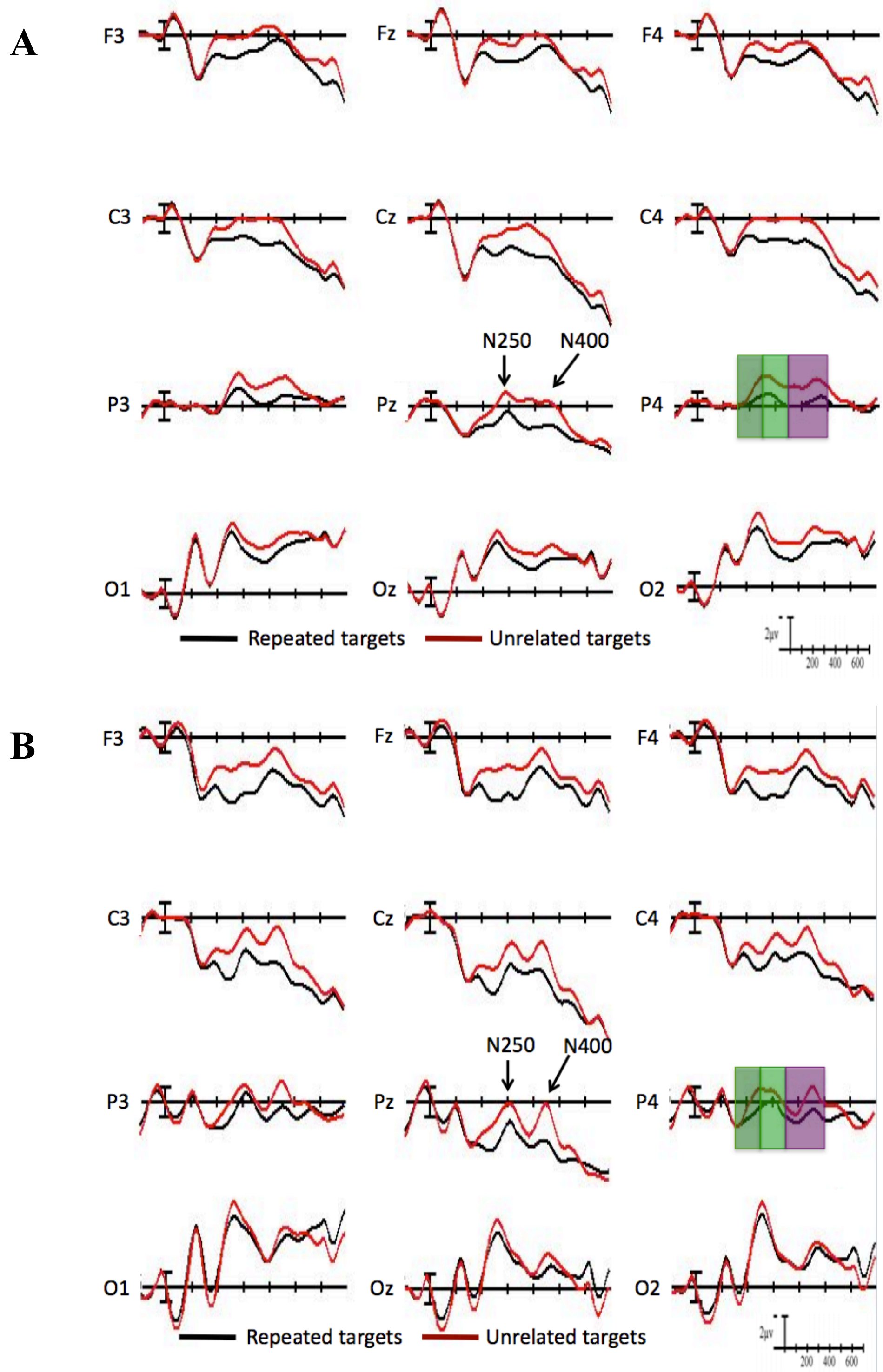

Figure 6. Children ages 10-12 (Panel A) and 7-9 (Panel B). ERPs from 12 electrode sites for repeated (black) and unrelated (red) targets, collapsed across prime durations. Arrows indicate the two ERP components of interest and colored bars at site P4 indicate the time windows used to measure the early N250 (dark green), late N250 (light green), and N400 (purple) effects.

Multiple Regression Results. Multiple regression analysis was used to test if the size of the early N250 in developing readers was predicted by their performance on tests requiring skilled orthographic processing (see Figure 7). The results of the regression indicated the subset of orthographic tests predicted 36.7% of the variance in the size of the early N250 priming effect at electrode Cz ($R^2 = .367$, $F(5,28) = 2.67$, $p = .048$). It was found that sight word reading fluency (ß = -.953, $p = .035$), rapid number naming (ß = .793, $p = .015$), and rapid letter naming (ß = -1.575, $p = .002$) significantly predicted effect size. Differentiating homophones ($p = .220$) and sight spelling ($p = .233$) were non-significant. At Pz, the results were similar, with sight spelling (ß = -.346, $p = .050$), rapid number naming (ß = .816, $p = .013$), and rapid letter naming (ß = -1.263, $p = .011$), but not differentiating homophones ($p = .126$) or sight word reading fluency ($p = .093$) contributing significantly to the model ($R^2 = .371$, $F(5,28) = 2.71$, $p = .045$). Surprisingly, the size of the late N250 was not predicted by our phonological skills model (*p's* > .371). Instead, we found that the size of the late N250 priming effect was related to *orthographic* ability at both site Cz ($R^2 = .387$, $F(5,28) = 2.91$, $p = .035$) and site Pz ($R^2 = .374$, $F(5,28) = 2.754$, $p = .043$) with the rapid naming subtests contributing significantly (*p's* < .05).

The N400 priming effect was related to the children's' lexical and semantic abilities. The multiple regression analysis showed that these subtests predicted 45% of the variance in these children's N400 priming effects ($R^2 = .457$, $F(6,26) = 2.81$, $p = .038$) only at site Cz (Pz: $p = .133$). Rapid letter (ß = -1.496, $p = .003$) and number (ß = 1.199, $p = .008$) naming were predictive within the model, but the other coefficients were not (sight word reading: ß = -.437, $p = .141$; receptive vocabulary: ß = -.292, $p = .193$; differentiating homophones: ß = .370, $p = .119$; sight spelling ß = -.072, $p = .669$). The N400 effect in children was not predicted by participants' reading fluency (*p's* > .5). Age and task accuracy did not correlate with masked priming effect size in any of the epochs.

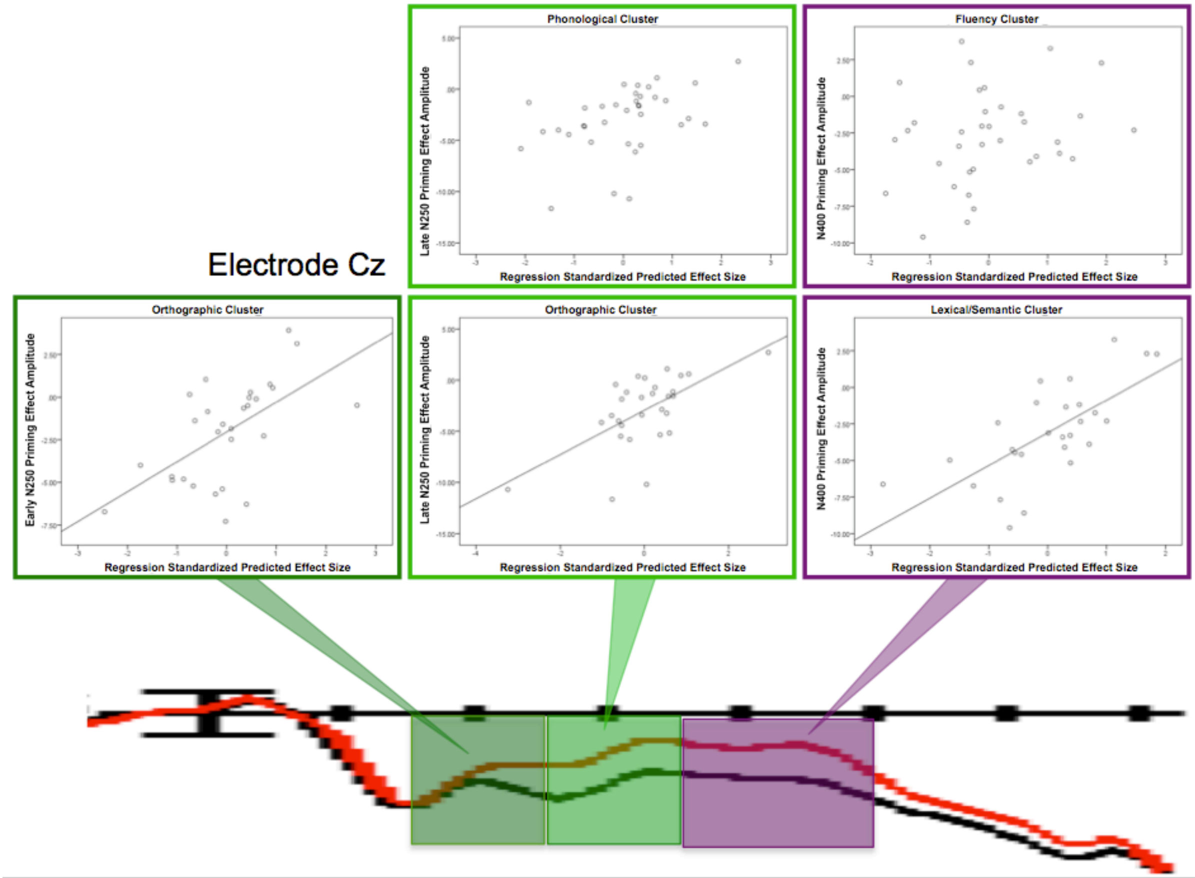

Figure 7. Scatter plots represent the relationship between the regression models' predicted effect size at site Cz and the actual amplitude of the priming effect. The orthographic test cluster significantly predicted both the early (dark green) and late (light green) N250 effect size. The lexical/semantic cluster predicted the N400 (purple) effect size.

Time-Course Analyses

To investigate the timing of priming effects in beginning, newly proficient, and fluent adult readers, we performed time-course analyses in 50 ms increments from 100 ms to 600 ms after the target word was presented (see Figure 8). Since the priming effect did not interact with prime duration for any of the age groups (Experiments 1 and 2), we collapsed across the three prime durations.

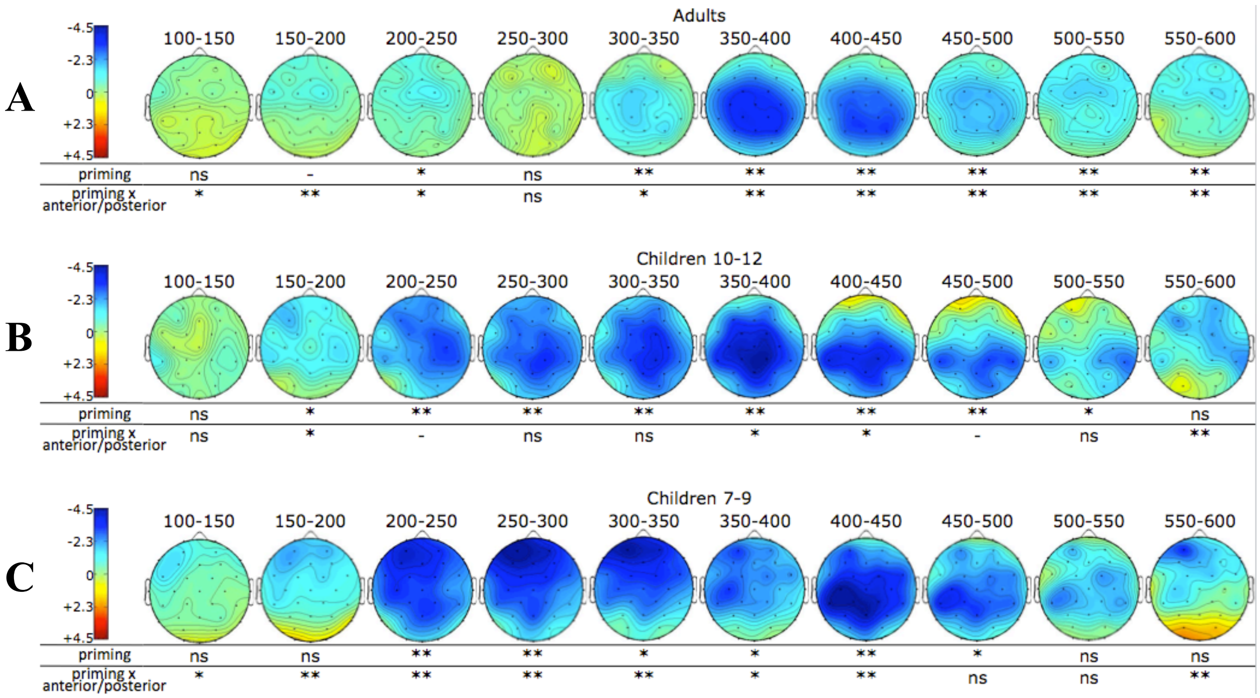

Figure 8. Time-course analyses of the priming (unrelated-repeated) effect for consecutive 50 ms bins for adults (Panel A), 10-to 12-year-old children (Panel B), and 7- to 9-year-old children (Panel C). Significance levels are designated as follows: ns = p > .1; – = .05 < p < .1; * = .01< p < .05; ** = p < .01.

Adults show their first significant priming effect from 150-200 ms at anterior sites (priming x anterior/posterior: $F(1, 17) = 6.49$, $p = .006$). This effect becomes more widely distributed from 200-250 ms (priming: $F(1, 17) = 6.30$, $p = .023$). Adults did not show any priming effects in the 250-300 ms window, but their N400 effect begins from 300-350 ms (priming: $F(1, 17) = 9.09$, $p = .008$, with large, widespread effects lasting for the rest of the N400 time window (all *p's* < .01). The full time course of these effects is summarized in Figure 8A.

The older group of children shows priming effects starting by 150-200 ms and remaining significant across the scalp until the 550-600 ms time window (all *p's* < .04). The younger group of children does not show a significant N250 priming effect until 200-250 ms, but they then show significant priming effects through the 450-500 ms time window (all *p's* < .03). Figures 8B and 8C illustrate these effects for 10- to 12-year-olds and 7- to 9-year-olds, respectively.

Discussion

The current study investigated masked priming effects and their relationship to reading proficiency in both adults (Experiment 1) and children (Experiment 2). Our results are consistent with previous ERP studies showing that both children and adults show N250 and N400 masked priming effects to high frequency words. Our further analyses of reading ability as predictors of ERP priming effect size may better explain how the ERP waveform indexes reading development. Our results also indicate that orthographic knowledge, word-reading ability, and reading fluency, rather than age per se, may account for the development of these components as children learn to read.

N250 Priming Effects

ERP Priming Effects

Consistent with previous research, in the context of an experimental paradigm with only high frequency words adults showed an early but not later N250 priming effect (Eddy, et al., submitted; Mitra, Eddy, Grainger, & Holcomb, in prep; cf. Grainger, et al., 2012). Analysis of the late N250 time window and the time course analysis indicated that the N250 effect in adults lasted only until around 250 ms. We have previously hypothesized that adults' reduced N250 to highly automatic words may be due to a reset mechanism for sublexical processing (Eddy, et al., submitted; Grainger, et al., 2012). The words presented here were all short and extremely high frequency. As our adult participants were all above average readers who had frequently encountered these words since they learned to read, one would expect these words to be highly automatized for the adults. As such, in reading these words, sublexical processing occurred quickly and efficiently and upon completion the hypothesized 'reset' mechanism frees up these processing capabilities for further input.

In contrast, both age groups of children showed large N250 priming effects in the early and late time windows of the epoch analyses, although the time-course analyses suggest that the earliest phase of the N250 started about 50 ms later in the younger children. Other than this onset differences we did not see consistent group differences between our younger and older groups of children. Age group did not interact with the effect of priming at any scalp sites during the epoch analyses of either the early or late N250 time windows. In other words, the size of the priming effect, which we hypothesized serves an index of developing automaticity within the visual word recognition system, did not significantly differ between the two groups. However, the difference in the onset of the early effect suggests that while the underlying reading processes are similar between these two groups there nevertheless are important differences in the timing of these processes.

The time course analyses also indicated that widespread N250 effects may begin somewhat later in the younger, less experienced readers than in fluent adults. This is consistent with previous accounts of ERP components in general and sublexical processing in particular occurring somewhat later in children than in adults (Coch, et al., 2012; Eddy, et al., submitted; Maurer, et al., 2005). The N250 also appears to extend further in time and is larger in amplitude in comparison to the shorter duration and smaller overall effect seen in adults.

Brain-Behavior Relationships

One possible explanation for the lack of overall amplitude differences between groups may lie in the fact that many of the children in our sample were reading above the average proficiency level for their age. As a result, chronological age may be an inadequate proxy for reading experience and ability within our sample. The standardized tests administered to our participants allowed us to disentangle the effects of reading ability on the ERP waveform from those of chronological age.

Early N250. The early N250 time window is known for indexing orthographic processing (Grainger, et al., 2006). However, adults did not show any relationship between orthographic ability and the early N250 priming effects. Our adults were all highly proficient and fluent readers and the words presented in the ERP experiment were all short and high-frequency. Due to the simplicity of the single-word stimuli, one would expect the adults to all be very efficient at reading these words. The subtle differences in adults' orthographic and phonological abilities were not reflected in the highly automatic processing seen in the N250 time window. In contrast, our developing readers have far less expertise in orthographic processing. Children's performance on the orthographic cluster of tests significantly predicted the early N250 priming effect, suggesting that the size of the priming effect is indeed related to behavioral performance although no single behavioral test alone is sufficient to explain the differences neural processing seen during this time window. Thus, when the orthographic forms of the words are less automatized, developing readers show a relationship between their orthographic skills and the size of the N250 priming effect. This is consistent with the finding that children's reading scores relate to transposed-letter priming effects in the early N250 time window, but adults' scores do not (Eddy, et al., in prep).

Late N250. The late N250 time window is known to index phonological processing in adults (Grainger, et al., 2006). Adults did not show any relationship between phonological or orthographic ability and late N250 priming effects. Again, this may be explained by participants' high degrees of expertise for the words and the resulting automaticity of sublexical processing for all of the adults. Alternately, ubiquitous high performance on some of the behavioral tasks may render these competency clusters ineffective at capturing the variability in our adults' phonological abilities.

For developing readers, many of whom may still somewhat rely on phonological strategies, we expected that phonological skills may be more closely related to later N250 priming effect. However, the phonological cluster of tests did not predict the children's late N250 priming effect. Instead, the late N250 priming effect was also predicted by the orthographic cluster of tests. Specifically, both the RAN letters and RAN numbers subtests both significantly contributed to the model. This result is rendered somewhat less surprising when considering the behavioral and neural changes that occur within this age group as novice readers begin to develop reading proficiency. As discussed above, we know that developing readers may show somewhat later orthographic processing and delayed reading-related ERP components, as compared with fluently reading adults. Previous work has focused heavily on the relationship between novice reader's orthographic knowledge and ERP effects in the first 300 ms of processing (Brem, et al., 2005; Maurer, et al., 2005; Maurer, et al., 2006). This is supported by our own findings that the N250 effect starts somewhat later in our youngest readers. As a result, orthographic ability may predict the size of the priming effect in the late N250 window because orthographic processing extends into this window for some or all of the developing readers.

An increased reliance on orthographic information is also consistent with our lab's findings that faster RAN naming speeds were associated with larger orthographic (i.e., transposed-letter) priming effects and with smaller phonological (i.e., pseudohomophone) priming effects (Eddy, et al., submitted). Another possibility is that the current repetition priming paradigm, which maximizes orthographic overlap between the prime and target, may minimize the influence of phonological processing. A paradigm that emphsizes phonological processing may better serve to elucidate the relationship between individual differences in phonological ability and ERP priming effects. Future work will explore the relationship between reading proficiency and automatic sublexical processing by further differentiating orthographic and phonological effects in the N250 time window.

N400 Priming Effects

ERP Priming Effects

In contrast to the N250, adults showed a long, widespread N400 priming effect, significant throughout the N400 time window, indicating robust activation of lexico-semantic information for these highly frequent words. As expected, this effect was widespread across the scalp, with the largest effects seen at centro-parietal sites. This is consistent with previous work showing that high-frequency words elicit particularly large N400 priming effects in fluent adult readers (Grainger, et al., 2012).

Children also showed large N400 priming effects across the scalp. As in adults, these effects were largest over centro-parietal sites. The size of N400 priming effect did not differ between the younger and older children. Comparison of the time-course analyses suggest that the N400 in children with less overall exposure to these words did not differ from adults who are more familiar with these words. All three groups show robust effects of priming across the N400 epoch. This indicates that our groups of proficient developing readers engaged similar lexico-semantic processes for words that were high-frequency in an elementary school corpora.

Brain-Behavior Relationships

Participants' behavioral performance on standardized reading measures once again provide insight into the individual variance see in N400 priming effect amplitude, that cannot be captured by traditional group analyses. Once again, chronological age was not related to differences in priming effect size, which were similar across all three age groups. Instead patterns of neural responses were shown to be related to measures of reading proficiency.

The N400 indexes lexico-semantic processing. However, as one might expect due to highly automatized processing of these frequent words in adults, there was no relationship between adults' lexico-semantic abilities and their N400 priming effects. However, reading fluency, despite adults' uniformly high skill level, predicted variance in the size of the N400 priming effect for adults.

In the children, the lexico-semantic cluster of behavioral tests significantly predicted the size of the N400 priming effects. In contrast to the adults, the fluency cluster did not predict N400 priming effects in the children. This dissociation between accuracy of lexico-semantic knowledge and fluency predicting the amplitude of the N400 priming effect at different ages may be due to the nature of reading development. As fluent reading builds on a foundation of accurate reading (Wolf & Katzir-Cohen, 2001), our children and adult readers' abilities are not distributed evenly along this continuum of reading skill. Rather, the adults have quite high accuracy and fluency, while the children, who are less accurate as a group, are not well represented in the higher fluency range.

These findings are consistent with previous work, using a variety of word reading paradigms, which show that word reading accuracy and lexical access are related to individual differences in N400 amplitude in children who are still learning to read (Bakker, Van Strien, Licht, & Smit-Glaudé, 2007; Coch & Holcomb, 2003; Coch, et al., 2012; Eddy, et al., in prep; Henderson, et al., 2011). However, few studies have investigated associations between adults' reading accuracy and the N400 and any such relationship may be limited to samples including poor readers (Landi & Perfetti, 2007). As discussed, we did not necessarily expect to see this relationship in our highly accurate adult readers. Rather, we saw a relationship between the N400 priming effects and reading fluency, consistent with previous findings that reading efficiency and the N400 are correlated in adults (Coch & Mitra, 2010; Eddy, et al., in prep). The relationship between reading efficiency and the N400 seems to be less widespread in children (Coch, et al., 2012; Eddy, et al., in prep), which may be due to the heterogeneity and overall lower reader fluency in these samples. Together these findings may suggest that early development of the N400 is closely tied children's increasing experience with lexical and semantic information, but as readers become more proficient these same processes subserve the development of fluent reading.

Conclusions

When presented with simple, high-frequency words, both children and adults show N250 and N400 masked repetition priming effects. These priming effects are remarkably similar across the three age groups studied here. The findings suggest that the maturation associated with chronological age has comparatively little effect on the size of masked priming effects in word recognition from the early elementary school years. Instead, the size of these priming effects is most sensitive to the development of reading proficiency. In developing readers, orthographic ability predicted the size of the N250 priming effect; whereas word-form and semantic knowledge predicted the size of the N400 effect. Even in adults who are highly skilled readers, the N400 priming effect is still related to their reading fluency. ERP masked priming paradigms may provide a measure of the development of automatic reading ability that is related to, but not entirely captured by simple behavioral measures of reading skill.

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