ERP Nonword Rhyming Effects in Children and Adults

Donna Coch[1,*], Giordana Grossi[1,], Wendy Skendzel[1], and Helen Neville[1]**

Abstract

■ In a simple prime–target auditory rhyming event-related potential (ERP) paradigm with adults and 6-, 7-, and 8-year-old children, nonword stimuli (e.g., *nin–rin*, *ked–voo*) were used to investigate neurocognitive systems involved in rhyming and their development across the early school years. Even absent semantic content, the typical CNV to primes and late rhyming effect (RE) to targets were evident in all age groups. The RE consisted of a more negative response to nonrhyming targets as compared to rhyming targets over posterior sites, with a reversal of this pattern at lateral anterior sites. The hypothesis that the CNV indexes phonological memory processes was not well supported by correlation analyses conducted with the ERP measures and scores on standardized behavioral tests. However, the onset of the rhyming effect was later in those scoring lower on phonological awareness measures. ■

INTRODUCTION

Over the past few decades, a small number of event-related potential (ERP) studies conducted with adults have investigated rhyme processing using real word stimuli. In the visual modality, when a pair of words (prime–target) is presented and the task involves making a phonemically based judgment, a consistent electrophysiological rhyming effect (RE) is observed (Rugg & Barrett, 1987; Rugg, 1984a, 1984b; Sanquist, Rohrbaugh, Syndulko, & Lindsley, 1980). This RE begins 250–300 msec after target onset, peaks at about 400–450 msec, is distributed maximally across midline and right temporo-parietal sites, and consists of a substantially larger negative deflection to nonrhyming as compared to rhyming targets. In addition to the RE for targets, a contingent negative variation (CNV) to primes largest over anterior left hemisphere sites has been reported (Rugg & Barrett, 1987; Rugg, 1984a, 1984b). In the auditory modality, a similar RE with an earlier onset and more symmetrical distribution has been observed for spoken word pairs (Dumay et al., 2001; Radeau, Besson, Fonteneau, & Castro, 1998; Perez-Abalo, Rodriguez, Bobes, Gutierrez, & Valdes-Sosa, 1994; Praamstra, Meyer, & Levelt, 1994; Praamstra & Stegeman, 1993). Targets spoken in a different voice than primes elicit this effect, confirming that the RE is not simply an index of physical–acoustic mismatch, but rather of phonological processing (Praamstra & Stegeman, 1993).

Recently, similar results have been reported in children and adolescents in both the visual and auditory modalities (Weber-Fox, Spencer, Cuadrado, & Smith, 2003; Coch, Grossi, Coffey-Corina, Holcomb, & Neville, 2002; Grossi, Coch, Coffey-Corina, Holcomb, & Neville, 2001; McPherson, Ackerman, Holcomb, & Dykman, 1998; Lovrich, Cheng, & Velting, 1996; Ackerman, Dykman, & Oglesby, 1994). In the visual modality, both the RE and the CNV were observed in 7- to 23-year-olds (Grossi et al., 2001). The latency and distribution of the RE were consistent across age groups while the frontal left-greater-than-right asymmetry of the CNV to primes increased with age (Grossi et al., 2001). For the same group of participants tested in the auditory modality, the size, distribution, and latency of the RE were again constant across age groups, but the amplitude of the CNV decreased until the late teens (Coch et al., 2002). Together, these results imply that different aspects of the rhyming process involve different neurocognitive systems, and that these systems have different developmental time courses.

Behaviorally, numerous studies have identified various dissociable aspects of phonological processing, including encoding in working memory and rhyme awareness. Phonological short-term memory may be specific to learning the phonological structure of new words (Gathercole, 1999), a process that occurs within the articulatory loop used for rhyme judgments by fluent and beginning readers (Arthur, Hitch, & Halliday, 1994; Baddeley & Hitch, 1994; Hitch, Halliday, & Littler, 1993; Baddeley, Lewis, & Valler, 1984). Theoretically, performance of an auditory rhyme task involves automatic registration of information from the speech code in the phonological input store, engagement of processes of phonemic segmentation and deletion while the information is retained within the articulatory loop, direct

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[1] University of Oregon
[*] Now at Dartmouth College
[**] Now at State University of New York at New Paltz

comparison of word-ending sounds, and execution of a decision and response (Baddeley et al., 1984). Behaviorally, phonological encoding in working memory is related to vocabulary knowledge and reading ability and has been targeted for intervention in cases of language impairment (Avons, Wragg, Cupples, & Lovegrove, 1998; Gillam & van Kleeck, 1996; McDougall, Hulme, Ellis, & Monk, 1994; Gathercole, Willis, & Baddeley, 1991). Electrophysiologically, it has been proposed that the CNV indexes retention or rehearsal of phonological information in working memory (Ruchkin, Johnson, Grafman, Canoune, & Ritter, 1992; Rugg, 1984b). However, in our previous ERP studies with children, there was no correlation between the amplitude of the CNV to primes and a behavioral proxy for working memory capacity (digit span) after controlling for age (Coch et al., 2002; Grossi et al., 2001).

Across behavioral studies, including longitudinal and cross-cultural studies, there is some agreement that phonological awareness (PA), a sensitivity to the sound structure of language, is one of the best predictors of progress in learning to read and variance in reading skills (McBride-Chang & Kail, 2002; Sénéchal & LeFevre, 2002; Wagner, Torgesen, & Rashotte, 1994; see Wagner & Torgeson, 1987 for a review). Rhyme awareness, one aspect of PA, has also been shown to be independently related to vocabulary and reading skills (Avons et al., 1998; Cronin & Carver, 1998; Wood & Terrell, 1998; Goswami, 1993; Bryant, MacLean, & Bradley, 1990; Bradley & Bryant, 1983; Byrne & Shea, 1979). Electrophysiologically, the RE may index the process of phonological mismatch or the awareness of nonrhyme (Coch et al., 2002; Grossi et al., 2001; Rugg, 1984b). However, in our previous ERP studies with children, there were no correlations between weak proxies for PA (reading and spelling scores from a standardized test) and the size of the RE after controlling for age (Coch et al., 2002; Grossi et al., 2001).

Most previous ERP rhyming studies with children have used real word stimuli, de facto including the potentially confounding factor of semantics (but cf. Ackerman et al., 1994; Taylor, 1993). Recent reports suggest that phonological effects tend to be occluded by semantic effects on the N400 in adults (Perrin & García-Larrea, 2003). Moreover, a number of neuroimaging studies with adults have documented the separable yet interacting effects of phonology and semantics by comparing activations to real word and nonword visual stimuli (Simos, Breier, Fletcher, Foorman, Castillo, et al., 2002; Henson, 2001; Simos, Breier, Fletcher, Foorman, Mouzaki, et al., 2001; Xu et al., 2001; Tagamets, Novick, Chalmers, & Friedman, 2000; Poldrack et al., 1999; Pugh et al., 1996). Visual and auditory ERP studies with adults employing nonword stimuli in a rhyming paradigm report the typical RE (Praamstra & Stegeman, 1993; Rugg, 1984a), and one reading study with children also reported a RE that was similar to real and nonsense words (Ackerman et al., 1994). In a recent auditory study, a typical RE was reported in preschoolers and beginning readers in a lexical decision task with nonword primes (Bonte & Blomert, 2004). In the present study with adults and 6- to 8-year-old children, we used auditory nonwords (e.g., *nin-rin*, *ked-voo*) in a simple prime–target rhyming ERP paradigm to directly investigate neurocognitive systems involved in auditory phonological matching and their development across the early school years. In addition, the children underwent standardized testing that specifically measured PA and phonological memory so that we could test the hypotheses that the CNV to primes is an index of working memory, while the RE to targets indexes PA or mismatch.

RESULTS

Behavioral Testing Results

Children were administered the core subtests of the Comprehensive Test of Phonological Processing (CTOPP, Wagner, Torgesen, & Rashotte, 1999) and selected subtests of the Woodcock Reading Mastery Tests—Revised (WRMT-R, Woodcock, 1987). Percentile rank scores for the PA and phonological memory composites from the CTOPP and standard scores for the Letter Identification, Word Identification, and Word Attack subtests of the WRMT-R are summarized in Table 1 for each age group. All scores on these composites and subtests were within normal limits.

Table 1. Behavioral Testing Results for 6-, 7-, and 8-Year-Olds[a]

Group	*CTOPP Phonological Awareness*	*CTOPP Phonological Memory*	*WRMT-R Letter ID*	*WRMT-R Word ID*	*WRMT-R Word Attack*	*CMMS*
6	77.5 (20.8)	74.0 (16.2)	110.5 (7.5)	117.6 (13.2)	114.5 (10.1)	79.5 (16.9)
7	68.9 (25.8)	64.5 (25.5)	99.9 (7.1)	113.4 (14.2)	117.1 (14.1)	74.5 (19.6)
8	68.1 (22.3)	61.6 (25.6)	100.3 (13.2)	109.9 (12.6)	112.7 (14.7)	79.0 (20.2)

Standard deviations are in parentheses.

[a] CTOPP and CMMS scores are percentile ranks, whereas WRMT-R scores are standard scores.

CTOPP measures of PA and phonological memory tended to correlate with one another ($p = .07$), while PA was correlated with letter identification ($r = .33$, $p < .05$), word identification ($r = .59$, $p < .001$), and word attack ($r = .59$, $p < .001$) skills and phonological memory was correlated with word identification ($r = .37$, $p < .01$) and word attack ($r = .50$, $p < .001$) measures. The three WRMT measures were also correlated with one another (letter identification and word identification, $r = .51$, $p < .001$; letter identification and word attack, $r = .28$, $p < .05$; word identification and word attack, $r = .80$, $p < .001$). The only measure that correlated with age was score on the WRMT Letter Identification subtest ($r = -.37$, $p < .01$).

Child participants were divided into two groups based on median scores on the PA index of the CTOPP; the high (mean 91.0, *SD* 5.18) and low (mean 51.8, *SD* 15.8) groups were significantly different in terms of scores [$t(50) = 12.1$, $p < .0001$] but not in terms of age [$t(50) = -1.2$, $p = .25$]. Children were also divided into two groups based on median scores on the phonological memory index of the CTOPP; these groups were not completely overlapping with the PA groups. Groups based on phonological memory scores (high: mean 84.8, *SD* 9.1; low: mean 45.3, *SD* 14.6) were also different in terms of score [$t(50) = 12.0$, $p < .0001$] but not in terms of age [$t(50) = -.51$, $p = .62$].

All scores on the Columbia Mental Maturity Scale (CMMS, Burgemeister, Blum, & Lorge, 1972) were also within normal limits. Percentile rank scores did not vary across the three groups of children ($p = .70$). Means and standard deviations for each group are summarized in Table 1. CMMS percentile rank was not significantly correlated with any other behavioral measure except accuracy in identifying rhymes during the ERP task ($r = .38$, $p < .01$).

ERP Task Behavioral Results

Accuracy of rhyme and nonrhyme responses during the ERP task for each group is plotted in Figure 1, in which it is clear that accuracy of responses to rhymes and nonrhymes varied by group [Condition × Group, $F(3,64) = 4.4$, $p < .01$]. All three groups of children were more accurate at identifying nonrhyming pairs, while adults were equally accurate at identifying rhyming and nonrhyming pairs. In follow-up comparisons by condition, accuracy was similar across groups for rhymes ($p = .10$, with a trend for adults to be more accurate than younger participants), but not nonrhymes [$F(3,64) = 3.8$, $p = .015$]. In paired comparisons, the 6- and 7-year-old groups ($p = .77$) and 7- and 8-year-old groups ($p = .18$) were similarly accurate at identifying nonrhymes, while 8-year-olds were more accurate in identification of nonrhymes than adults [$t(31) = 2.6$, $p = .022$].

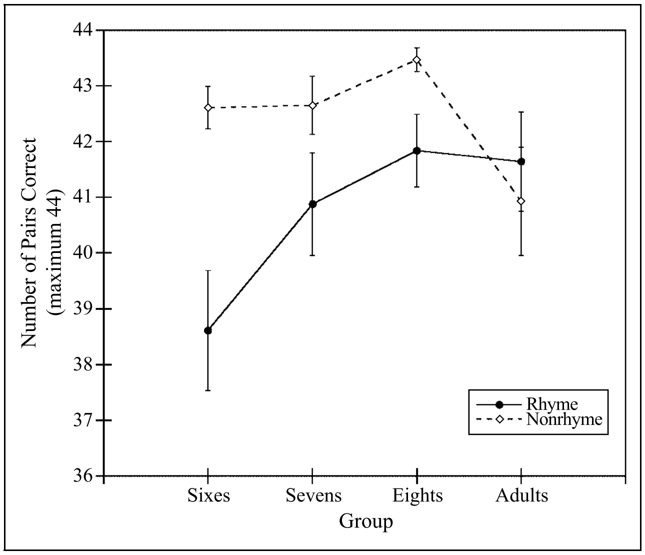


Figure 1. Accuracy on the rhyme/nonrhyme judgment task used during the ERP session for each group. Maximum number correct for rhyming pairs (rhyme) and nonrhyming pairs (nonrhyme) was 44. Children, but not adults, were more accurate at identifying nonrhymes than rhymes. Children were more accurate than adults in identification of nonrhymes, with a trend for the opposite pattern with rhymes.

ERP Results

CNV to Primes

In analyses of nonnormalized mean amplitude data, CNV amplitude varied by group [$F(3,64) = 5.5$, $p < .01$], necessitating normalization procedures to investigate developmental effects. While the amplitude of the CNV across the three groups of children was not significantly different (6 vs. 7: $p = .58$; 7 vs. 8: $p = .41$; 6 vs. 8: $p = .16$), the children as a group had larger CNVs than the adults [$F(1,66) = 14.0$, $p < .001$; see Figure 2].

In analyses of normalized mean amplitude data, overall across groups, the CNV was largest at the right hemisphere, lateral, posterior sites [Hemisphere × Anterior/Posterior × Lateral/Medial, $F(5,320) = 8.5$, $p < .001$]. However, the distribution of the CNV varied by group such that for adults the CNV was relatively evenly distributed across the anterior/posterior scalp, particularly across sites anterior to the occipitals, while for children, the CNV was largest posteriorly, particularly at lateral sites [Anterior/Posterior × Lateral/Medial × Group, $F(15,320) = 2.3$, $p < .05$; see Figure 3]. Thus, children as compared to adults evidenced a smaller fronto-temporal and temporal CNV and a larger occipital CNV.

An average measure of CNV mean amplitude across the three most posterior rows (refer to Figure 4), where the CNV was largest in children, did not correlate with CTOPP phonological memory scores ($p = .12$), nor Woodcock word identification scores ($p = .68$); neither did an average measure of CNV amplitude across the three most anterior rows ($p = .36$ and $p = .91$,

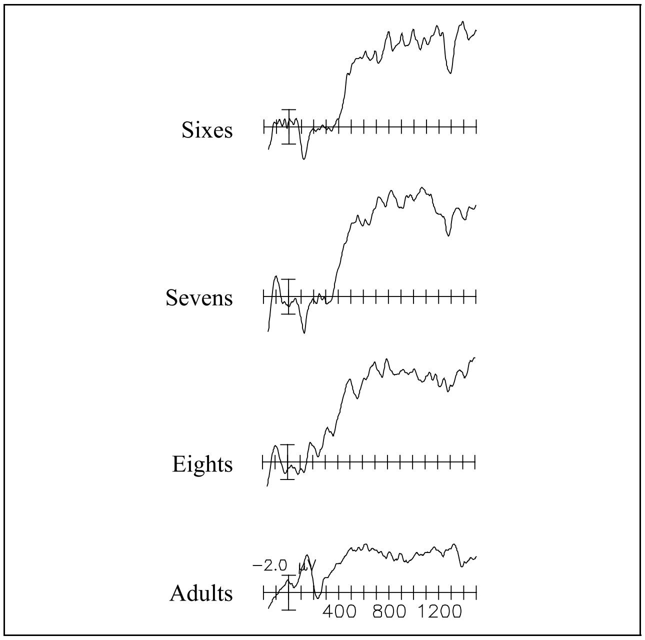


Figure 2. ERP waveforms for each age group at site CT6 illustrating the larger size of the CNV in children as compared to adults.

respectively). A median split of children into those scoring high on the CTOPP phonological memory index and those scoring low yielded no differences between groups in CNV amplitude across the three most posterior ($p = .33$) or anterior ($p = .54$) rows.

Onset of the RE

Analyses were conducted for consecutive 20-msec epochs between 0 and 500 msec in order to temporally locate the onset of the RE for each group; significant effects involving condition in three consecutive epochs were taken to indicate onset of an RE within the first epoch.

For adults, an effect of condition onset during the 300–320 msec epoch (Condition × Hemisphere, Condition × Hemisphere × Lateral/Medial, Condition × Anterior/Posterior × Lateral/Medial, all $p < .05$; Condition × Anterior/Posterior, $p < .01$) and continued through the subsequent epochs (320–340: Condition × Hemisphere, Condition × Anterior/Posterior, Condition × Lateral/Medial, all $p < .05$; 340–360: Condition × Hemisphere, $p < .05$).

For 8-year-olds, an effect of condition onset considerably later, during the 480–500 msec window (Condition × Anterior/posterior, $p < .05$), and continued through the 500–520 (Condition × Anterior/Posterior, $p < .05$) and 520–540 msec (Condition × Anterior/Posterior, $p < .05$) epochs. Earlier effects starting in the 420–440 and 440–460 msec windows ($p < .05$) were not maintained within the 460–480 msec epoch (all $p \geq .1$).

For 7-year-olds, the RE onset during the 360–380 msec window (Condition × Anterior/Posterior, $p < .05$) and continued into the following windows (380–400 and 400–420 msec: Condition × Anterior/Posterior, both $p < .01$). For 6-year-olds, the RE also began during the 360–380 msec window (Condition × Anterior/Posterior, $p < .05$), and continued into the 380–400 and 400–420 msec windows (Condition × Hemisphere, Condition × Anterior/Posterior, Condition × Lateral/Medial, all $p < .05$).

Dividing the children into two groups based on scores on the PA index of the CTOPP revealed a striking pattern. In the group with higher PA scores, the RE onset during the 320–340 msec time window (Condition × Hemisphere × Lateral/Medial, $p < .05$) and continued into the subsequent epochs (340–360: Condition × Anterior/Posterior, $p < .05$; 360–380: Condition × Anterior/Posterior, $p < .01$). In comparison, the onset of the RE in the low PA group was delayed by 80 msec, with the RE not beginning until the 400–420 msec window (Condition × Anterior/Posterior, $p < .05$) and continuing into the 420–440 and 440–460 msec epochs (Condition × Anterior/Posterior, both $p < .05$).

Amplitude of the RE

In analyses with nonnormalized data, there were no significant condition effects involving group, indicating that the amplitude of the late RE was similar across the four groups. As can be seen in Figures 5 and 6, the typical RE such that nonrhymes were more negative than rhymes was greatest at posterior medial sites, while the reverse pattern—rhymes more negative than nonrhymes—was true at fronto-temporal and temporal lateral sites [Condition × Anterior/Posterior, $F(5,320) = 21.5$, $p < .001$; Condition × Lateral/Medial, $F(1,64) = 7.3$, $p < .01$; Condition × Anterior/Posterior × Lateral/Medial, $F(5,320) = 3.6$, $p < .05$].

Analyses with normalized data further confirmed that the amplitude of the late RE was similar across the four groups, as there were no significant condition effects involving group. Indeed, analyses with normalized data replicated the findings with nonnormalized data [Condition × Anterior/Posterior, $F(5,320) = 47.8$, $p < .001$; Condition × Lateral/Medial, $F(1,64) = 7.9$, $p < .01$; Condition × Anterior/Posterior × Lateral/Medial, $F(5,320) = 5.1$, $p < .01$].

The distribution of the late RE was even more clearly evident in difference waves (see Figure 7). Analyses of difference waves confirmed that neither the mean amplitude ($p = .94$) nor the peak latency ($p = .26$) of the late RE varied by age group. The RE peaked earliest at posterior sites [anterior/posterior, $F(5,320) = 3.9$, $p < .05$].

Measurements of difference wave mean amplitude at P3/4 and FT7/8 correlated with one another ($r = .44$, $p < .001$) but did not correlate with age, CMMS scores,

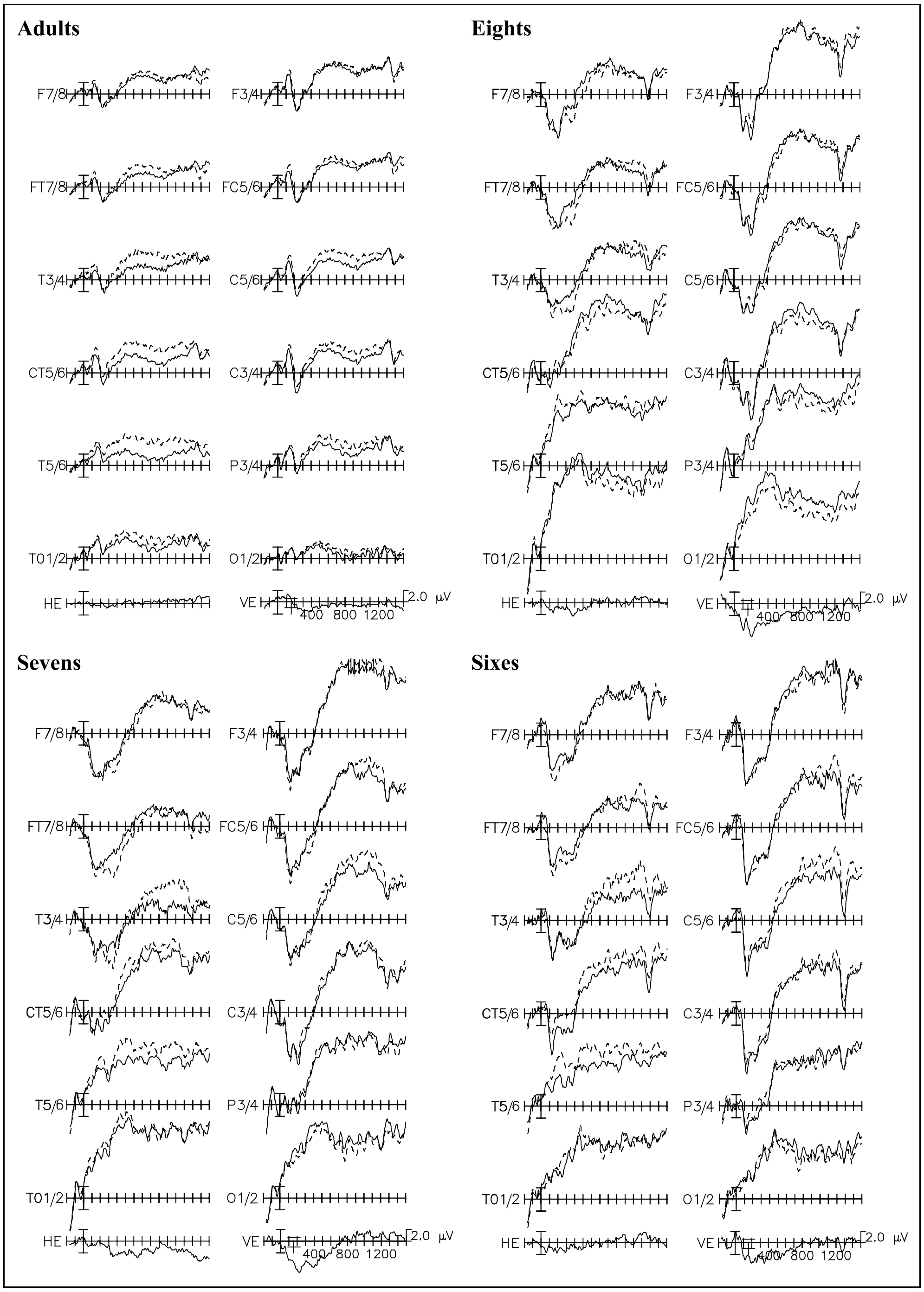


Figure 3. ERP waveforms for each age group showing the CNV elicited by primes. The solid line represents the CNV recorded over left hemisphere sites, while the dashed line represents the CNV recorded over right hemisphere sites. Note the marked CNV in all age groups, with a more posterior distribution in children. Within each age group, lateral sites are in the left column while medial sites are in the right column. VE is an electrode placed beneath the right eye to record blinks and vertical eye movements and HE represents a bipolar recording from the outer canthi of the two eyes. Onset is the vertical calibration bar and negative is "plotted up."

CTOPP PA scores, or Woodcock word identification scores; nor did difference wave peak latency measured across the two most posterior rows.

DISCUSSION

Nonword stimuli (e.g., *nin–rin*, *ked–voo*) were used in a simple ERP auditory rhyming paradigm with adults and 6-, 7-, and 8-year-old children in order to investigate the development of neurocognitive systems involved in rhyming, absent semantic content or context. As previously reported in studies using real word stimuli (Coch et al., 2002; Grossi et al., 2001), both a CNV to primes and a late RE to targets were evident in children and adults in the present study. In addition to the ERP measures, children underwent standardized behavioral testing that specifically measured PA and phonological memory. There was little evidence to support the hypothesis that the CNV to primes indexes phonological

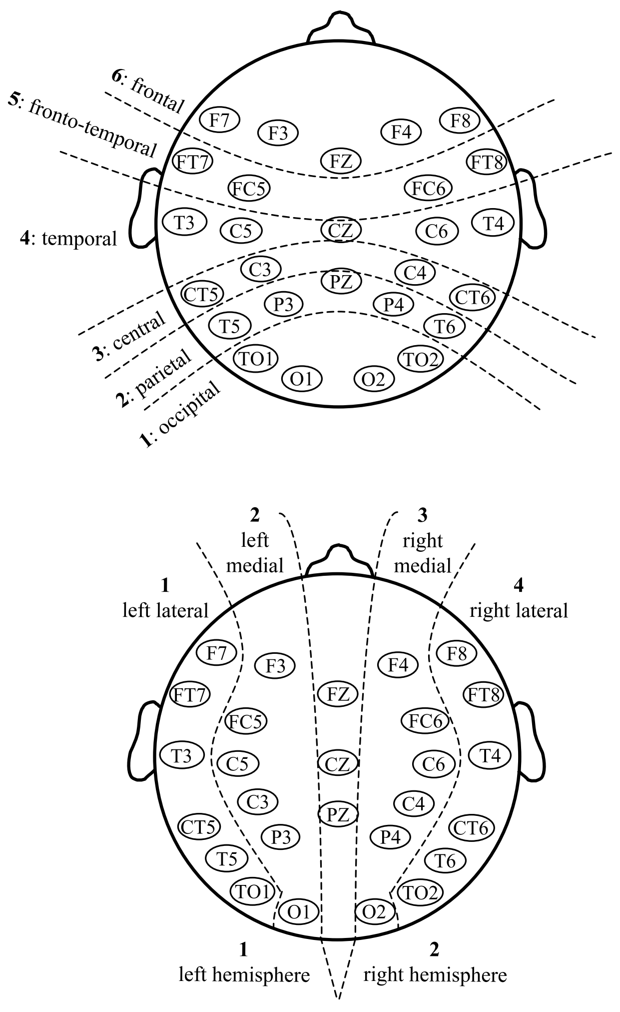


Figure 4. Schematic representation of the electrode montage and the factors used in analyses. At the top, six levels of the anterior/posterior factor are illustrated. At the bottom, two levels of the lateral/medial factor and two levels of the hemisphere factor are indicated.

memory. However, there was evidence that the RE to targets indexes PA.

The CNV

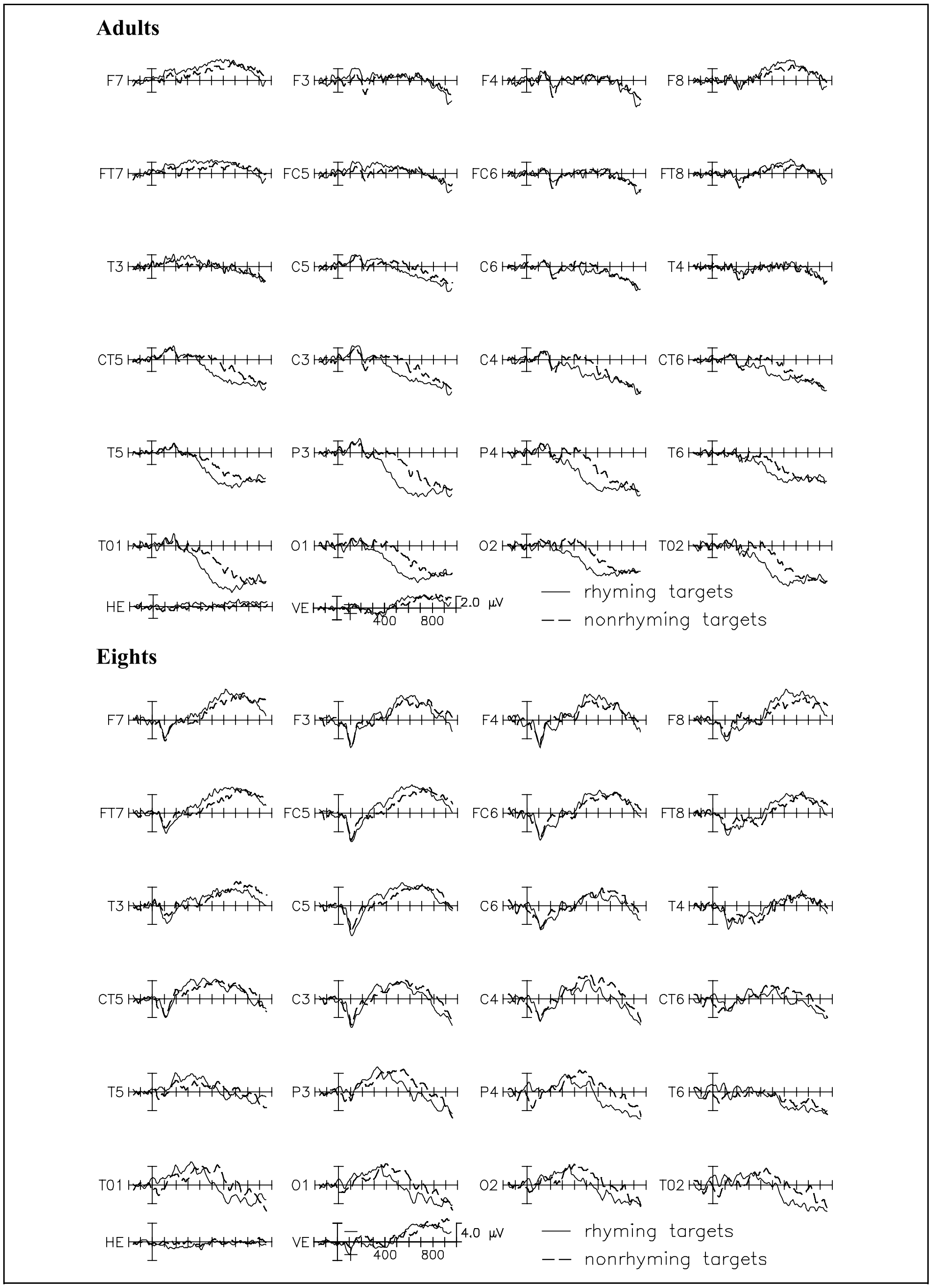
The overall amplitude of the CNV evidenced developmental changes. While the amplitude of the CNV did not vary across the three groups of children, the CNV was smaller in adults than in children, showing a decrease in amplitude with increasing age starting sometime after the age of 8. This pattern is consistent with the decline in CNV amplitude across the second decade of life observed in our previous auditory rhyming study with real word stimuli (Coch et al., 2002), but opposite the increase in CNV amplitude over developmental time observed in our previous visual rhyming study (Grossi et al., 2001). It is also consistent with the contention that the amplitude of negative slow waves is related to the difficulty of the task; with increasing age and language experience over developmental time, the rhyming task presumably becomes less difficult and the CNV becomes smaller.

Interestingly, CNV amplitude was not correlated with phonological memory composite scores on the CTOPP (Wagner et al., 1999), providing no support for the hypothesis that the CNV indexes phonological short-term memory processes in rhyming tasks (e.g., see Ruchkin et al., 1992; Rugg, 1984b). A previous study of auditory rhyming also reported no correlation between digit span (as a proxy for short-term memory capacity) and CNV amplitude (Coch et al., 2002). It is possible that the short stimulus onset asynchrony (SOA) used in each of these studies precluded rehearsal of the prime in memory prior to presentation of the target (see Baddeley & Hitch, 1994), although many of the stimuli in the present study were quite short and theoretically there would have been ample time for memorial rehearsal for at least some of the stimuli.

Measures of the CNV were also not correlated with scores on the Word Identification subtest of the Woodcock Reading Mastery Tests—Revised (Woodcock, 1987), which is consistent with previous results from auditory rhyming studies (Coch et al., 2002). Contrariwise, results from visual studies indicate a relationship between frontal CNV asymmetry to primes and reading ability (Grossi et al., 2001) and between diagnosis of dyslexia and parietal CNV amplitude (Chayo-Dichy, Ostrosky-Solis, Meneses, Harmony, & Guevara, 1990). Overall, it would appear that the CNV elicited in visual tasks (Grossi et al., 2001; Chayo-Dichy et al., 1990; Rugg, 1984b) has a different character than the CNV elicited in auditory rhyming tasks such as the present one. This is consistent with the proposal that the CNV is a generalized negativity upon which task- and modality-specific slow waves are superimposed (Kutas & Donchin, 1980).

This hypothesis is also consistent with the view that the CNV is a topographical indicator of global resource allocation or usage across brain regions (e.g., Rösler, Heil, and Röder, 1997; Rockstroh, Müller, Wagner, Cohen, & Elbert, 1993). Interestingly, the distribution of the CNV in the present study differed for children and adults: CNV was maximal across posterior lateral sites and minimal across fronto-temporal sites for children, while relatively widely distributed across the scalp at all sites anterior to the occipital sites for adults. This pattern is in contrast to the wide distribution of the CNV across all sites anterior to occipital sites for all ages observed in our previous auditory rhyming study (Coch et al., 2002). To the extent that ERPs can speak to localization, the specialized lateral posterior distribution of the CNV observed here in children suggests that posterior brain regions may have been more heavily recruited for the nonword rhyming task in children; in particular, temporo-occipital areas. The difference

Figure 5. ERP waveforms for each age group illustrating the typical rhyming effect (nonrhyming targets more negative than rhyming targets) at posterior sites and the reversal of that effect at left hemisphere anterior sites. Within each age group, anterior sites are toward the top and posterior sites are toward the bottom; medial sites are toward the center and lateral sites are toward the edges; onset is at the vertical calibration bar (note the difference in scale for children and adults); and negative is "plotted up."

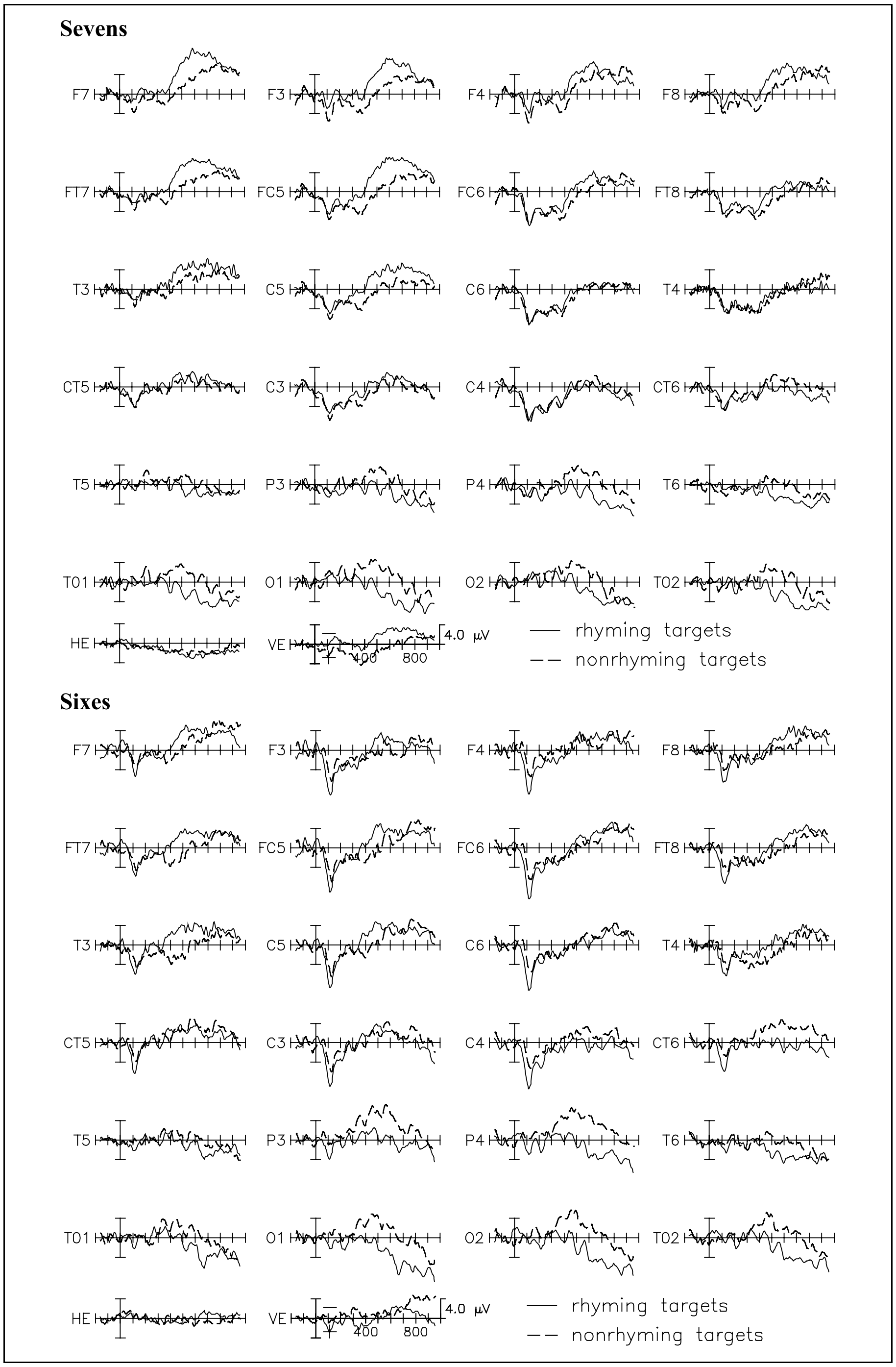


across auditory rhyming studies in the distribution of the CNV in children suggests that the more posterior CNV in the present study may reflect phonological processing of the primes absent semantic influence and processing. Indeed, (visual) fMRI studies show more bilateral inferior parietal activation for phonological as compared to semantic processing (McDermott, Petersen, Watson, & Ojemann, 2003) and PET studies show that nonword rhyming activates the left inferior occipito-temporal junction more than word rhyming (Xu et al., 2001).

The Rhyming Effect

Nonrhyming nonword targets elicited a more negative bilateral posterior response than rhyming nonword targets, replicating the typical RE found with real word stimuli in both children and adults (Coch et al., 2002; Grossi et al., 2001; Radeau et al., 1998; Praamstra et al., 1994; Praamstra & Stegeman, 1993; Rugg, 1984b) as well as the effect found with nonwords in adults (Rugg, 1984a). Also consistent with previous studies (Coch et al., 2002; Grossi et al., 2001), the direction, size,

Figure 5. (*continued*)



distribution, and peak latency of this RE did not vary with age, indicating that rhyming processes indexed by this posterior response in such simple tasks are already adult-like by the age of 6. Indeed, the behavioral data corroborate this claim: Accuracy was quite high overall.

Within the same time window as the typical posterior effect, a reversal of this effect was apparent at anterior lateral sites, such that rhyming targets were more negative than nonrhyming targets. This effect is similar to the reversal effect at anterior sites reported in our previous auditory rhyming study, but is not characterized by the left-greater-than-right hemispheric asymmetry observed with real word stimuli (Coch et al., 2002). It is interesting to speculate that the previously observed hemispheric asymmetry may have been due to the semantic nature of the stimuli, and is not seen here precisely because of the lack of semantic content. Nonetheless, the same general pattern of the typical RE at posterior sites and the reverse of that effect at anterior sites is seen with nonword stimuli.

While the onsets of the late REs in visual and auditory paradigms using real word stimuli have been shown to

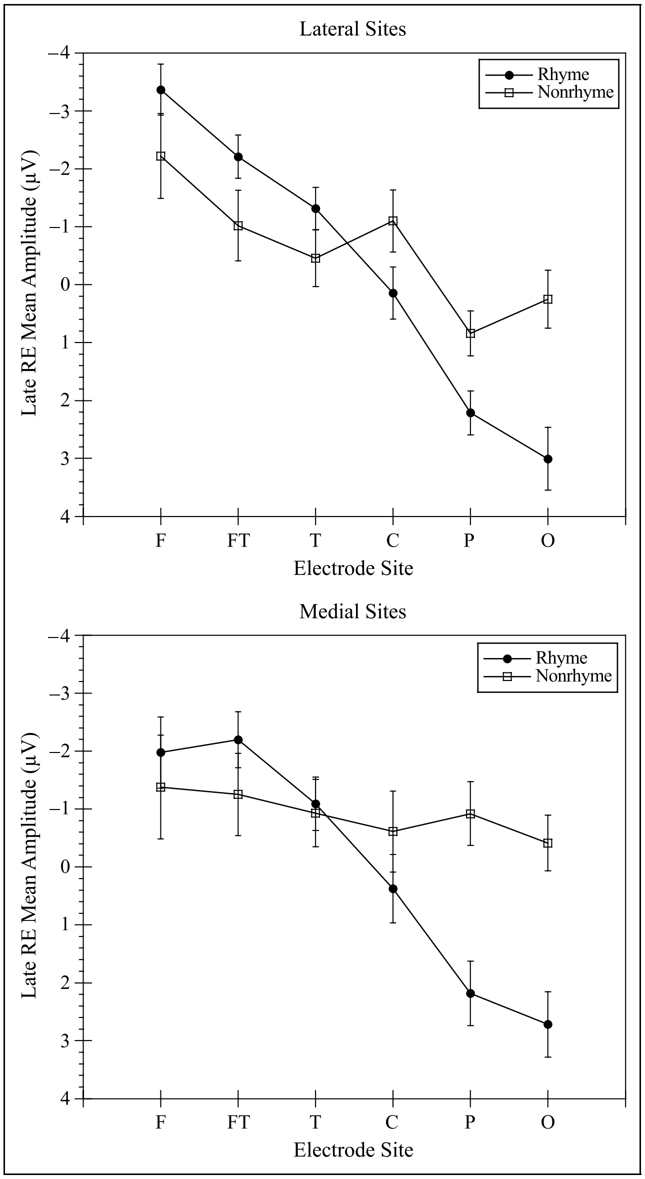


Figure 6. Graphic illustration of the rhyming effect, collapsed across age groups. The typical RE in which nonrhymes were more negative than rhymes was greatest at posterior medial sites. However, rhymes were more negative than nonrhymes at fronto-temporal and temporal lateral sites. F = frontal; FT = fronto-temporal; T = temporal; C = central; P = parietal; O = occipital (refer to Figure 4).

be constant across age (Coch et al., 2002; Grossi et al., 2001), the onset of the RE in the present study varied with age. The RE onset was at about 300 msec in adults, 480 msec in 8-year-olds, and 360 msec in 6- and 7-year-olds. These onsets are substantially later than the 100–150 msec onset of the late RE observed with real word auditory stimuli (Coch et al., 2002), suggesting that rhyming with nonwords is a more difficult task. Intuitively, it would seem that semantics might provide a bootstrapping function for phonology in real word processing that would be absent in nonword processing (e.g., Stanovich, 1980). The early onset of the late auditory RE to words was taken as an indication that spoken word recognition occurs on-line, prior to the arrival of all of the acoustic information contained in a word (e.g., Connine, Blasko, & Titone, 1993; Marslen-Wilson, 1987); this process is not possible with nonwords and may have contributed to the delayed onset of the RE. While there is some evidence of a developmental progression from later to earlier onset of the late RE with age, the remarkably late onset of the effect in 8-year-olds was puzzling.

In order to further investigate the onset of the RE, children were divided into two groups based on scores on the PA composite of the CTOPP. In the group with higher PA scores, the RE onset was at about 320 msec; in the group with lower PA scores, the late RE onset was 80 msec later, at about 400 msec. These results indicate that the ERP RE is sensitive to PA in terms of its onset timing. Moreover, this pattern may also clarify the curiously late start to the RE in 8-year-olds: While the high and low PA groups did not differ in terms of age, 5 of the 12 lowest scorers on the PA composite were 8-year-olds. Interestingly, neither the size nor the peak latency of the RE correlated with PA scores and, consistent with previous findings (Coch et al., 2002; Grossi et al., 2001), there was no correlation between reading scores and measures of the late RE—only the onset of the effect was related to a direct measure of PA.

It may be important to note that an earlier component (N240) has been reported by previous authors to be sensitive to auditory phonological matching in both real word rhyming (Coch et al., 2002; Praamstra et al., 1994; Praamstra & Stegeman, 1993) and sentence processing (PMN, Connolly & Phillips, 1994; N250, Hagoort & Brown, 2000; N2b, D'Arcy, Connolly, & Crocker, 2000; N200, van den Brink, Brown, & Hagoort, 2001) tasks. Connolly and Phillips (1994) hypothesized that this early component indexes mismatch between the initial acoustic–phonological features of a word and the expectancy established by the preceding context. Correlation analyses in our previous study indicated no relationship between the left frontal N240 RE and the bilateral posterior late RE, suggesting that these two effects index distinct processes, but no further evidence was available to separate these processes (Coch et al., 2002). In the present study, however, there is evidence of separability: There is no N240 (analyses by 20-msec epochs revealed no early REs in any age group) and there is a clear late RE. This pattern is consistent with the hypothesis that the N240 is an index of initial mismatch based partly on foregoing semantic context—absent semantic context in the present task, no expectancies are established, and no N240 is evident. Alternately, these differences may simply reflect the effect of familiarity, such that words are more familiar than nonword stimuli.[1] The influences of meaning and famil-

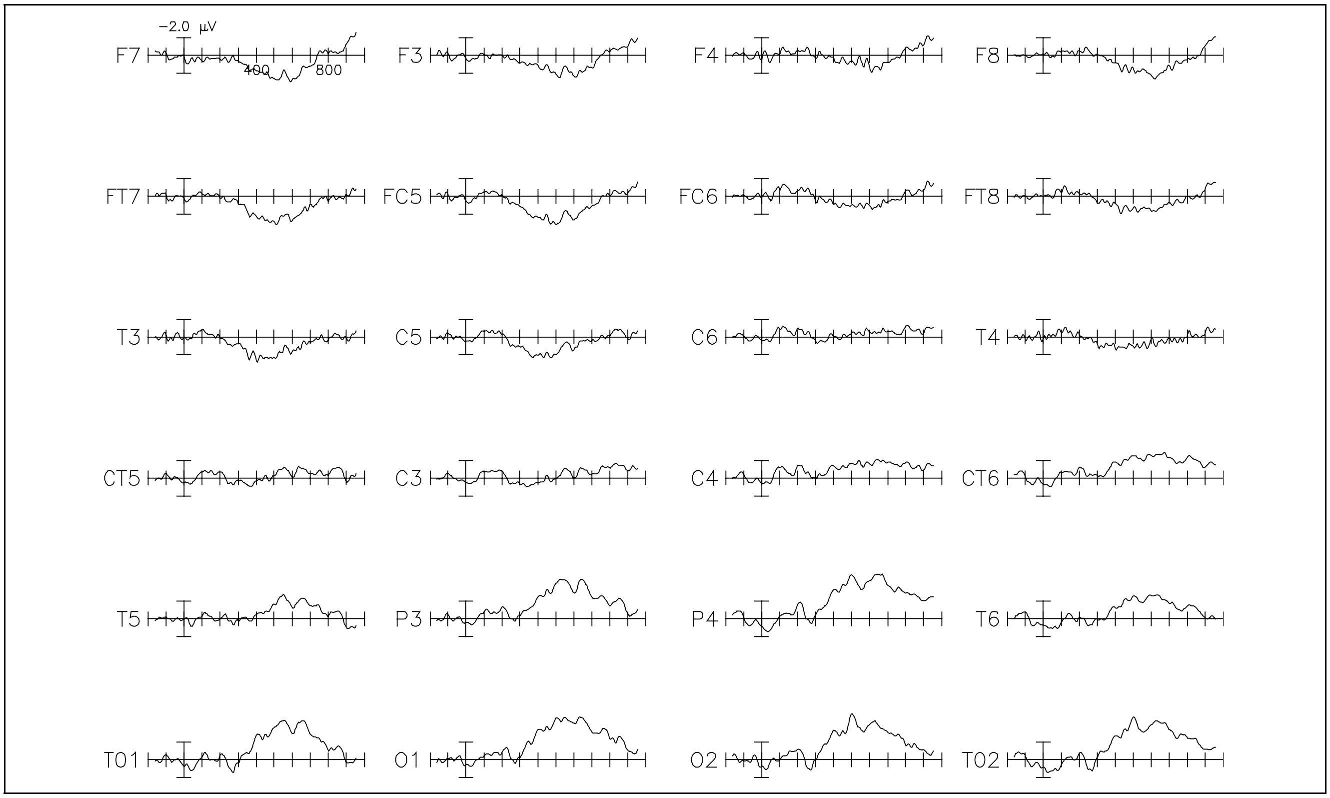


Figure 7. ERP difference waves, collapsed across age groups and created by subtracting the rhyme condition from the nonrhyme condition, showing the distribution of the late rhyming effect across the scalp.

iarity on ERP REs remain an empirical question for further investigation.

Summary and Conclusion

Nonwords elicited ERP REs similar to real words in both adults and school-age children. The CNV to primes was larger in children than in adults but was not related to phonological memory skills. The late RE consisted of the typical greater posterior negativity to nonrhyming targets and a greater anterior negativity to rhyming targets. Latency of the RE was delayed with nonword as compared to word stimuli. Moreover, onset timing of this late effect was related to PA.

For the most part, these results are consistent with previous results (Coch et al., 2002; Grossi et al., 2001) in indicating that the neurocognitive systems for processing rhyme in simple paradigms, such as the present one, are generally well established by the age of 6. However, onset timing of the RE to targets varied with age, indicating that the speed and efficiency of systems involved in auditory nonword processing is not adult-like by the age of 9 (cf. Weber-Fox et al., 2003, for visual rhyme). Thus, abstracting semantic content reveals a developmental trend in phonological processing abilities not observable in studies using real word stimuli.

There is a large behavioral literature showing that auditory rhyming skills develop quite early in life, during the preschool years or before, and make a direct contribution to the development of early reading skills (e.g., Avons et al., 1998; Wood & Terrell, 1998; Goswami, 1993; Bryant, MacLean, Bradley, & Crossland, 1990). We have found little ERP evidence of a relationship to reading ability in the present study or in our previous auditory rhyme research (Coch et al., 2002), perhaps because we have studied children who for the most part are already readers, as evidenced by the scores on the WRMT. The next step in this series of ERP rhyming studies is to study prereading, younger children and to control for the potentially confounding influence of semantics by once again presenting nonword stimuli.

METHODS

Subjects

Participants were right-handed (Oldfield, 1971), monolingual English speakers with no history of neurological dysfunction or language disorder. All were volunteers paid for their participation. The socioeconomic status of children's families ranged from lower middle to upper class on the Hollingshead Index of Social Position, with a middle class average. Adults reported normal hearing and all children passed a standard hearing screening (1, 2, and 4 kHz under headphones). In addition, all children passed a standard oral–motor screening. Participants included 14 adults (8 women), average age 23;0 (*SD* 3;2); nineteen 8-year-olds (10 girls), average 8;4 (*SD* 0;3); eighteen 7-year-olds (9 girls), average 7;5 (*SD* 0;3); and seventeen 6-year-olds (8 girls), average 6;6 (*SD* 0;3).

Behavioral Testing

All children[2] were administered the core subtests of the CTOPP (Wagner et al., 1999); scores on these subtests contribute to the PA and phonological memory composite scores for this test. In addition, children were given the Letter Identification, Word Identification, and Word Attack subtests of the Woodcock Reading Mastery Tests—Revised (Woodcock, 1987). The Columbia Mental Maturity Scale, a nonverbal test of intelligence, was also administered (Burgemeister et al., 1972). Behavioral and ERP testing occurred in different sessions separated by no more than 35 days.

ERP Stimuli

A master list of 88 pairs of rhyming nonwords was created. Nonwords adhered to the orthographic and phonological rules of English, but had no semantic content. The form of the nonwords was loosely based on the rhyming words used in previous studies (Coch et al., 2002; Grossi et al., 2001), and, with the exception of one pair (*fauer–blauer*), all nonwords were one syllable. From the master list of 88 pairs, two lists, each consisting of 44 pairs of rhyming nonwords and 44 pairs of nonrhyming nonwords, were created. Nonrhyming pairs were formed by associating the prime of a rhyming pair with the target of another rhyming pair, such that all the targets were preceded by the same primes in both rhyming and nonrhyming conditions across the two lists. Prime–target pairs were intermixed across the two lists so that each nonword appeared as a target in only one list. The two lists were counterbalanced across subjects (see Appendix for complete stimulus lists).

Stimuli were spoken in a female voice and presented in random order (with order of prime–target pairs in each list fixed across subjects). Nonwords were digitally recorded (44.1 kHz, 16-bit resolution) using an Electro-Voice 1750 microphone connected to a Macintosh computer running a sound editing program (SoundEdit 16, Version 2). Each nonword stimulus was stored in a separate file and was carefully edited for precise time of onset to permit synchronization with ERP digitization. Stimuli varied in length from 361.4 msec (*gee*) to 906.1 msec (*stide*), with an average length of 576.0 msec (*SD* 93.5). During the experiment, nonwords were presented over a speaker located 57 in. directly in front of the participant. SOA between prime and target onset for each nonword pair was 1167 msec. Stimuli were presented at a comfortable listening level of 65 dB SPL (A-weighted) on average.

Procedure

Procedures were explained to children and parents as well as to adult participants before the actual test session and any questions were addressed. Parents and adult participants signed consent forms, while children signed assent forms. Participants were tested in a sound-attenuating, electrically shielded booth. For children, a practice session preceded the actual test session.[3] Following the practice session, the actual experiment was begun: A fixation cross appeared in the middle of the screen; 500 msec later, a box appeared around the fixation cross; 500 msec after that, a nonword pair was played from the speaker; 1000 msec later, the box disappeared from the screen; participants provided an answer; and the feedback ‘‘Right!’’ or ‘‘Wrong’’ appeared on the screen. Participants were instructed not to blink and to ‘‘keep their eyes on the plus’’ while the sounds were playing and the box was on the screen, and to verbally respond ‘‘rhyme’’ or ‘‘not rhyme’’ when the box disappeared from the screen. Eye movements were monitored by an experimenter seated next to the child and by closed-circuit video; the experimenter recorded the child’s response to each stimulus pair with a button press device. For adults, there was no practice session and participants themselves pressed the buttons to respond (response hands for rhyme/nonrhyme were counterbalanced across adult participants); all else was the same as for children.

EEG/ERP Recording and Analysis

Electroencephalogram (EEG) was recorded from 29 tin electrodes mounted in an elastic cap (Electro-Cap International, Eaton, OH). These included three midline sites (Fz, Cz, and Pz) and 13 pairs of lateral sites (FP1/2, F7/8, FT7/8, F3/4, FC5/6, C3/4, C5/6, T3/4, CT5/6, P3/4, T5/6, TO1/2, and O1/2; refer to Figure 4). Electrodes were also placed beneath the lower right eye and at the outer canthi of the left and right eyes in order to monitor eye movements (EOG); in addition, recordings from FP1/2 were used to reject trials that were contaminated by eyeblink artifacts. Activity at the right mastoid was recorded during the experiment, but all on-line recordings were referenced to the left mastoid; recordings were re-referenced to averaged mastoids in the final data averaging. Eye electrode impedances were maintained below 10 KΩ, mastoid electrodes below 2 KΩ, and scalp electrodes below 3 KΩ.

The EEG was amplified with Grass 7P511 amplifiers (−3 dB cutoff, bandpass 0.01 to 100 Hz) and digitized on-line (sampling rate 4 msec). Off-line, separate ERPs to rhyming and nonrhyming targets were averaged for each subject at each electrode site over a 1000-msec epoch, using a 200-msec prestimulus-onset baseline; ERPs to primes were averaged over a 1500-msec epoch using a 200-msec baseline. Only trials on which participants responded correctly were included, and trials contaminated by eye movements, muscular activity, or electrical noise were not included in analyses. Standard artifact rejection parameters were initially employed, and data were subsequently analyzed on an individual basis for artifact rejection. A minimum of 10 artifact-free trials in each of the three main conditions was imposed. The average number of useable trials in the rhyme condition was 35.2 (*SD* 7.6) for adults, 27.2 (*SD* 8.5) for 8-year-olds, 25.9 (*SD* 8.2) for 7-year-olds, and 20.7 (*SD* 8.1) for 6-year-olds. Average number of useable trials in the nonrhyme condition was 34.3 (*SD* 8.1) for adults, 28.0 (*SD* 8.1) for 8-year-olds, 25.1 (*SD* 8.3) for 7-year-olds, and 22.0 (*SD* 8.1) for 6-year-olds. Average number of useable trials in the prime condition was 61.2 (*SD* 27.9) for adults, 39.5 (*SD* 19.7) for 8-year-olds, 32.7 (*SD* 15.3) for 7-year-olds, and 34.8 (*SD* 19.1) for 6-year-olds.

Mean amplitude measures were taken for the RE to targets and the CNV to primes. Within each group, analyses by consecutive 20-msec epochs from 0 to 500 msec were conducted in order to more precisely temporally locate the onset of the RE in each group; significant results involving condition across three consecutive epochs were considered an indication of onset in the earliest epoch. In the main analyses, the RE was measured within the 325–900 msec window for children and the 300–900 msec time window for adults and the CNV was measured within the 300–1200 msec time window for both children and adults.

To control for the typical overall larger amplitude waves in children, amplitude data were normalized based on the formula (score − mean/*SD*) where score was an ERP average amplitude value (one for each condition and scalp site for each subject), mean was the mean amplitude across all subjects in each age group, and *SD* was the standard deviation of the mean amplitude (see Holcomb, Coffey, & Neville, 1992). In addition, difference waves (waves resulting from the subtraction of the rhyme condition from the nonrhyme condition) were created to better measure the RE.

Mixed-design analyses of variance (ANOVAs) were performed on the ERP data. The between-subjects factor was age group (four possible levels: 6, 7, 8, adult) or ability group (two possible levels: high, low) and the within-subject factors were condition (two possible levels: rhyme, nonrhyme), anterior/posterior (six possible levels: frontal, fronto-temporal, temporal, central, parietal, occipital), lateral/medial (two possible levels), and hemisphere (two possible levels) (refer to Figure 4). Additional ANOVAs by group and by condition were conducted to further clarify results. The Greenhouse–Geisser correction was applied to all within-subjects measures with more than two levels. In addition, Pearson's correlations were calculated in order to investigate specific relationships among behavioral and electrophysiological measures. All results are significant at the .05 level unless otherwise noted.

APPENDIX

List One: Prime–Target

jite–fauer
grize–yise
kow–deeb
dreat–ged
murze–thurze
yi–marp
grood–bood
dabe–lum
clate–pline
mun–lun
ky–tate
vease–meeze
bry–pag
crail–lale
demp–semp
zeer–pud
nake–dake
siff–piff
stam–glig
daf–coom
trum–pum
drere–vair
gines–rabe
floos–cho
sarp–cly
chole–thole
dorde–morde
gee–blail
blane–vox
poom–dite
daip–laip
feap–neap
bome–slines
nef–gef

trin–phy
nobe–drobe
gox–brocks
frield–geeled
dat–lat
fum–zi
ked–voo
nilled–dilled
kile–spile
shum–hane
jate–yate
doan–pone
zare–jare
kun–gree
crute–doot
yocks–toos
blug–kroar
pake–spake
gour–druze
vore–jore
maft–yaft
bro–slore
nin–rin
drig–stug
gite–clite
nool–shull
mag–yare
blauer–flam
sare–nare
foo–breet
fam–cham
vite–balf
prail–stobe
stee–kwee

pooze–lauer
moce–boce
throre–slin
bly–gry
doode–keer
glir–flir
blore–plo
mide–gome
poe–trow
plew–snew

chuz–luz
taid–chy
plol–groll
rine–clum
neeb–stide
poat–hoat
quo–zow
slair–jun
ji–claid
krobe–zite

List Two: Prime–Target

foo–voo
nin–laip
bro–plo
dorde–gry
plew–dilled
gour–lauer
murze–hoat
daip–piff
stee–spile
trin–slin
grize–morde
nobe–kwee
blug–stug
blore–slore
shum–lum
nake–trow
moce–rin
jate–yise
grood–nare
rine–pline
stam–flam
blauer–fauer
nilled–groll
mag–pag
neeb–deeb
quo–jare
gox–luz
gee–gree
fum–clum
kow–cho
drig–glig
nef–doot
dabe–rabe
poe–flir
sare–cham
mun–gef
krobe–stobe
yi–cly
blane–hane
frield–bood
kun–jun
throre–kroar
dat–clite
nool–drobe

plol–neap
trum–dake
kile–pone
glir–meeze
vore–lun
doan–lat
floos–toos
daf–balf
poom–coom
bry–chy
feap–vair
jite–zite
gines–slines
crute–lale
chuz–semp
pake–brocks
crail–thole
fam–zow
siff–jore
sarp–marp
zeer–keer
clate–tate
pooze–druze
gite–thurze
chole–pum
ky–phy
demp–geeled
dreat–breet
bome–gome
doode–pud
poat–spake
vite–dite
maft–snew
prail–blail
ked–ged
yocks–vox
vease–boce
zare–yaft
bly–shull
taid–claid
mide–stide
drere–yate
ji–zi
slair–yare

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Reprint requests should be sent to Donna Coch, Department of Education, Dartmouth College, USA, or via e-mail: Donna.Coch@Dartmouth.edu.

Notes

1. We thank an anonymous reviewer for suggesting this alternative account.
2. With the exception of one 7-year-old girl and one 7-year-old boy.
3. The practice session consisted of a series of questions to which the child provided answers: ‘‘Do you know what it means for two words to rhyme?,’’ ‘‘Can you think of some words that rhyme with ‘pie’?,’’ ‘‘Can you think of some words that don’t rhyme with ‘pie’?,’’ and ‘‘Here’s a made-up word: ji. Can you think of some words that would rhyme with ‘ji’?’’ In cases in which the child did not answer a question, the experimenter provided an answer and then prompted the child to provide a different answer. Participants were then told ‘‘That’s what this game is all about: deciding whether two made-up words rhyme or do not rhyme—deciding whether they sound the same or not.’’

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