Fine Neural Tuning for Orthographic Properties of Words Emerges Early in Children Reading Alphabetic Script

Jing Zhao[1,2,3], Kerstin Kipp[4], Carl Gaspar[2,3], Urs Maurer[5,6], Xuchu Weng[2,3], Axel Mecklinger[7], and Su Li[1]

Abstract

■ The left-lateralized N170 component of ERPs for words compared with various control stimuli is considered as an electrophysiological manifestation of visual expertise for written words. To understand the information sensitivity of the effect, researchers distinguish between coarse tuning for words (the N170 amplitude difference between words and symbol strings) and fine tuning for words (the N170 amplitude difference between words and consonant strings). Earlier developmental ERP studies demonstrated that the coarse tuning for words occurred early in children (8 years old), whereas the fine tuning for words emerged much later (10 years old). Given that there are large individual differences in reading ability in young children, these tuning effects may emerge earlier than expected in some children. This study measured N170 responses to words and control stimuli in a large group of 7-year-olds that varied widely in reading ability. In both low and high reading ability groups, we observed the coarse neural tuning for words. More interestingly, we found that a stronger N170 for words than consonant strings emerged in children with high but not low reading ability. Our study demonstrates for the first time that fine neural tuning for orthographic properties of words can be observed in young children with high reading ability, suggesting that the emergent age of this effect is much earlier than previously assumed. The modulation of this effect by reading ability suggests that fine tuning is flexible and highly related to experience. Moreover, we found a correlation between this tuning effect at left occipitotemporal electrodes and children's reading ability, suggesting that the fine tuning might be a biomarker of reading skills at the very beginning of learning to read. ■

INTRODUCTION

Literate people possess a special form of visual expertise that allows their visual system to process words efficiently (McCandliss, Cohen, & Dehaene, 2003; Rayner & Pollatsek, 1989). A negative component of the ERP, peaking about 170 msec after orthographic stimulus onset and termed N170 (N1 in some studies), is believed to be an electrophysiological marker for such word expertise. This orthographic N170 is typically more pronounced over the left than over the right hemisphere (Maurer, Zevin, & McCandliss, 2008; Maurer, Brandeis, & McCandliss, 2005). In various ERP studies, the early electrophysiological activity evoked by visually presented words were compared with that of two types of control stimulus—symbol strings (Maurer et al., 2008; Maurer, Brandeis, et al., 2005; Wong, Gauthier, Woroch, DeBuse, & Curran, 2005; Bentin, Mouchetant-Rostaing, Giard, Echallier, & Pernier, 1999) and consonant strings (alphabetic scripts; Proverbio, Vecchi, & Zani, 2004; McCandliss, Posner, & Givon, 1997) or false characters (logographic scripts; Zhao et al., 2012; Lin et al., 2011). These studies suggest that, although the N170 amplitude difference between words and symbol strings may reflect coarse neural tuning for print (Maurer et al., 2006), the N170 amplitude difference between words and consonant strings or between real and false Chinese characters may reflect fine neural tuning within orthographic patterns (Lin et al., 2011; Posner & McCandliss, 2000).

A number of ERP studies in children attempt to examine the emergence and developmental trajectory of N170 tuning effects for words, showing that these effects appear to emerge and develop sequentially during children's acquisition of reading skill. The coarse tuning for words is established rapidly and shortly after children begin to learn to read. Maurer, Brandeis, et al. (2005) found that the N170 amplitude difference between words and symbol strings was absent in nonreading preschool children (6.5 years old), but a larger N170 for words than symbol strings quickly developed in the same group of children after only 1.5 years of reading training in primary school (8.3 years old; Maurer et al., 2006). However, the fine

[1]Chinese Academy of Sciences, Beijing, China, [2]Hangzhou Normal University, [3]Zhejiang Key Laboratory for Research in Assessment of Cognitive Impairments, Hangzhou, China, [4]University of Ulm, [5]University of Zurich, [6]University of Zurich and ETH Zurich, [7]University of the Saarland, Saarbrücken, Germany

doi:10.1162/jocn_a_00660

tuning for words seems to develop slowly over the course of reading acquisition in childhood. Posner et al. (2000) reported the N170 amplitude differences between words and consonant strings in fourth grade children (10 years old) but not in first grade children (7 years old) and preschool children (4 years old). Unlike the N170 response to words in adults (McCandliss et al., 1997), the 10-year-olds did not show a difference between unfamiliar words and consonant strings. This study hence indicated that even in 10-year-olds the fine tuning for words was not fully developed (Posner et al., 2000). In summary, the existing ERP literature appears to show that the coarse tuning for words is present in very young children, whereas the fine tuning occurs much later.

It is important to note, however, that the majority of N170 studies in children did not take account of individual difference in reading abilities, whereas there is compelling evidence that the degree of reading ability varies widely across children including those who have not yet received formal reading training (e.g., Jenkins, Fuchs, Van Den Broek, Espin, & Deno, 2003; Whitehurst & Lonigan, 1998; Gillon & Dodd, 1994; Daneman, 1991). Moreover, there is a large body of behavioral evidence suggesting that young children have acquired advanced skills of visual word form perception. For example, children as young as 6 years old showed improved performance on a letter matching task compared with a symbol matching task although the symbols were similar to letters in terms of low-level visual features such as size and number of lines (Turkeltaub, Gareau, Flowers, ZeYro, & Eden, 2003; Miller & Wood, 1995). Burgund, Schlaggar, and Perterson (2006) reported that this visual perceptual specificity in letter processing was associated with children's reading ability. Also, previous developmental studies found that young children had acquired some orthographic knowledge (such as acceptable letter combinations and acceptable letter positions in a word) and could discriminate words from other similar visual forms. As early as the first half of Grade 1, children were able to discriminate letter strings with acceptable combinations in English spelling from those with illegal combinations (Cassar & Treiman, 1997) and differentiate words and consonant strings with a high accuracy (about 80%; Levy, Gong, Hessels, Evans, & Jared, 2006). Cunningham, Perry, and Stanovich (2001) further found that the knowledge of orthographic regularity was specifically related to children's reading skill after controlling for the influence of variance in memory and nonverbal intelligence.

Given that there is a large body of behavioral evidence suggesting, as discussed above, reading ability varies widely across young children at the early phase of reading acquisition and some young children have acquired advanced reading skills, we decided to reconsider the emergent age of neural tuning effects for words by measuring ERPs in young children (7 years old, first grade) and grouping the children into low and high reading ability groups. The grouping design accounts for individual difference, thus providing a more sensitive approach to tracking the emergent age of these tuning effects.

To minimize potential confounders in the grouping design, children in the two groups were matched in terms of age, socioeconomic status (SES), home literacy experience, and formal reading training time. As our goal was to characterize the normal development of N170 for words, dyslexic children were excluded. To better characterize the neural tuning effects for words, in addition to words, three types of control stimuli were included: pseudowords, consonant strings, and symbol strings (seen in Figure 1A). These control stimuli were constructed on the basis of two variables: the visual aspect of print (letter feature) and the orthographic regularity. Specifically, symbol strings were matched with words, pseudowords, and consonant strings in the level of basic visual property including character size, font size, and string length, but they differed from the other three stimulus categories in the presence of letter features. Pseudowords and consonant strings all consist of letters, but they differed in orthographic regularity: The position of letters in a pseudoword was acceptable in spelling, whereas that in a consonant string was illegal in spelling. We used a color matching task, which can minimize the influence of potential phonological activation and differential top–down modulations across different stimulus categories (see Zhao et al., 2012, for discussion).

We predicted that children with high reading ability would show an N170 difference between words and consonant strings, if individual difference is indeed an important factor relates to the emergence of fine tuning for words. We further predicted that, similar to real words, pseudowords would evoke a greater N170 relative to consonant strings, if the fine tuning for words reflects sensitivity to orthographic regularity as pseudowords are orthographically equivalent to real words. In addition, according to the previous ERP results in children (Maurer et al., 2006), both groups of children, regardless of their reading ability, would show an increased N170 response to words than symbol strings. Furthermore, if the coarse tuning effect for words reflects selectivity of letter

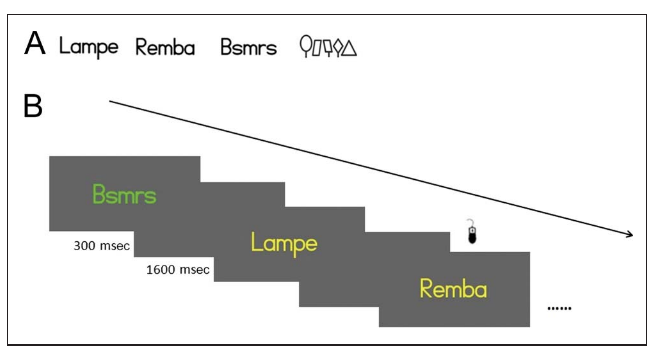

Figure 1. (A) Examples of stimuli: word, pseudoword, consonant string, and symbol string from the left side to the right side. (B) Sketch map of the 1-back color repetition detection task.

features, both pseudowords and consonant strings would evoke a larger N170 than symbol strings. We did not have strong expectations about the lateralization of tuning, as previous developmental studies have found a more bilateral N170 response to words compared with adults (Maurer et al., 2006). However, we suspect that high reading ability may be associated with tuning that is left-lateralized, as this is the pattern of results found in adults (Zhao et al., 2012; Lin et al., 2011; Maurer et al., 2008; Bentin et al., 1999). Given the prominent role of orthographic pattern detection in models of visual word recognition (Dehaene, Cohen, Sigman, & Vinckier, 2005; Coltheart, Curtis, Atkins, & Haller, 1993; Seidenberg & McClelland, 1989), evidence for the neural development of this skill in accordance with reading acquisition would be significant.

METHODS

Participants

Thirty-three children (16 boys, mean age = 7.13 years, *SD* = 0.44, range = 6.33–8.00 years) took part in the study. All of the children were native German speakers and were students in primary schools in the suburban area of Saarbruecken, Germany. They had normal or corrected vision. According to the Edinburgh handedness inventory (Oldfield, 1971), 27 of them were right-handed, 4 of them were left-handed, and 2 of them were not dominantly handed. They were paid for their participation, and their parents signed an informed consent. In addition, children's parents were also required to evaluate their family's SES and the home literacy experience of their child (i.e., various literacy activities of the child and the degree to which they were initiated by the child) by using questionnaires (Levy et al., 2006; Hollingshead, 1975).

Because pseudoword naming is a common way to assess one's decoding ability, which is the most critical component in learning to read, especially in the early phase of reading acquisition (Share, 1995), we used a pseudoword naming test as an index of children's reading ability. This test is one subtest of the Salzburg Reading and Spelling Test (Salzburger Lese-und Rechtschreibtest [SLRT]; Landerl, Wimmer, & Moser, 1997). Children were instructed to read a list of pseudowords as quickly and accurately as possible, and reading time and errors were recorded.

As our goal was to characterize normal development, dyslexic children were excluded. Considering that dyslexia is usually only diagnosed after first grade, we used a conservative 2 *SD* criterion (i.e., reading score of two standard deviations below the average of the population used for the SLRT norms; Brambati et al., 2006; Lachmann, Berti, Kujala, & Schröger, 2005). Three participants thus were excluded. In addition, two participants were excluded in final analyses because their hit rates in the 1-back color repetition detection task were two standard deviations below the average of the children group. Using a median split, the 28 participants were grouped into two groups with low and high reading ability (see Table 1). Data were analyzed in independent samples t test. Results showed that both groups of children could correctly name most of the pseudowords (mean accuracy = .93, *SD* = .06), and children with high reading ability were significantly more accurate, $t(26) = 2.50$, $p < .05$. As there was no speed–accuracy tradeoff, reading speed served as the basis for grouping. Results showed that children of the two groups significantly differed in reading speed, $t(26) = 6.06$, $p < .001$. However, they were equated for age, $t(26) = 0.44$, $p > .05$, the SES score, $t(26) = 1.05$, $p > .05$, the score of home literacy experience, $t(26) = 0.29$, $p > .05$, and formal reading training time, $t(26) = 0.62$, $p > .05$. Formal reading training time was defined by the date when children took part in the experiment minus the date when they entered schools. All participants had received reading training for at least 4 months in the study.

Material

Four categories of stimuli were used in the ERP experiment including words, pseudowords, consonant strings, and symbol strings. Examples of the materials are illustrated in Figure 1A. Specifically, words were composed of concrete German nouns from children's first grade textbooks with high-frequency of occurrence (CELEX psycholinguistic database: mean frequency = 79.03/million). Pseudowords were pronounceable nonsense words.

Table 1. Mean Age, SES, Home Literacy Experience (HLE), Reading Training Time (RTT), and Reading Performance (Error and Speed)

Group	*Age*	*SES*	*HLE*	*RTT*[a]	*Error*	*Speed*[b]
Low ability	7.13 (0.14)	55.43 (4.24)	3.09 (0.13)	0.64 (0.04)	2.36 (0.45)	4.79 (0.30)
High ability	7.20 (0.08)	61.79 (4.35)	3.14 (0.07)	0.67 (0.04)	1.07 (0.25)	2.62 (0.20)

Standard errors of means are given in parentheses.

[a]Time interval between attending a school to participating in the experiment (years).

[b]In seconds per word.

Similar to the procedure used in the previous studies (e.g., Friedrich & Friederici, 2005, 2006), all pseudowords were prosodically, phonologically, and phonotactically legal in German (e.g., Remba, Salfo, Zumi). They all consisted of two syllables, and the intonation, if one was to pronounce them, was always on the first syllable. Consonant strings were randomly ordered consonant letters, in which the position of letters was illegal in spelling. Symbol strings consisted of geometric figures. All the stimuli were matched for character and font size as well as string length (extended 3.3–7.5 cm). All the stimuli that were composed of letters (words, pseudowords, and consonant strings) were written in lowercase letters except for starting with an uppercase letter, which is the common appearance of nouns in German. Words and pseudowords were composed of two syllables. For each category, 36 stimuli were created.

Procedure

The ERP experiment consisted of eight blocks. Each block consisted of 72 trials. The four categories of stimuli were presented randomly, but an additional rule prohibited two successive stimuli to be of the same type. Each stimulus was presented in one of the three colors (green, red, or yellow) on a gray background in the center of the screen. The horizontal visual angle of stimuli was 1.6° to 3.6°, and the vertical visual angle of stimuli was 1.2°. Each color appeared the same number of times across stimulus types. Each specific trial was constructed as follows: fixed stimulus duration of 300 msec and an ISI, uniformly distributed among 1450, 1525, 1600, 167, and 1750 msec and randomized across trials. Participants were instructed to press a button whenever the color of a stimulus occurred twice in a row (the 1-back color repetition detection as shown in Figure 1B). To get enough trials for ERP averaging, all stimuli were presented four times as nontargets. A similar procedure was used in previous studies (Li et al., 2013; Zhao et al., 2012; Cao, Li, Zhao, Lin, & Weng, 2011; Lin et al., 2011; Maurer et al., 2008). A subset of six stimuli per category was additionally presented four times as the targets (16.67% of all stimuli). There were 144 trials (with 120 nontarget trials and 24 target trials in each stimulus category). The assignment to give the answer with the left or right index finger was balanced across participants. Both the ERP and the behavioral data were collected in the same session. The reading skills were measured before the beginning of the ERP recordings.

Electrophysiological Recording and Analysis

EEG signal was recorded from 28 Ag/AgCl electrodes secured in an elastic cap according to the extended 10–20 system (Sharbrough et al., 1994). The EEG data were recorded by using a DC-amplifier system (NeuroScan, Inc., El Paso, TX). The software for EEG recording was BrainVision Recoder (Brainsystems, Inc.). The C_Z electrode served as an online reference, and the data were offline rereferenced to an average reference. Horizontal EOG was recorded in a bipolar lead from two additional electrodes placed on the outer canthi of the two eyes. Vertical EOG was recorded in a bipolar lead from additional electrodes placed on the supraorbital and infraorbital ridges of the right eye. All electrode impedances were kept below 5 kΩ. EEG and EOG were recorded continuously and were amplified with a band pass from AC 0.1 to 100 Hz at a sampling rate of 500 Hz.

Offline data processing involved band-pass filtering (low-pass filtering at 30 Hz and high-pass filtering at 0.5 Hz). Before averaging, each recording epoch was manually scanned for artifacts. Trials containing eye movement artifacts were corrected offline using a modified version of Gratton, Coles, and Donchin's (1983) regression procedure. Trials were epoched and baseline-corrected offline with a 200-msec prestimulus period. The duration of the poststimulus period was 800 msec. For all four stimulus categories, only nontarget trials for which no false positive (target) responses occurred entered the analyses. Before averaging, segments with error responses and artifacts exceeding ±100 μV (about 50% of all trials) were automatically rejected. The mean trial numbers used for ERP averaging were 51 for words, 53 for pseudowords, 53 for consonant strings, and 54 for symbol strings for the low reading ability group. The corresponding values for the high ability group were 65 for words, 63 for pseudowords, 64 for false words, and 64 for symbol strings. One pair of channels (P7/P8) was selected according to the topographic maxima in the negative field on the occipitotemporal area over both hemispheres. These channels were typical channels for measuring the N170 response (Li et al., 2013; Wang, Kuo, & Cheng, 2011; Maurer et al., 2008; Bentin et al., 1999). The peak values of amplitude and associated latencies on these channels for N170 segment were obtained between 150 and 300 msec after stimulus onset. This time window was selected based on visual inspection of our data and the previous developmental studies (Li et al., 2013; Cao et al., 2011; Maurer et al., 2006).

Behavioral responses to targets were analyzed in two-way ANOVAs with repeated measures on hit rate and RT using Reading Ability as between-subject factor and Stimulus Category as within-subject factor. To investigate coarse tuning, N170 measures were analyzed in a three-way ANOVA for repeated measures with Reading Ability as between-subject factor and Stimulus Category (four levels) and Lateralization as within-subject factors. A similar ANOVA was computed to investigate fine tuning for orthographic patterns, but including only the three orthographic conditions in the analysis. For all ANOVAs, F values associated with more than one degree of freedom in the nominator have been corrected for sphericity violations with the Greenhouse–Geisser procedure (Greenhouse & Geisser, 1959), and corrected degrees of freedom and p values are reported. To further examine the role of reading ability, we computed the correlations between children's reading speed and N170 tuning effects.

RESULTS

Behavioral Results

Trials with RTs longer or shorter than two standard deviations from the mean were discarded. Totally, 3.28% of the target trials in the low reading ability group and 3.35% of the trials in the high reading ability group were excluded from further analyses. Hit rates and RTs were analyzed for target trials of the four stimulus categories. The hit rates were calculated by using the number of target trials, which were judged as targets divided by the total number of target. Means and standard deviations are illustrated in Table 2. Hit rates were analyzed in a mixed 4 × 2 two-way ANOVA with Stimulus Category (word, pseudoword, consonant string, symbol string) as a within-subject factor and Reading Ability (low vs. high) as a between-subject factor. Results showed that neither the main effect nor the interaction was significant: Stimulus Category, $F(2.80, 72.90) = 1.95$, $p = .13$, Reading Ability, $F(1, 26) = 0.02$, $p = .89$, and Stimulus Category × Reading Ability, $F(2.80, 72.90) = 0.45$, $p = .71$. For RTs, outcomes of a similar ANOVA revealed that neither the main effect of Reading Ability, $F(1, 26) = 0.01$, $p = .98$, nor the interaction of Stimulus Category × Reading Ability, $F(2.63, 68.39) = 0.07$, $p = .97$, was significant. Although the main effect of Stimulus Category was marginally significant, $F(2.63, 68.39) = 2.84$, $p = .05$, results of the post hoc test (ANOVA with Bonferroni adjustment) revealed no significant difference between two types of stimuli (all ps > .05). Taken together, these results suggest that children with low and high reading ability did not show any significant difference in behavioral response. This is not surprising given that the task which participants performed was content irrelevant.

N170 Results

N170 Peak Amplitude

Figure 2 shows the grand-averaged ERP waveforms and topographic maps for four stimulus categories separately for both children groups. The waveforms were collected from the occipitotemporal electrodes (left: P7 and right: P8). In particular, a robust N170 component was observed in the four stimulus categories at these electrodes in both groups. Figure 3 depicts the averaged N170 peak amplitudes for four categories of stimuli separately on these electrodes in both groups of children.

Coarse tuning for print was investigated by analyzing the data of the N170 peak amplitudes in a mixed 4 × 2 × 2 ANOVA with two within-subject factors Stimulus Category (4: word, pseudoword, consonant string, symbol string) and Lateralization (left vs. right) and a between-subject factor Reading Ability (low vs. high). The outcome of this analysis revealed a significant main effect of Stimulus Category, $F(2.43, 63.24) = 25.42$, $p < .001$, a significant main effect of Lateralization, $F(1, 26) = 4.73$, $p = .04$, and a significant interaction of Stimulus Category × Lateralization × Reading Ability, $F(2.82, 73.35) = 3.77$, $p = .02$. Neither the main effect of Reading Ability nor the other interactions were significant: for Reading Ability, $F(1, 26) = 0.01$, $p = .92$; for Stimulus Category × Reading Ability, $F(2.43, 63.24) = 1.95$, $p = .14$; for Lateralization × Reading Ability, $F(1, 26) = 0.43$, $p = .52$; for Stimulus Category × Lateralization, $F(2.82, 73.35) = 1.40$, $p = .25$. To interpret the interaction and examine our hypothesis for coarse tuning, we broke down the three-way interaction by Reading Ability and Lateralization. For children with low reading ability, the analyses revealed significant effect of Stimulus Category: at the left OT electrodes, $F(2.40, 31.16) = 8.70$, $p = .001$; at the right OT electrodes, $F(2.29, 29.82) = 7.90$, $p = .001$. ANOVAs (Bonferroni adjustment) were used for post hoc comparisons. Results showed that words evoked stronger N170 amplitude than symbol strings over the left hemisphere (MD = 5.38, $p = .001$) and over the right hemisphere (MD = 4.61, $p = .001$). Furthermore, the other categories of stimuli containing letters (i.e., pseudowords and consonant strings) evoked significantly larger N170 amplitudes than symbol strings: over the left hemisphere, consonant strings versus symbol strings (MD = 4.10, $p = .01$); and over the right hemisphere, pseudowords versus symbol strings (MD = 4.58, $p = .001$), consonant strings versus symbol strings (MD = 4.91, $p = .003$). Similarly, for children with high reading ability, results showed that

Table 2. Mean Hit Rate and RTs in the 1-back Color Repetition Detection Task

	Low Reading Ability		*High Reading Ability*	
Stimulus Category	*Hit Rate*	*RTs (msec)*	*Hit Rate*	*RTs (msec)*
Word	0.82 (0.03)	763 (32)	0.82 (0.03)	758 (47)
Pseudoword	0.81 (0.04)	768 (32)	0.78 (0.04)	772 (45)
Consonant	0.79 (0.03)	787 (27)	0.79 (0.04)	788 (44)
Symbol	0.77 (0.04)	790 (24)	0.78 (0.04)	795 (49)

Standard errors of means are given in parentheses.

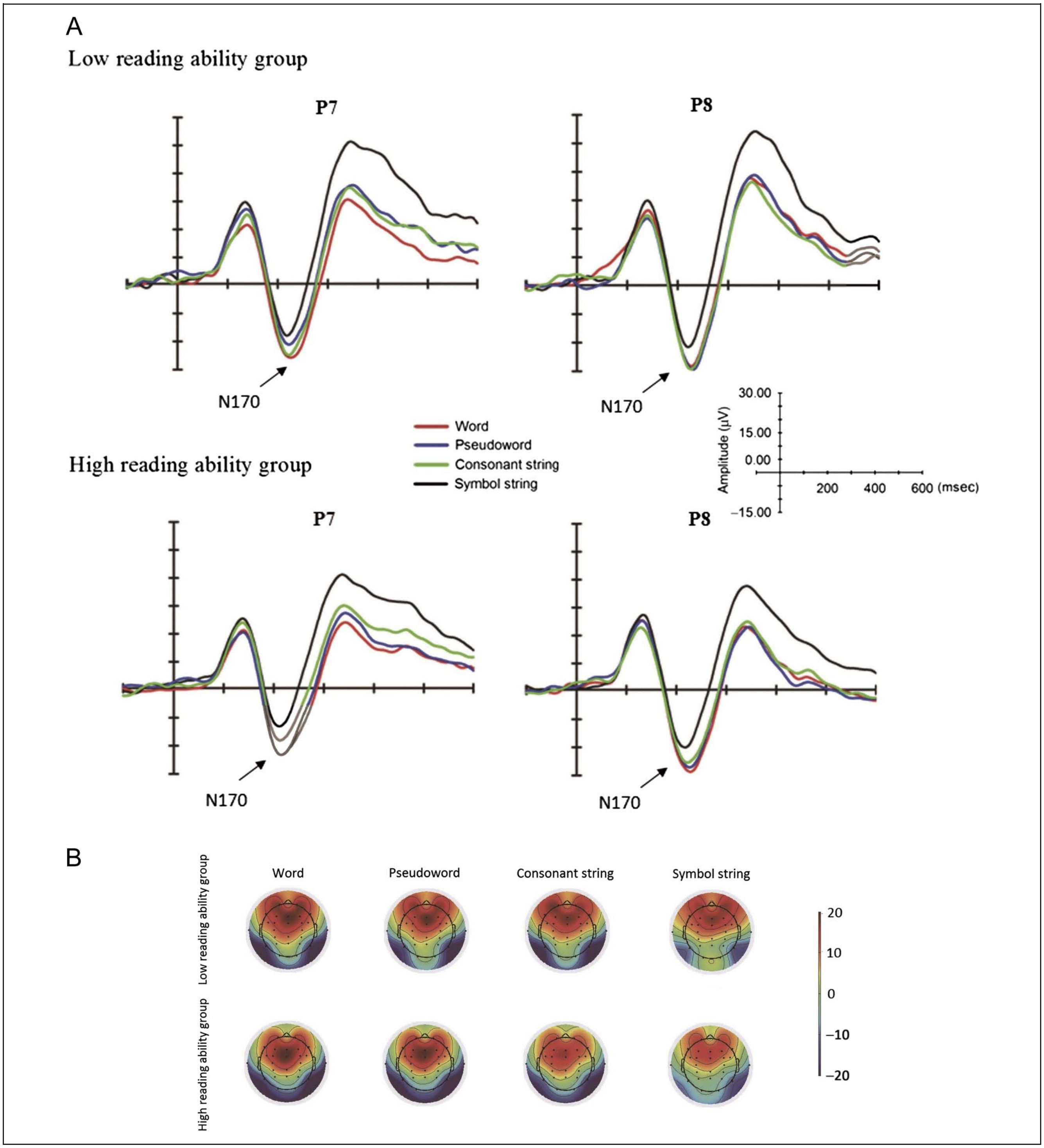

Figure 2. (A) Grand-averaged ERP waves of four categories of stimuli at P7/P8 in children with low and high reading ability. (B) Topographic maps at the N170 peak (225 msec) of four categories of stimuli in both groups of children.

the effect of Stimulus Category was significant either over the left hemisphere, $F(1.93, 25.15) = 14.33$, $p < .001$, or over the right hemisphere, $F(2.70, 35.08) = 11.74$, $p < .001$. Results of post hoc test (ANOVA with Bonferroni adjustment) showed that words evoked stronger N170 amplitude than symbol strings either over the left hemisphere (MD = 6.19, $p < .001$) or over the right hemisphere (MD = 4.98, $p = .001$). Furthermore, the other categories of stimuli containing letters (i.e., pseudowords and consonant strings) evoked significantly or marginally significantly stronger N170 amplitude than symbol strings: over the left hemisphere, pseudowords versus symbol strings (MD = 5.87, $p < .001$), consonant strings versus symbol strings (MD = 3.25, $p = .08$); and over the right hemisphere, pseudowords versus symbol strings (MD = 3.94, p = .01), consonant strings versus symbol strings (MD = 3.35, p = .07).

As noted before, fine tuning for visual words refers to the N170 difference between words/pseudowords and consonant strings. Results of our study show that children regardless of reading ability showed larger N170 for words/pseudowords/consonant strings than symbol strings. Thus, to examine our hypothesis for fine tuning more clearly, we mainly focused on the N170 responses to the three types of stimuli that consist of letters. Data were analyzed in a 3 × 2 × 2 three-way ANOVA with two within-subject factors Stimulus Category (word, pseudoword, consonant string) and Lateralization (left vs. right) as well as a between-subject factor Reading Ability (low vs. high). The outcomes of this analysis revealed a marginally significant main effect of Stimulus Category, $F(1.51, 39.13) = 3.60$, $p = .05$, a significant main effect of Lateralization, $F(1, 26) = 4.53$, $p = .04$, and a marginally significant interaction between Stimulus Category and Reading Ability, $F(1.51, 39.13) = 3.49$, $p = .05$. Importantly, there was a significant interaction of Stimulus Category × Lateralization × Reading Ability, $F(1.96, 51.06) = 4.88$, $p = .01$. Neither the main effect of Reading Ability nor the other interactions of the variables were significant: Reading Ability, $F(1, 26) = 0.02$, $p = .88$; Stimulus Category × Lateralization, $F(1.96, 51.06) = 2.24$, $p = .12$; Lateralization × Reading Ability, $F(1, 26) = 0.21$, $p = .65$. Figure 3 illustrates that children with low and high reading ability showed different patterns of N170 response to words, pseudowords, and consonant strings at the left OT electrodes but not at the right OT electrodes. To confirm this pattern and examine our hypothesis for fine tuning, we broke down the three-way interaction by Lateralization and Reading Ability. Specifically, for children with low/high reading ability, we conducted the analyses for the three stimulus categories within the hemispheres separately. Over the left hemisphere, in children with high reading ability, results revealed a significant main effect of Stimulus Category, $F(1.47, 19.09) = 7.67$, $p = .01$. Results of post hoc test (ANOVA with Bonferroni adjustment) showed that words evoked a significantly stronger N170 than consonant strings (MD = 2.94, p = .009). Moreover, pseudowords evoked a marginally stronger N170 than consonant strings (MD = 2.62, p = .07). No difference was found between words and pseudowords (MD = 0.31, p = 1.00). In children with low reading ability, the main effect of Stimulus Category was significant, $F(1.54, 20.05) = 5.35$, $p = .02$. Results of post hoc test showed that no significant difference was found either between words and consonant strings or between pseudowords and consonant strings (all ps > .05). Words evoked a stronger N170 than pseudowords (MD = 3.82, p = .01). Over the right hemisphere, however, in children with either low or high reading ability, there was no significant main effect of Stimulus Category (all ps > .05).[1]

As noted above, the results suggest that the fine N170 tuning for words is flexible and highly related to reading ability. To further examine this idea, we computed correlations between the fine tuning effect and children's reading ability. As outlined before, pseudowords were different from consonant strings mainly in terms of orthographic regularity, whereas words were different from consonant strings not only in orthographic regularity but also in visual familiarity and semantic features. In other words, the pseudoword versus consonant string comparison isolates orthographic regularity better (see Posner et al., 2000, for more discussion). We thus focused on the pseudowords–consonant string contrast in the correlation analysis. Also, the reading ability was indexed by the speed of pseudoword naming rather than word naming. Results showed that the N170 difference between pseudowords and consonant strings increased significantly with increases in reading speed over the left occipitotemporal area ($r = .43$, $p < .05$), that is, children with faster reading speed showed larger N170 response to

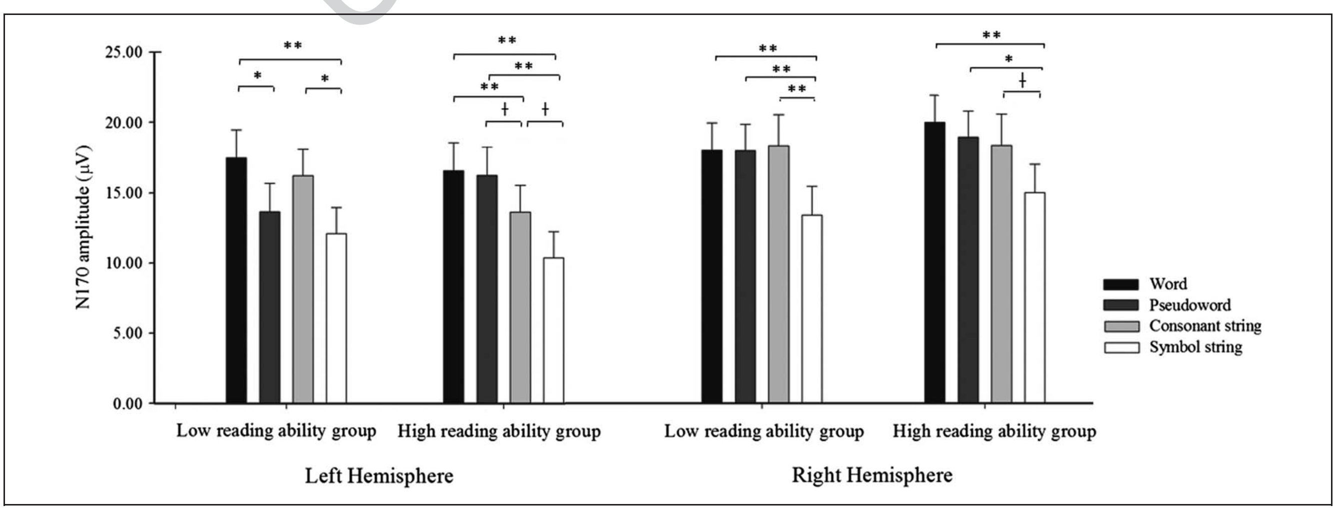

Figure 3. The mean of N170 amplitude for the four stimulus categories at P7/P8 in each children group. $^{\dagger}p < .1$, $^{*}p < .05$; $^{**}p < .01$.

pseudowords relative to consonant strings, whereas no significant correlation was found over the right hemisphere ($r = .22$, $p > .05$).

Although both groups were matched for external factors such as age or SES, we further explored whether other factors besides reading ability related to the N170 results. Data were analyzed in a mixed 4 × 2 × 2 ANCOVA with two within-subject factors Stimulus Category and Lateralization and a between-subject factor Reading Ability as well as with the SES, age, home literacy experience, and reading training time as covariates. Results showed that the three-way interaction of Stimulus Category × Lateralization × Reading Ability was still significant, $F(2.87, 63.03) = 3.00$, $p = .04$. These results suggest that the above factors did not affect the critical N170 effects.

We also computed partial correlations between the N170 pseudoword–consonant string difference and reading speed by controlling for influences of children's age, SES, home literacy experience, and formal reading training time. Results show that the N170 difference was also significantly correlated with reading speed at the left OT electrodes ($r = .44$, $p < .05$). Again, no significant correlation was found at the right OT electrodes ($r = .25$, $p > .05$).

N170 Peak Latency

Means and standard deviations of N170 peak latency for the four stimulus categories in children with low and high reading ability are illustrated in Table 3. Data were analyzed in a 4 × 2 × 2 ANOVA with within-subject factors Stimulus Category (word, pseudoword, consonant string, symbol string) and Lateralization (left vs. right) and a between-subject factor Reading Ability (low vs. high). The outcome of this analysis revealed that the main effect of Stimulus Category was significant, $F(2.28, 59.27) = 7.70$, $p = .001$. Results of post hoc test (Bonferroni adjusted for multiple comparisons) further showed that the peak latency of N170 evoked by words, pseudowords, and consonant strings was significantly longer than symbol strings (all ps < .01), whereas no significant difference was found between words, pseudowords, and consonant strings (all ps > .05). Neither the main effect of other variables nor the interaction of variables reached the significance level: Reading Ability, $F(1, 26) = 1.59$, $p = .22$, Stimulus Category × Reading Ability, $F(2.28, 59.27) = 2.03$, $p = .13$, Stimulus Category × Lateralization, $F(2.70, 70.20) = 1.50$, $p = .23$, and the other F values < 1.

Table 3. Mean N170 Latency (msec) of Four Categories of Stimuli at P7/P8 in Children with Low and High Reading Ability

	Low Reading Ability		*High Reading Ability*	
	LH	*RH*	*LH*	*RH*
Word	230 (5)	228 (3)	229 (7)	226 (5)
Pseudoword	227 (4)	231 (4)	223 (5)	228 (5)
Consonant	232 (4)	227 (3)	221 (4)	226 (5)
Symbol	223 (4)	226 (4)	216 (3)	215 (5)

Standard errors of means are given in parentheses.

DISCUSSION

Consistent with previous studies, we find that even young children aged 7 have the coarse tuning for print (i.e., N170 amplitude difference between words and symbol strings). More interestingly, our results for fine tuning (i.e., N170 amplitude difference between words and consonant strings) suggest that the brain sensitivity for orthographic patterns earlier in life than previously assumed. The existing ERP studies in children suggest that this fine tuning effect does not emerge in children younger than age of 10 (Posner et al., 2000). By separating children into two groups according to their reading ability, we observed this tuning effect in young children with high reading ability. Furthermore, correlations between fine tuning and reading skills suggest tight coupling between the development of visual expertise for orthographic patterns and the progress of reading acquisition at the beginning of learning to read.

Coarse N170 Tuning for Print

We observed a stronger N170 for words than for symbol strings in young children, irrespective of their reading ability, shortly (within 1 year) after learning to read in primary school. The results confirm the earlier findings that coarse neural tuning for words is established rapidly in children at the age of 7–8 (1.8 years of learning to read; Maurer et al., 2006; Parviainen, Helenius, Poskiparta, Niemi, & Salmelin, 2006).

Previous results in skilled adult readers and in children show that both real and pseudowords evoke a larger N170 than symbol strings (Maurer et al., 2007; Maurer, Brandeis, et al., 2005). In this study, we found that pseudowords and consonant strings (two stimulus categories that contained letters) similarly evoked a stronger N170 than symbol strings in both children groups, suggesting that the coarse tuning for words may reflect the selectivity of letter features. Recently, a training study in nonreading preschool children (about 6 years old) found that after learning to read letters (only total 3.6 hr), children rapidly displayed an increased N170 effect for words compared with symbol strings (Brem et al., 2010). This suggests that the coarse neural tuning may reflect specialization for letters or letter strings, which could be because of visual exposure or because of learning grapheme–phoneme conversion rules. The notion of such a coarse tuning is supported by the larger N170 for consonant strings compared with symbol strings in this study, which thus extends the findings of the previous studies employing just words and pseudowords as stimuli (Maurer et al., 2006). Although coarse tuning was reduced in dyslexic readers in previous studies (Araújo, Bramão, Faísca, Petersson, & Reis, 2012; Mahé, Bonnefond, Gavens, Dufour, & Doignon-Camus, 2012; Maurer et al., 2007; Helenius, Tarkiainen, Cornelissen, Hansen, & Salmelin, 1999), which suggest that coarse tuning is sensitive to the disruption of reading ability, it may be less sensitive to variation in reading skills among normal readers.

Fine N170 Tuning for Words

Interestingly, we found a stronger N170 response at left OT electrodes to words than to consonant strings in children as young as 7 years old with high reading ability but not in those with low reading ability. The emergence of this effect is much earlier than that reported by Posner et al. (2000), which found that it was not until 10 years of age did children show obvious N170 difference between words and consonant strings. A plausible interpretation for the earlier onset of fine neural tuning for words in this study is that individual differences in reading ability can exert a greater influence on N170 sensitivity than age on its own.

It is important to note that we found that, similar to real words, pseudowords evoked a greater N170 relative to consonant strings in children with high reading ability, which is in line with the previous findings in adults (Proverbio et al., 2004). As the critical difference between pseudowords and consonant strings lies in orthographic regularity, our results further indicated that the fine tuning for words reflects sensitivity for familiar orthographic patterns. Because of the tight relation between orthography and phonology in alphabetic scripts, it is difficult to demonstrate that such a fine tuning for words reflects the sensitivity for orthography, but not pronounceability. However, our results revealed no significant group difference either in the hit rate or in the RT in the color matching task, which suggested that children with low and high reading ability did not show any significant difference in behavioral response. Given that the task which participants performed was content irrelevant, the top–down regulations were largely minimized in this study. Our results thus may point to a perceptual origin for this ERP response, although higher levels of reading-related processes (e.g., grapheme-sound mapping) could also be involved. Consistently, a recent study in Chinese adults found that pseudocharacters produced a larger N170 than false characters despite both types of stimuli being unpronounceable (Lin et al., 2011). Thus, combining our results with those in adults, it is more likely that orthography serves as the main driver for the fine tuning for words. Furthermore, our results strongly suggest that the development of fine N170 tuning for words was specifically related to the increase of reading ability. Correlation analyses showed that children with faster reading speed had larger N170 differences between pseudowords and consonant strings over the left hemisphere even after controlling for the influence of age, SES, home literacy experience, and time of formal reading training. Specifically, this fine tuning effect was related to decoding skill as children's reading ability was indexed by the pseudoword naming speed in this study. With the development of decoding skill, children's reading strategy changes accordingly (Ehri, 1999). For example, children with low reading ability may read words and pseudowords by analyzing and remembering their spelling as distinct letter-based forms bounded fully to their pronunciation. However, children with high reading ability may read a word or pseudoword by analyzing and remembering chunks of letters or orthographic units that symbolize blends of sounds (Lindberg et al., 2011; Farrington-Flint, Coyne, Stiller, & Heath, 2008; Harm, McCandliss, & Seidenberg, 2003). This idea was consistent with results in a recent study, which suggest that orthographic spelling training can enhance reading and spelling ability in spelling-disabled children learning to read German (Ise & Schulte-Körne, 2010). It is thus possible that the difference in reading strategies is a potential mechanism for the emergence and development of N170 selectivity to orthographic regularity. In other words, it is likely that the potential difference in reading strategies between two reading ability groups results in the different N170 responses to words/pseudowords relative to consonant strings. Yet this explanation still requires empirical verification in future studies. By using a larger set of tests that measure specific processes and examining their contribution to the fine tuning, further results may provide more evidence for clarifying the critical subprocess that is associated with fine neural tuning for words.

Interestingly, although stimuli were presented in a short duration (300 msec) and the task was content irrelevant, the fine neural tuning recorded was specifically associated with children's reading ability. This finding suggests that, for children who read words fluently, word reading is a fast and automatic process. In other words, for children with skilled reading ability, higher levels of reading-related processes may be involved even while performing a nonlinguistic color matching task. On the basis of our data, however, it is difficult to infer the causality between fine neural tuning for words and reading ability, and it cannot be excluded that the N170 sensitivity to the fine tuning of words reflects an individual disposition for the acquisition of reading abilities. In the future, a longitudinal study may provide a precise measure of the change within individual and make it easier to relate the neural and behavioral changes (Ben-Shachar, Dougherty, Deutsch, & Wandell, 2011).

Left-lateralized N170 Effect

It should be important to note that there are two major methods to index the lateralization of word N170 in the existing literature. One is directly comparing absolute word N170 amplitudes between the left and right hemispheres, whereas the other is analyzing the word N170 amplitudes within each hemisphere in reference to control stimuli. The former method relies on an oversimplified assumption that the two hemispheres are anatomically symmetrical (Zhao et al., 2012). Moreover, in this study, we focused on the information sensitivity of the N170 effect. Thus, we explored the lateralization of the N170 amplitude differences in reference to control stimuli (i.e., the lateralization of the tuning effect). We found that the increased N170 for words/pseudowords relative to consonant strings was specific to the left OT electrodes and only in children with high reading ability, which suggest that a left-lateralized N170 was established and associated with reading experience at an early age (7 years old). Because of the low number of electrodes in our study, we did not conduct source modeling (Lantz, Grave de Peralta, Spinelli, Seeck, & Michel, 2003; Luu et al., 2001). However, results of source analyses with high spatial density revealed a larger dipole in the left hemisphere for words during the time interval of N170, which indicates a strong hemispheric effect at the level of N170 (Rossion, Joyce, Cottrell, & Tarr, 2003). Furthermore, results in previous studies with spatially sensitive techniques revealed an individual difference in the degree of hemispheric lateralization of word processing, which was related to variation in reading-related abilities (Uusvuori, Parviainen, Inkinen, & Salmelin, 2008; Pugh et al., 1997). For example, Pugh and his colleagues (1997) found that individual differences in the magnitude of phonological effects in word recognition, as indicated by spelling-to-sound regularity effects on lexical decision latencies and by sensitivity to stimulus length effects, were strongly related to differences in the degree of hemispheric lateralization in the extrastriate region and the inferior frontal gyrus. Our results combined with results in previous studies with spatial sensitive techniques suggest that an individual difference in the hemispheric lateralization of word processing was associated with the variations in reading-related abilities.

In addition, there are recent findings suggesting that the nature of the writing system may affect the word N170 and its lateralization (Zhang et al., 2011; Kim, Yoon, & Park, 2004). Using the first method described above and a highly similar color matching task as in this study, Cao et al. (2011) found that 7-year-old Chinese children show a left-lateralized N170 for Chinese characters. Conversely in this study, we found no left-lateralized N170 response to words in 7-year-old German children regardless of their reading ability. Although the participants in the two studies have the same age, importantly, they differed in reading experience. The youngest children in Cao et al.'s study have received about 1.5 years of formal reading training, whereas in this study, the German children only received about 0.6 years of reading training (see Table 1). Thus, these two studies suggest that reading experience rather than the nature of the writing system affects the N170 to words and its lateralization pattern even in younger children (Li et al., 2013).

Whereas several previous studies investigated coarse neural tuning and fine neural tuning for print separately (e.g., Brem et al., 2010; Maurer et al., 2006; Parviainen et al., 2006; Maurer, Brandeis, et al., 2005; Posner et al., 2000), this study extends these previous studies by combining both types of tuning in the same study and investigating two groups of children with high and low reading ability in the first year of learning to read. Generally, we find that even children who could not read fluently show coarse N170 tuning for words, whereas only children with high ability show fine tuning over the left hemisphere. Whereas coarse tuning was shown to differentiate between dyslexic and normal readers in several studies (Araújo et al., 2012; Mahé et al., 2012; Maurer et al., 2007; Helenius et al., 1999), this was not the case for high and low ability normal readers in this study. These results suggest that in the normal reading range measures of fine tuning in combination with shallow reading tasks may be more sensitive to detect variations in reading skills at the beginning of reading acquisition. Moreover, the distinct developmental pattern of coarse and fine tuning for words seems significant in the light of models of visual word processing (Dehaene et al., 2005; Coltheart et al., 1993; Seidenberg & McClelland, 1989). These models typically assume progressive processing of visual features, letters, orthographic patterns formed by letter combinations and entire words. The present results contribute to these models by clarifying the developmental time course of some of these processing steps. Coarse tuning underlying processing of letters develops quickly in normally reading children, whereas the development of fine tuning underlying processing of orthographic patterns related to the level of reading skill: It also develops quickly in children with high reading ability, but more slowly in children with low reading ability.

In conclusion, through the grouping method and multiple-stimulus comparisons, our study directly and clearly demonstrates that fine N170 tuning for words can be observed in young children who learn to read alphabetic scripts (7 years old), suggesting that the emergent age of this effect is much earlier than previously reported. Furthermore, this effect was specific to the left OT electrodes and positively correlated with the children's reading ability. The importance of reading ability suggests that the fine tuning effect is flexible and highly related to an individual's reading experience.

UNCITED REFERENCES

Maurer, Blau, Yoncheva, & McCandliss, 2011
Maurer, Brem, Bucher, & Brandeis, 2005
Spironelli & Angrilli, 2009

Acknowledgments

This work was supported by the National Science Foundation of China (31271109, 31070905) and the German Research Foundation (DFG; IRTG 1457). We thank Florian Beier for his great help with data collection and analyses.

Reprint requests should be sent to Su Li, Key Laboratory of Behavioral Science, Institute of Psychology, Chinese Academy of Sciences, No. 16, Lincui Road, Chaoyang District, Beijing, China, 100101, or via e-mail: lis@psych.ac.cn.

Note

1. As shown in Figure 2A, for children with low reading ability, larger P100 amplitude was evoked by symbol strings than words/consonant strings (all $ps < .01$) over the left hemisphere and pseudowords ($p < .05$)/consonant strings ($p = .08$) over the right hemisphere. Also, larger P100 amplitude was evoked by pseudowords than words ($p < .05$) over the left hemisphere. For children with high reading ability, larger P100 amplitude was found for symbol/consonant strings over words (all $ps < .05$) over the left hemisphere. These results suggest that some of the differences found in the N170 already started earlier during the P100 time window, but that these effects were generally more robust in the N170 time window.

REFERENCES

Araújo, S., Bramão, I., Faísca, L., Petersson, K. M., & Reis, A. (2012). Electrophysiological correlates of impaired reading in dyslexic pre-adolescent children. *Brain and Cognition, 79,* 79–88.

Ben-Shachar, M., Dougherty, R. F., Deutsch, G. K., & Wandell, B. A. (2011). The development of cortical sensitivity to visual word forms. *Journal of Cognitive Neuroscience, 23,* 2387–2399.

Bentin, S., Mouchetant-Rostaing, Y., Giard, M. H., Echallier, J. F., & Pernier, J. (1999). ERP manifestations of processing printed words at different psycholinguistic levels: Time course and scalp distribution. *Journal of Cognitive Neuroscience, 11,* 235–260.

Brambati, S. M., Termine, C., Ruffino, M., Danna, M., Lanzi, G., Stella, G., et al. (2006). Neuropsychological deficits and neural dysfunction in familial dyslexia. *Brain Research, 1113,* 174–185.

Brem, S., Bach, S., Kucian, K., Guttorm, T. K., Martin, E., Lyytinen, H., et al. (2010). Brain sensitivity to print emerges when children learn letter-speech sound correspondences. *Proceedings of the National Academy of Sciences, U.S.A., 107,* 7939–7944.

Burgund, E. D., Schlaggar, B. L., & Perterson, S. E. (2006). Development of letter-specific processing: The effect of reading ability. *Acta Psychologica, 122,* 99–108.

Cao, X. H., Li, S., Zhao, J., Lin, S. E., & Weng, X. C. (2011). Left-lateralized early neurophysiological response for Chinese characters in young primary school children. *Neuroscience Letters, 492,* 165–169.

Cassar, M., & Treiman, R. (1997). The beginnings of orthographic knowledge: Children's knowledge of double letters in words. *Journal of Educational Psychology, 89,* 631–644.

Coltheart, M., Curtis, B., Atkins, P., & Haller, M. (1993). Models of reading aloud—Dual-route and parallel-distributed-processing approaches. *Psychological Review, 100,* 589–608.

Cunningham, A. E., Perry, K. E., & Stanovich, K. E. (2001). Converging evidence for the concept of orthographic processing. *Reading and Writing, 14,* 549–568.

Daneman, M. (1991). Individual differences in reading skills. In R. Barr, M. Kamil, P. B. Mosenthal, & P. D. Pearson (Eds.), *Handbook of reading research* (pp. 512–538). Hillsdale, NJ: Erlbaum.

Dehaene, S., Cohen, L., Sigman, M., & Vinckier, F. (2005). The neural code for written words: A proposal. *Trends in Cognitive Science, 9,* 335–341.

Ehri, L. C. (1999). Phases of development in learning to read words. In J. Oakhill & R. Beard (Eds.), *Reading development and the teaching of reading: A psychological perspective* (pp. 79–108). Malden, MA: Blackwell Publishers.

Farrington-Flint, L., Coyne, E., Stiller, J., & Heath, E. (2008). Variability in children's early reading strategies. *Educational Psychology, 28,* 643–661.

Friedrich, M., & Friederici, A. D. (2005). Phonotactic knowledge and lexical-semantic processing in one-year-olds: Brain responses to words and nonsense words in picture contexts. *Journal of Cognitive Neuroscience, 17,* 1785–1802.

Friedrich, M., & Friederici, A. D. (2006). Early N400 development and later language acquisition. *Psychophysiology, 43,* 1–12.

Gillon, G., & Dodd, B. J. (1994). A prospective study of the relationship between phonological, semantic and syntactic skills and specific reading disability. *Reading and Writing, 6,* 321–345.

Gratton, G., Coles, M. G., & Donchin, E. (1983). A new method for off-line removal of ocular artifact. *Electroencephalography and Clinical Neurophysiology, 55,* 468–484.

Greenhouse, S. W., & Geisser, S. (1959). On methods in the analysis of profile data. *Psychometrika, 24,* 95–112.

Harm, M. W., McCandliss, B. D., & Seidenberg, M. S. (2003). Modeling the successes and failures of interventions for disabled readers. *Scientific Studies of Reading, 7,* 155–182.

Helenius, P., Tarkiainen, A., Cornelissen, P., Hansen, P. C., & Salmelin, R. (1999). Dissociation of normal feature analysis and deficient processing of letter-strings in dyslexic adults. *Cerebral Cortex, 9,* 476–483.

Hollingshead, A. D. B. (1975). *Four factor index of social status* (pp. 1–24). Department of Sociology, Yale University.

Ise, E., & Schulte-Körne, G. (2010). Spelling deficits in dyslexia: Evaluation of an orthographic spelling training. *Annual of Dyslexia, 60,* 18–39.

Jenkins, J. R., Fuchs, L. S., Van Den Broek, P., Espin, C., & Deno, S. L. (2003). Sources of individual differences in reading comprehension and reading fluency. *Journal of Educational Psychology, 95,* 719.

Kim, K. H., Yoon, H. W., & Park, H. W. (2004). Spatiotemporal brain activation pattern during word/picture perception by native Koreans. *NeuroReport, 15,* 1099–1103.

Lachmann, T., Berti, S., Kujala, T., & Schröger, E. (2005). Diagnostic subgroups of developmental dyslexia have different deficits in neural processing of tones and phonemes. *International Journal of Psychophysiology, 56,* 105–120.

Landerl, K., Wimmer, H., & Moser, E. (1997). *SLRT Salzburger Lese-und Rechtschreibtest (Salzburg Reading and Orthography Test)*. Huber.

Lantz, G., Grave de Peralta, R., Spinelli, L., Seeck, M., & Michel, C. M. (2003). Epileptic source localization with high density EEG: How many electrodes are needed? *Clinical Neurophysiology, 114,* 63–69.

Levy, B. A., Gong, Z. Y., Hessels, S., Evans, M. A., & Jared, D. (2006). Understanding print: Early reading development and the contributions of home literacy experiences. *Journal of Experimental Child Psychology, 93,* 63–93.

Li, S., Lee, K., Zhao, J., Yang, Z., He, S., & Weng, X. C. (2013). Neural competition as a developmental process: Early hemispheric specialization for word processing

delays specialization for face processing. *Neuropsychologia, 51,* 950–959.
Lin, S. E., Chen, H. C., Zhao, J., Li, S., He, S., & Weng, X. C. (2011). Left-lateralized N170 response to unpronounceable pseudo but not false Chinese characters: The key role of orthography. *Neuroscience, 190,* 200–206.
Lindberg, S., Lonnemann, J., Linkersdörfer, J., Biermeyer, E., Mähler, C., Hasselhorn, M., et al. (2011). Early strategies of elementary school children's single word reading. *Journal of Neurolinguistics, 70,* 1–15.
Luu, P., Tucker, D. M., Englander, R., Lockfeld, A., Lutsep, H., & Oken, B. (2001). Localizing acute stroke-related EEG changes: Assessing the effects of spatial undersampling. *Journal of Clinical Neurophysiology, 18,* 302–317.
Mahé, G., Bonnefond, A., Gavens, N., Dufour, A., & Doignon-Camus, N. (2012). Impaired visual expertise for print in French adults with dyslexia as shown by N170 tuning. *Neuropsychologia, 50,* 3200–3206.
Maurer, U., Blau, V. C., Yoncheva, Y. N., & McCandliss, B. D. (2011). Development of visual expertise for reading: Rapid emergence of visual familiarity for an artificial script. *Developmental Neuropsychology, 35,* 404–422.
Maurer, U., Brandeis, D., & McCandliss, B. D. (2005). Fast, visual specialization for reading in English revealed by the topography of the N170 ERP response. *Behavioral and Brain Functions, 1,* 1–13.
Maurer, U., Brem, S., Bucher, K., & Brandeis, D. (2005). Emerging neurophysiological specialization for letter strings. *Journal of Cognitive Neuroscience, 17,* 1532–1552.
Maurer, U., Brem, S., Bucher, K., Kranz, F., Benz, R., Steinhausen, H. C., et al. (2007). Impaired tuning of a fast occipito-temporal response for print in dyslexic children learning to read. *Brain, 130,* 3200–3210.
Maurer, U., Brem, S., Kranz, F., Bucher, K., Benz, R., Halder, P., et al. (2006). Coarse neural tuning for print peaks when children learn to read. *Neuroimage, 33,* 749–758.
Maurer, U., Zevin, J. D., & McCandliss, B. D. (2008). Left-lateralized N170 effects of visual expertise in reading: Evidence from Japanese syllabic and logographic scripts. *Journal of Cognitive Neuroscience, 20,* 1–14.
McCandliss, B. D., Cohen, L., & Dehaene, S. (2003). The visual word form area: Expertise for reading in the fusiform gyrus. *Trends in Cognitive Sciences, 7,* 293–299.
McCandliss, B. D., Posner, M., & Givon, T. (1997). Brain plasticity in learning visual words. *Cognitive Psychology, 33,* 88–110.
Miller, S. L., & Wood, F. B. (1995). Electrophysiological indicants of black-white discrimination performance for letter and non-letter patterns. *International Journal of Neuroscience, 80,* 299–316.
Oldfield, R. C. (1971). Assessment and analysis of handedness: Edinburgh inventory. *Neuropsychologia, 9,* 97–113.
Parviainen, T., Helenius, P., Poskiparta, E., Niemi, P., & Salmelin, R. (2006). Cortical sequence of word perception in beginning readers. *The Journal of Neuroscience, 26,* 6052–6061.
Posner, M., & McCandliss, B. D. (2000). Brain circuitry during reading. In R. Klein & P. McMullen (Eds.), *Converging methods for understanding reading and dyslexia* (pp. 305–337). Cambridge, MA: MIT Press.
Proverbio, A. M., Vecchi, L., & Zani, A. (2004). From orthography to phonetics: ERP measures of grapheme-to-phoneme conversion mechanisms in reading. *Journal of Cognitive Neuroscience, 16,* 301–317.
Pugh, K. R., Shaywitz, B. A., Shaywitz, S. E., Shankweiler, D. P., Katz, L., Fletcher, J. M., et al. (1997). Predicting reading performance from neuroimaging profiles: The cerebral basis of phonological effects in printed word identification. *Journal of Experimental Psychology: Human Perception and Performance, 23,* 299.
Rayner, K., & Pollatsek, A. (1989). *The psychology of reading*. Routledge.
Rossion, B., Joyce, C. A., Cottrell, G. W., & Tarr, M. J. (2003). Early lateralization and orientation tuning for face, word, and object processing in the visual cortex. *Neuroimage, 20,* 1609–1624.
Seidenberg, M. S., & McClelland, J. L. (1989). A distributed, developmental model of word recognition and naming. *Psychological Review, 96,* 523–568.
Sharbrough, F., Chatrian, G., Lesser, R. P., Luders, H., Nuwer, M., & Picton, T. W. (1994). American EEG Society guidelines for standard electrode position nomenclature. *Journal of Clinical Neurophysiology, 8,* 200–202.
Share, D. (1995). Phonological recoding and self-teaching: Sine qua non of reading acquisition. *Cognition, 55,* 151–218.
Spironelli, C., & Angrilli, A. (2009). Developmental aspects of automatic word processing: Language lateralization of early ERP components in children, young adults and middle-aged subjects. *Biological Psychology, 80,* 35–45.
Turkeltaub, P. E., Gareau, L., Flowers, D. L., ZeYro, T. A., & Eden, G. F. (2003). Development of neural mechanisms for reading. *Nature Neuroscience, 6,* 767–773.
Uusvuori, J., Parviainen, T., Inkinen, M., & Salmelin, R. (2008). Spatiotemporal interaction between sound form and meaning during spoken word perception. *Cerebral Cortex, 18,* 456–466.
Wang, M. Y., Kuo, B. C., & Cheng, S. K. (2011). Chinese characters elicit face-like N170 inversion effects. *Brain and Cognition, 77,* 419–431.
Whitehurst, G. J., & Lonigan, C. J. (1998). Child development and emergent literacy. *Child Development, 69,* 848–872.
Wong, A. C., Gauthier, I., Woroch, B., DeBuse, C., & Curran, T. (2005). An early electrophysiological response associated with expertise in letter perception. *Cognitive, Affective, & Behavioral Neuroscience, 5,* 306–318.
Zhang, M. X., Jiang, T., Mei, L. L., Yang, H. M., Chen, C. S., & Xue, G. (2011). It's a word: Early electrophysiological response to the character likeness of pictographs. *Psychophysiology, 48,* 950–959.
Zhao, J., Li, S., Lin, S. E., Cao, X. H., He, S., & Weng, X. C. (2012). The selectivity of N170 in the left hemisphere as an electrophysiological marker for expertise in reading Chinese. *Neuroscience Bulletin, 28,* 577–584.