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Masked priming and ERPs dissociate maturation of orthographic and semantic components of visual word recognition in children

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Abstract

This study examined the time-course of reading single words in children and adults using masked repetition priming and the recording of event-related potentials. The N250 and N400 repetition priming effects were used to characterize form- and meaning-level processing, respectively. Children had larger amplitude N250 effects than adults for both shorter and longer duration primes. Children did not differ from adults on the N400 effect. The difference on the N250 suggests that automaticity for form processing is still maturing in children relative to adults, while the lack of differentiation on the N400 effect suggests that meaning processing is relatively mature by late childhood. The overall similarity in the children's repetition priming effects to adults' effects is in line with theories of reading acquisition, according to which children rapidly transition to an orthographic strategy for fast access to semantic information from print.

Descriptors: Reading development, N250, N400, Event-related potentials (ERPs), Masked priming

Learning to Read

Learning to read, unlike learning to speak, requires formalized training to establish the relationship between spoken and written word forms. Once acquired, reading words can be conceptualized as occurring in two interactive stages: processing of form and processing of meaning. Form-level processing involves the mapping of visual features onto whole-word form representations via intermediary representations such as letters and phonemes. Meaning-level processing, on the other hand, involves the mapping of whole-word form representations onto semantics, and establishing relations between semantic representations. Given that the end goal of reading is the extraction of meaning from print, the optimization of this process should aim to economize on form-level processing in order to focus on meaning. Indeed, a substantial body of research (Grainger & Holcomb, 2009) using electrophysiological measures has demonstrated that, in skilled adult readers, form-level processing during single word reading is rapid and short-lived, while word-level semantic processing occurs later and is relatively long-lived (e.g., Holcomb & Grainger, 2007).

From a developmental perspective, children in their early elementary school years start out with relatively good semantic knowledge about words that are already part of their spoken language vocabulary, but are still in the process of optimizing the association of the unfamiliar printed forms of words with familiar sounds and meaning. This suggests that children who are learning to read, but not yet adultlike in reading proficiency, might be less efficient in processing form-level information compared with meaning-level information. In order to test this hypothesis, as well as to better characterize the temporal dynamics of word processing in beginning readers in general, we recorded event-related potentials (ERPs) during a masked repetition priming paradigm in children, ages 8 to 12, and a comparison group of skilled young adult readers.

Masked Priming

For almost three decades, masked priming has been used to examine both form and meaning processing during visual word recognition in adults. The logic of this paradigm is that if two words are presented at very short intervals, processing of the first (prime) item will overlap with and therefore influence processing of the second (target) item (see Kinoshita & Lupker, 2003). A few behavioral studies have used masked priming in children, and the primary finding is that priming effects seem to be modulated by grade level with larger effects in higher grades (e.g., Acha & Perea,

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2008; Castles, Davis, Cavalot, & Forster, 2007). One possibility for such changes is a shift to increasingly automatized orthographic processing during reading acquisition, combined with a decline in the use of the slow and effortful process of phonological recoding (the sequential translation of letters into their corresponding sounds; e.g., Grainger & Ziegler, 2011). However, while children may rapidly shift from phonological recoding, there is evidence that at least some aspects of orthographic processing develop more slowly to become automatized and adultlike (Grainger, Lété, Bertrand, Dufau, & Ziegler, 2012). Behavioral measures alone make it difficult to untangle the differential contributions of multiple processes on single word reading.

In adults, masked priming has been used to associate different ERP effects with specific stages of visual word recognition (reviewed in Grainger & Holcomb, 2009). ERP priming effects of particular interest for the current study are a middle latency component (the N250) that reflects mapping of sublexical orthographic information onto whole-word representations, and a late component (the N400) that reflects processing at the form-meaning interface whereby word-based form information is mapped onto meaning with larger N400s for less efficient mappings (Holcomb & Grainger, 2007). Repetition suppression or a reduction in activity due to overlap between a target and a prime has been suggested to be a marker for increased processing efficiency (Grill-Spector, Henson, & Martin, 2006). Smaller N250 and N400 responses have been associated with more efficient (faster or more accurate) behavioral responses, including faster responses related to facilitation from repetition priming (reviewed in Grainger & Holcomb, 2009). Thus, smaller magnitudes of the N250 and N400 responses appear to be electrophysiological indices of more efficient form and meaning analyses, respectively, of printed words.

In addition to being sensitive to orthographic overlap between a prime and a target, the N250 is modulated by word frequency, such that larger N250 effects are observed for low-frequency than high-frequency words. This frequency effect is thought to reflect the engagement of a reset mechanism used to suppress activity in form representations once a unique word-form has been identified during normal sentence reading (Grainger, Lopez, Eddy, Dufau, & Holcomb, 2012). In a masked priming paradigm, a reset mechanism operates on the output of prime-driven processing only when the prime is processed efficiently enough to be identified as a separate event from the following target. This is more likely to occur with high-frequency words than low-frequency words, hence the influence of word frequency on N250 priming effects.

Present Study

The current study applied the combination of masked priming and ERPs in order to differentially examine form-level (N250) and meaning-level (N400) processing in children relative to adults. Children reading at or above grade level and skilled reading adults were presented with repeated pairs (table-TABLE) or unrelated pairs (space-TABLE) of words while performing a go/no-go semantic categorization task so that no participant saw the same word twice, but across counterbalanced lists each word appeared in every possible position. The critical trials were no-go trials, so that brain responses would reflect typical reading processes rather than atypical categorization responses. High-frequency words were used to minimize age differences that simply reflected vocabulary gains. Because it is unknown how long primes need to be presented to produce robust ERP priming in developing readers, two different prime durations were employed (107 ms and 53 ms), while holding the stimulus onset asynchrony (SOA) constant, as studies have shown that differences in SOA influence priming effects (Holcomb & Grainger, 2007; Grainger, Lopez et al., 2012).

It was hypothesized that, because of still developing automaticity in processing orthographic form, children who are still learning to read would reveal a larger N250 priming effect than more skilled adult readers. Further, if the reset mechanism in children is slower, then children ought to exhibit an extended priming effect relative to adults. The extension of priming effects would be due to the prolonged activation of form-level representations. Manipulation of prime duration allowed us to examine how rapidly the form reset mechanism operates in children relative to adults. For high-frequency words in adults, this reset mechanism comes into play relatively quickly (Grainger, Lopez et al., 2012). If children have a slower reset mechanism for form-level processing (leading to extended activation of form-level representations), then they may exhibit priming over longer prime durations than adults (whereas adults' reset mechanism operates faster and leads to reduced priming effects at longer durations). Therefore, we predicted that children would show priming effects at both shorter and longer prime durations, whereas adults may only show effects at the shorter duration on the N250 component. In contrast, it was hypothesized that, because of their well-established ability to comprehend meaning in spoken language, developing readers and skilled adult readers would show a similar pattern of N400 priming effects for printed words.

Table 1. *Means and Standard Deviations of Standard Scores for Children*

Test	Mean	*SD*	*N*
KBIT-2—Matrices	121	13.0	17
TOWRE—Sight word efficiency	111	11.5	17
TOWRE—Phonemic decoding efficiency	112	11.1	17
CTOPP—Elision	11.8	2.0	17
CTOPP—Blending	11.1	2.2	17

Method

Participants

Table 1 summarizes the means and standard deviations of standard scores for the children in the current study.[1] The participants were 18 children (mean = 9.75, *SD* = 1.48 years; range 8–12, 9 males) and 18 adults (mean = 21.5, *SD* = 2.2 years; range 18–26 years, 10 males). Data from three additional children were collected, but were not included due to excessive artifacts. All were native English speakers with normal or corrected-to-normal vision. None had reading difficulties or other diagnoses. The adults all reported being good readers with no history of reading deficits. Children were good readers (parent report), which was verified by two reading skill tests: Test of Word Reading Efficiency (TOWRE), which measures timed single word reading, and the Comprehensive Test of Phonological Processing (CTOPP), which measures phonological processing. Nonverbal intelligence (Kaufman Brief Intelligence Test, 2nd ed., KBIT-2—Matrices) subtest was also normal. All participants were compensated for participation.

1. Scores were available for all but one child on the standardized behavioral tests. Note that the mean for all tests is well above average.

Materials

The critical stimuli consisted of 240 three- to five-letter, open-class, English words selected to be easily recognizable by beginning readers with a mean first grade frequency of 571 occurrences per million (Zeno, Ivens, Millard, & Duvvuri, 1995) while still being common in adult corpora with mean frequency of 388 occurrences per million (Kucera & Francis, 1967). 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 (40), the same word was presented in the prime and target positions (repeated condition), and in the other half, two different unrelated words were paired (unrepeated condition). Each word was presented in only one trial and was 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 and the other half in target position (30 appeared in the prime position, 30 in the target position).

Procedure

Participants sat in a sound attenuated, dimly lit room where words were presented in the center of the screen time-locked to the vertical refresh rate of the monitor (75 Hz) for one of two durations: 53 ms or 107 ms. The two durations of presentation were pseudorandomly presented (intermixed together with no more than three occurrences of a condition in a row). The prime word was preceded by a 500-ms forward mask (#######) and followed by a backward mask (#######). The target word was presented immediately after the backward mask in uppercase letters for 500 ms. The prime-target SOA was held constant by varying the duration of the backward mask (67 or 13 ms). Participants were instructed to blink during the time between trials (2.5 s) and performed a go/no-go semantic categorization task (see below).

Participants performed a go/no-go semantic categorization task where they were instructed to press a button on a game pad any time they saw an animal word (noncritical trials). Accuracy was emphasized over speed of response. For trials with nonanimal words (i.e., critical trials), no response was required. A description of what constituted an animal word was given to participants, and they practiced until they understood how to correctly perform the task. This task engaged the participant in semantic processing of words (mimicking silent reading for meaning), but did not require a response for critical trials, thereby allowing the ERPs to be uncontaminated by motor movements and atypical categorization processes.

EEG Recording

A BioSemi ActiveTwo System (BioSemi B.V., Amsterdam, The Netherlands) using active Ag-AgCl electrodes mounted on an elastic cap (Electro-Cap, Inc.) was used to collect electroencephalogram (EEG) from 32 (adults) or 64 (children) scalp sites (10–20 system positioning). Vertical and horizontal eye channels were used to monitor for eye artifacts, and two mastoid electrodes were averaged offline and served as the reference. The EEG was recorded at 512 Hz sampling rate and filtered offline between 0.16–20 Hz. Average ERPs time-locked to target onset were formed for repeated and unrepeated trials (−50 to 50 ms baseline), and trials containing eye blinks, eye movements, muscle artifact, or other types of artifact such as movement were removed prior to averaging. The baseline included a small post-target window in order to obtain overlapping waves between conditions; therefore, we extended the baseline into the first 50 ms after target presentation.[2]

Participants with fewer than 25 out of 40 trials for any one condition were excluded. For children, the analysis included on average 32 trials per condition (*SD* = 3.4) for the 53-ms repetition condition, 33.4 (*SD* = 3.9) for the 53-ms unrepeated condition, 32.4 (*SD* = 4.3) for the 107-ms repetition condition, and 32.3 (*SD* = 5.2) for the 107-ms unrepeated condition. For adults, the analysis included 38.5 trials (*SD* = 1.7) for the 53-ms repetition condition, 37.9 (*SD* = 2.04) for the 53-ms unrepeated condition, 38.2 (*SD* = 1.7) for the 107-ms repetition condition, and 38.1 (*SD* = 1.6) for the 107-ms unrepeated condition. While children and adults did differ in the number of trials included in the average, we used mean amplitude measurements that should not be affected by slight differences in the number of trials per condition (Luck, 2005).

Data Analysis

Following previous masked ERP priming studies, we analyzed data from the following 12 sites: F3, Fz, F4, C3, Cz, C4, P3, Pz, P4, O1, Oz, O2. Mean amplitude measurements were taken between 200–325 ms (N250 epoch), and 350–500 ms (N400 epoch). Mixed design analyses of variance (ANOVAs) including the within-subjects factors of duration (53 ms vs. 107 ms), repetition (repeated vs. unrepeated), anterior-posterior electrode position (4 rows reflecting anterior to posterior gradient), and laterality (left vs. middle vs. right) as well as the between-subjects factor of group (adult vs. child) were used. To test specific predictions made in the introduction, we also ran a limited set of planned (a priori) follow-up comparisons breaking down Group × Repetition and Repetition × Duration interactions on the N250 epoch. In addition, given our a prior predictions, we also compared the groups on Repetition Effects × Duration. The Geisser and Greenhouse (1959) correction was applied to all repeated measures having more than one degree of freedom.

Results

Behavioral Results

Participants in both age groups detected the majority of the 30 probe words in the target position (92% on average), although the adults were more accurate (mean = 97%) than the children (mean = 87%, $t(34) = 3.72$, $p = .001$). In the prime position, both groups detected fewer of the animal probe words, especially at the shorter prime duration (children, 19% at 53 ms and 28% at 107 ms; adults, 62% at 53 ms and 83% at 107 ms), although overall adults detected more of these items, $t(34) = 5.53$, $p = .000003$.

Event-Related Potentials

Figure 1 illustrates the main findings for children and adults for the N250 and N400 effects.

N250 epoch (200–325 ms). During the N250 epoch, there was a main effect of repetition, $F(1,34) = 31.57$, $p = .00001$, $\eta_p^2 = .4814$,

2. We tried both pre- and post-target baselines and found that the baseline including some post-target time worked better at lining up the ERPs in the early part of the target ERP; note that we ran analyses with both baselines and found similar patterns of effects.

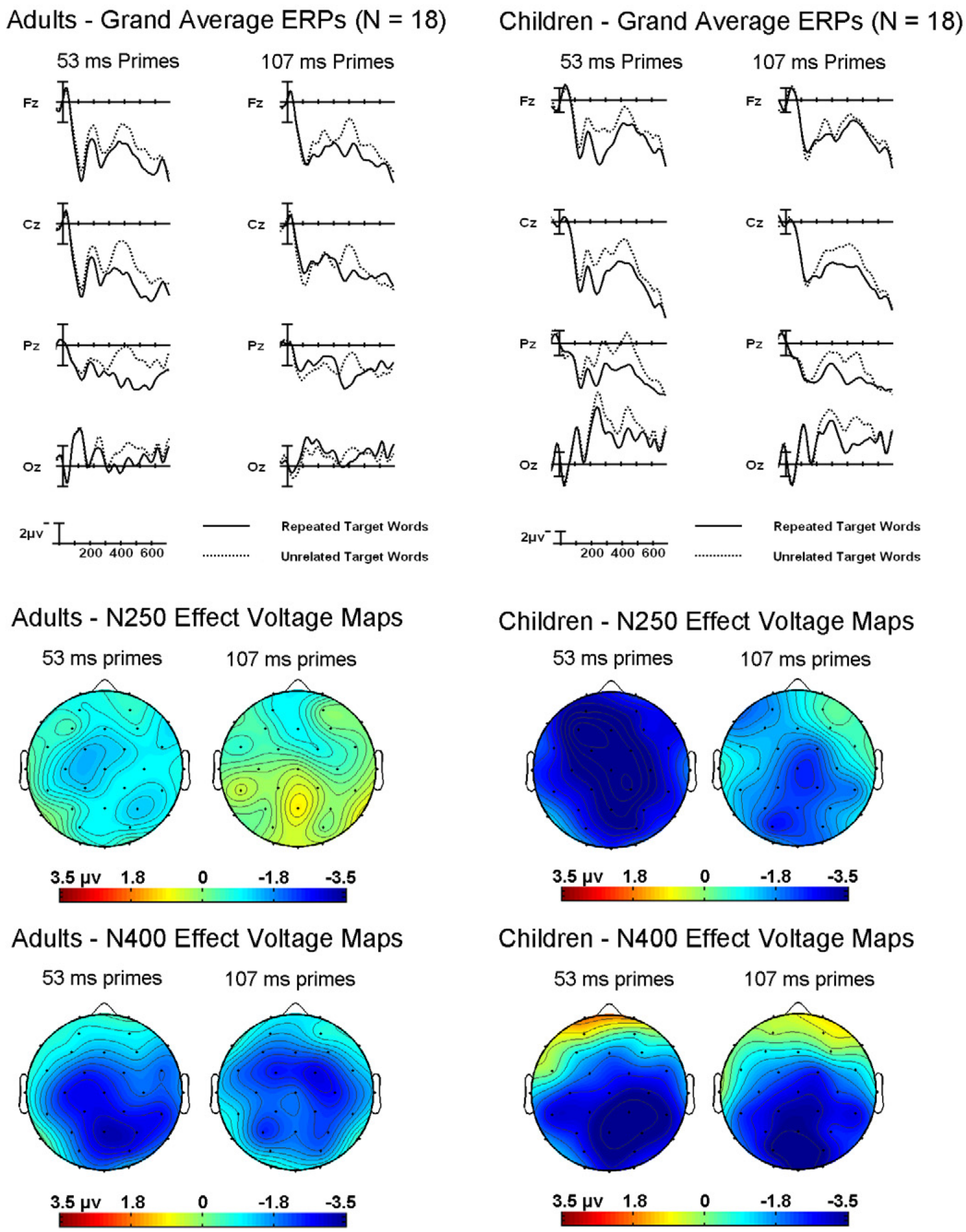

Figure 1. Grand average ERPs and voltage maps. Top left: ERP waveforms for adults. Bottom left: Voltage maps for adults. Top right: ERP waveforms for children. Bottom right: Voltage maps for children. Note the difference in scale between the adults' and children's ERP waveforms due to overall larger ERPs in the children. Voltage maps are on the same scale and reflect unrepeated minus repeated voltage differences.

reflecting a more negative-going amplitude for unrepeated targets relative to repeated targets. In addition, there were differences in the repetition effect between the two groups (Repetition × Group interaction: $F(1,34) = 15.74$, $p = .0004$, $\eta_p^2 = .3165$). Planned follow-up comparisons to examine the Repetition × Group interaction revealed, when examining repetition effects for each group separately, that there was a significant priming effect for the children across the two durations, $F(1,17) = 28.96$, $p = .00001$, $\eta_p^2 = .6301$, but the adults only showed a trend towards a significant priming effect, $F(1,17) = 3.29$, $p = .0872$, $\eta_p^2 = .1623$. There was also a Repetition × Duration interaction across the two groups, $F(1,34) = 4.18$, $p = .0486$, $\eta_p^2 = .1096$.

Planned follow-up comparisons examining repetition effects for each of the durations separately revealed larger priming effects for the shorter duration, $F(1,34) = 19.07$, $p = .0001$, $\eta_p^2 = .359$; mean amplitude of priming effect = −1.96 µV, relative to longer duration, $F(1,34) = 9.1$, $p = .0048$, $\eta_p^2 = .211$; mean amplitude of the priming effect = −.827 µV. Although there was not a significant Group × Repetition × Duration interaction, we predicted that the adults and children would differ in priming effects between the two durations. Therefore, we performed planned comparisons on the priming effects for the short and longer durations for adults and children separately. These comparisons revealed only significant priming effects for the adults at the short prime duration (short duration:

$F(1,17) = 6.58$, $p = .02$, $\eta_p^2 = .279$; long duration: $p > .99$), whereas children showed priming effects at both durations (short duration: $F(1,17) = 13.65$, $p = .0018$, $\eta_p^2 = .445$; long duration: $F(1,17) = 11.05$, $p = .004$, $\eta_p^2 = .394$). Both groups had significant priming effects at the 53-ms prime duration, but children had larger priming effects than adults for the 53-ms condition—comparing size of priming effect (unrepeated–repeated), main effect of group: $F(1,34) = 6.45$, $p = .016$, $\eta_p^2 = .159$, mean amplitude of priming effect $= -3.1$ μV for children; mean amplitude of priming effect $= -.82$ μV for adults. Children, but not adults, showed a priming effect at the longer prime duration (107 ms), with children having significantly larger priming effects at this duration—comparing mean amplitude of priming effect (unrepeated–repeated) for the 107-ms condition between groups (main effect of group: $F(1,34) = 9.14$, $p = .005$, $\eta_p^2 = .212$, mean amplitude of priming effect $= -1.66$ μV for children; mean amplitude of priming effect $= .001$ μV for adults.

N400 epoch (350–500 ms). The overall ANOVA during the N400 epoch produced a main effect of repetition, $F(1,34) = 35.52$, $p = .00001$, $\eta_p^2 = .512$, with unrepeated targets showing a larger negativity than repeated targets. This effect was present at both durations and in both groups, as Figure 1 illustrates the lack of any interaction involving the group, duration, and repetition variables (all ps $> .44$). There were, however, interactions between repetition and anterior-posterior electrode position and between repetition and laterality (Repetition × Electrode position: $F(3,102) = 6.32$, $p = .0024$, $\eta_p^2 = .16$; Repetition × Laterality: $F(2,68) = 4.28$, $p = .024$, $\eta_p^2 = .11$). These interactions reflect the typical central-posterior distribution of the N400, as can be seen in the voltage maps in Figure 1.

Discussion

We found a developmental dissociation for visual processing of words between adults and children such that there was a developmental difference on an ERP component indexing form-level processing, the N250, but no developmental difference on another ERP component indexing meaning-level processing, the N400. The enhanced N250 effect in children suggests that developing readers between 8 and 12 years old have less efficient form-level analysis for visual word recognition, which may reflect lesser automatization of early-stage orthographic processing. Overall, the developmental differences occurred in the context of a quite similar pattern of ERP responses in adults and children across the scalp, allowing for form- and meaning-level contributions to word processing to be distinguished.

N250 Effect

The N250, thought to index form processing, was immature in children (different than adults) in that children had larger N250 effects than adults overall. When examining the groups separately, as we predicted, children produced N250 effects that were significant at both short and long prime durations, whereas adults only showed significant effects for the shorter prime duration (although there was not a significant three-way interaction). The clear presence of an N250 effect in the children is consistent with prior behavioral findings that relatively automatic, parallel orthographic processing is performed by children in the age range tested in the present study (Acha & Perea, 2008; Castles et al., 2007; Grainger, Lété et al., 2012).

The electrophysiological differences in children are also consistent with previous behavioral findings indicating that form-level processing is still developing throughout elementary and middle school (Castles et al., 2007; Grainger, Lété et al., 2012). The extended N250 effect in children may reflect less efficient processing of orthographic information that prevented operation of the kind of reset mechanism thought to be responsible for diminished N250 repetition priming effects with high-frequency compared to low-frequency words in adults (Grainger, Lopez et al., 2012). In adults, the reduced N250 for high-frequency prime words is thought to be due to efficient processing that enables partial suppression of form representations (but not meaning representations) activated by the prime stimulus prior to processing target words. The efficiency of this reset mechanism in adults was demonstrated in the present study by presence of the N250 effect after a 53-ms prime, but an absence of the N250 effect after a 107-ms prime. For the children, less efficient and more extended orthographic processing of the same prime words led to a reduction or absence of engaging this reset mechanism resulting in N250 priming effects at both prime durations. The fact that the N250 was observed at the longer prime duration for children, but not adults, suggests this reset mechanism is not yet fully developed in the children. Future studies that manipulate frequency, word familiarity, orthographic neighborhood size, and other factors related to efficiency of visual word recognition may help further clarify the specific process underlying the N250 effects observed in the current experiment.

N400 Effect

The N400 component, thought to index the mapping of whole-word form representations onto semantic representations, was mature in children in that there were no significant differences between adults and the children. The lack of a difference between children and adults in the current study suggests that the processes underlying these priming effects have already developed in the youngest children that were tested in the present study. In addition, consistent with the idea that semantic effects are longer lived than form-level effects, the N400 effect was observed in the longer prime duration condition in both children and adults. Indeed, previous research suggests that the N400 emerges a few months after the first year of life to spoken words, and children as young as kindergarten exhibit adultlike N400s for spoken words (e.g., Coch, Maron, Wolf, & Holcomb, 2002; Friedrich & Friederici, 2004; Hahne, Eckstein, & Friederici, 2004). The present study indicates that children ages 8–12 exhibit adultlike N400s for high-frequency printed words.

Summary

These findings indicate that the most significant changes at the level of single-word recognition that arise during the course of reading acquisition are more closely related to orthographic (and possibly phonological) processing as opposed to the processing of semantic information. This could be attributed to the fact that children begin to learn to read with an already established system for mapping phonological forms, from spoken words on to semantics. These same semantic representations continue to be exploited during reading comprehension, but orthographic representations must be established from scratch. Therefore, N400 effects would be expected as soon as the beginning reader has the means to convert a string of letters into some form of sublexical phonological representation and make contact with familiar whole-word phonological representations and their associated meanings, especially since the words used in the current experiment were all of high frequency and familiar to the children. The N400 here is interpreted in the context of single monomorphemic words of relatively high frequency. These high-frequency words were used to match performance as much as possible between the adults and children. However, with more complex semantic processing involving multiple words or morphologically complex words that a child is less familiar with, N400 effects could continue to develop beyond the age range of children tested in the present study (e.g., Holcomb, Coffey, & Neville, 1992).

The developmental ERP findings for reading print were found in the context of a go/no-go experimental design. Such a design is often associated with response inhibition processes (in particular the no-go N2) that also develop with age, but it seems unlikely that response inhibition was relevant for the major findings in the present study because the critical contrasts between repeated and unrepeated prime-target pairs and between prime-target durations held response inhibition constant within each participant.

Conclusions

The findings in this study suggest a developmental dissociation between neural systems supporting orthographic and semantic processing of words. Children ages 8–12 exhibited a clear N250 effect, suggesting that they have already established a system for parallel orthographic processing in reading with some level of orthographic automaticity. This processing, however, appears to be still developing in such children, as reflected by increased amplitude of the N250 priming effect compared with adults. The enhanced N250 effect in children may reflect less efficient orthographic processing and an inability to disengage rapidly from form-level representations. In contrast, the N400 effect was similar in children and adults, suggesting that semantic processes may be developed by ages 8–12 (at least for high-frequency words). These findings are in accord with results from other studies suggesting that developing readers are still fine-tuning orthographic representations, which can lead to changes in orthographic priming with reading experience. In order to separate out the contributions of orthographic and phonological representations on these ERP priming effects, further experiments are needed where orthographic and phonological relationships between prime and target stimuli are explicitly manipulated.

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