

Neural competition as a developmental process: Early hemispheric specialization for word processing delays specialization for face processing

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ABSTRACT

Little is known about the impact of learning to read on early neural development for word processing and its collateral effects on neural development in non-word domains. Here, we examined the effect of early exposure to reading on neural responses to both word and face processing in preschool children with the use of the Event Related Potential (ERP) methodology. We specifically linked children's reading experience (indexed by their sight vocabulary) to two major neural markers: the amplitude differences between the left and right N170 on the bilateral posterior scalp sites and the hemispheric spectrum power differences in the γ band on the same scalp sites. The results showed that the left-lateralization of both the word N170 and the spectrum power in the γ band were significantly positively related to vocabulary. In contrast, vocabulary and the word left-lateralization both had a strong negative direct effect on the face right-lateralization. Also, vocabulary negatively correlated with the right-lateralized face spectrum power in the γ band even after the effects of age and the word spectrum power were partialled out. The present study provides direct evidence regarding the role of reading experience in the neural specialization of word and face processing above and beyond the effect of maturation. The present findings taken together suggest that the neural development of visual word processing competes with that of face processing before the process of neural specialization has been consolidated.

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1. Introduction

Learning to read is an essential cultural experience for children. Evidence abounds that early exposure to reading has many positive effects (Olson, 1994; Whitehurst & Lonigan, 1998). Surprisingly, we have limited knowledge about its impact on early neural development for word processing (Ben-Shachar, Dougherty, Deutsch, & Wandell, 2011; Brem et al., 2010; Maurer, Brem, Bucher, & Brandeis, 2005; Maurer et al., 2006; Parviainen, Helenius, Poskiparta, Niemi, & Salmelin, 2006), and its collateral effects on neural development in non-word domains (Dehaene & Cohen, 2007; Dundas, Plaut, & Behrmann, 2012).

To bridge this gap, we specifically compared the impact of early reading experience on neural development of word and face processing in preschool children. One reason to do so is that among the many skills young children must acquire, the skills to

read and process faces are amongst the most prominent. Deficiencies in either of these domains are associated with debilitating impairments (e.g., dyslexia, autism). Further, studies using electroencephalography (EEG) show that when seeing words and faces, children produce morphologically similar event-related potentials (ERPs); these similar responses also undergo a comparable developmental course until adolescence when neural responses to words and faces become differentiated (Brem et al., 2006, 2009; Itier & Taylor, 2004).

A growing number of neuroimaging studies with adults revealed that the left mid-fusiform region, which has been labeled as the Visual Word Form Area (VWFA) (Cohen et al., 2000, 2002; McCandliss, Cohen, & Dehaene, 2003), plays an important role in the processing of written words. Different from the left-lateral activation of written word processing, a right (sometimes bilateral) ventral occipito-temporal area, including parts of the middle fusiform gyrus, is more strongly activated by faces than other objects (Kanwisher, McDermott, & Chun, 1997; Puce, Allison, Asgari, Gore, & McCarthy, 1996; Tarkiainen, Cornelissen, & Salmelin, 2002). Perhaps related to these regions, many electrophysiological studies have identified a negative event-related

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potential component, known as N170. N170 can be readily recorded over the left posterior scalp sites when skilled readers are presented with visual words in different scripts. The N170 for alphabetic words at the posterior electrodes in the left hemisphere is greater for word processing than for processing of symbol strings or line-drawings of common objects (Bentin, Mouchetant-Rostaing, Giard Echallier, & Pernier, 1999; Mercure, Dick, Halit, Kaufman, & Johnson, 2008; Maurer et al., 2005; Rossion Joyce, Cottrell, & Tarr, 2003). The N170 response for Chinese characters was especially stronger than that of line-drawings in the left hemisphere (Cao, Li, Zhao, Lin, & Weng, 2011). Also, the real Chinese characters evoked greater N170 in the left posterior region than false-characters and stroke combination (Lin et al., 2011). A recent study revealed a more robust pattern of left-lateralization N170 for Chinese character: the left N170 but not the right N170 differentiated Chinese characters from control stimuli (Zhao et al., 2012). Thus, this left-lateralized N170 effect appears to be robust across different types of scripts and may reflect the specialized processing of words in skilled readers.

A similar N170 component has been found for face processing in adults as well. At about 170 ms post-stimulus presentation, negative event-related potentials are larger for faces than for many other categories of stimuli, especially in the right hemisphere (Bentin, Allison, Puce, Perez, & McCarthy, 1996; Carmel & Bentin, 2002; Mercure et al., 2008). This ERP is highly sensitive to faces; even the simplest hint of a face, such as a face outline or even just a line-drawing of a single component (e.g. eyes), can readily elicit N170 to an extent similar to that elicited by a real, complete face image (Bentin et al., 1996; Henderson, McCulloch, & Herbert, 2003; Taylor, Itier, Allison, & Edmonds, 2001a).

Collectively, the results from neural imaging and EEG studies with adults suggest that different kinds of visual expertise may have differential neural bases in the left or right VOT. Word processing may be more localized in the left hemisphere, whereas face processing may be more localized in the right hemisphere. Presumably, this differential hemispheric specialization for faces and words is a consequence of the decade-long acquisition of face and word processing expertise during childhood.

Studies using electroencephalography (EEG) consistently show that the development of electrophysiological responses to word processing gradually emerges during childhood. Maurer and colleagues (Maurer et al., 2005) investigated the ERP responses to written German words in kindergarten children who had no reading experience (average age of 6.5 years). They found that the word–symbol difference of the N170 effect was absent in children with low letter knowledge but marginally significant in children with high letter knowledge (the N170 latency was between 164 ms and 269 ms). When the same group of children was in the 2nd grade (average age of 8.3 years), and had received formal reading training for one year, a larger N170 was observed for letter strings than symbol strings at both the group and individual levels, but this N170 effect was not yet left-lateralized (Maurer et al., 2006). Cao et al. (2011) found an increased and left-lateralized N170 response for Chinese words compared to line drawings among 7- to 13-year-old children. This N170 latency was found to decrease with age. For 7 year olds the latency was approximately 236 ms, whereas in 9 year olds it was approximately 228 ms. Additionally, Brem and colleagues found a left lateralized tuning effect of N170 for visual words, compared to symbols, in 10-year-old children. In addition to a similar decrease in latency, this effect also decreased in amplitude throughout adolescence and continued to decrease into adulthood (Brem et al., 2006, 2009). Thus, although the exact timing of left lateralization for visual word N170 appears to differ in different

scripts, both studies in Chinese and non-Chinese children showed highly similar developmental pattern (Cao et al., 2011).

With regard to face processing, by 3 months of age, the N290, the component of similar morphology to the adult N170, showed adult-like patterns of enhanced amplitude to faces relative to visual noise images containing the amplitude spectra of a face (de Haan, Pascalis, & Johnson, 2002; Halit, Csibra, Volein, & Johnson, 2004). With increased age, this ERP component occurs earlier in latency and begins to resemble the adult N170 (e.g., right lateralized). For example, gray scale photographs of faces evoked N170 in 4- to 5-year-olds with a latency period lasting between 230 and 300 ms (Taylor, Edmonds, McCarthy, & Allison, 2001b). Schematic pictures of faces evoked N170 in 4-year-olds and 8- to 10-year olds with a latency period of about 240 ms, and about 220 ms respectively (Henderson et al., 2003). Nevertheless, the N170 response to faces in 14-year-olds still has a smaller amplitude and a longer latency period than that of adults, regardless of whether the stimuli are schematic faces or photographs (Itier & Taylor, 2004; Taylor, McCarthy, Saliba, & Degiovanni, 1999). The existing evidence taken together suggests that, like those associated with word processing, specific electrophysiological responses to faces emerge early but remain immature and continue to develop and become more adult-like throughout childhood.

As made clear by the above literature review, there exist considerable similarities as well as differences between the neurodevelopment of visual word processing and that of face processing. In particular, the neural markers (e.g., N170) for both word and face processing seem to develop in a similarly protracted time course. Further, the neural activities associated with word and face processing seem to be highly similar during the early stages of development, and then, with increased age, become differentiated in terms of lateralization. Word processing becomes increasingly left lateralized, whereas face processing tends to become more right lateralized, particularly in the ventral occipital–temporal cortex (VOT).

This early similarity and later differentiation may reflect interactions between the two developing neural systems as a result of learning to read. One possibility is that reading experience facilitates the development of both the word and face neural systems, leading to their eventual differentiation (*the facilitation hypothesis*). Alternatively, due to neural competition, reading experience may facilitate the development of the word system but concurrently delay that of the face system (*the competition hypothesis*: Dehaene & Cohen, 2007). Perhaps, similarities between children's neural responses to words and faces are simply coincidental. Thus, children's neural responses to faces should neither be related to reading experience or neural responses to words (*Null hypothesis*).

We directly tested the three possibilities in 5- and 6-year-olds prior to formal schooling through examining ERP responses to words and schematic faces. To disentangle the effect of age-related maturational factors and reading experience, we capitalized on the considerable variability in preschoolers' reading experience. Without formal schooling, some preschoolers merely know a handful of written words, whereas others have a large sight vocabulary (Whitehurst & Lonigan, 1998). We specifically linked children's reading experience (indexed by sight vocabulary, i.e. the words that appear frequently in most reading materials children encounter and could be recognized by children) to two major neural markers. The first was the amplitude differences between the left and right N170, a negative ERP obtained about 170 ms after the onset of word or face stimuli, located in the bilateral posterior scalp sites. Evidence shows that in the mature brain, the word N170 is more left-lateralized whereas the face N170 is more right-lateralized (Bentin et al., 1996; 1999; Cao

et al., 2011; Lin et al., 2011; Maurer et al., 2005; Rossion et al., 2003). As reported in previous developmental studies, the time window of children's N170 to words and to faces is longer than that of adults. Therefore, a larger window of time will be selected to detect the amplitude of the word and face N170 in the present study, but the term "N170 amplitude" will be used for ease of description and understanding.

The second neural marker was the spectrum power in the γ band on the same posterior sites. It is hypothesized that spectral analysis of the EEG will reveal broadband energy distribution, and that from this spectrum of energy distribution we will be able to differentiate among certain cognitive processes. Although neural signals in the gamma frequency range (roughly 30–80 Hz) may not be unique to, or specific indicators of, certain cognitive function (Herrmann, Munk, & Engel, 2004), they are widely implicated in human perceptual processes (Herrmann, Mecklinger & Pfeifer, 1999; Senkowski & Herrmann, 2002; Tallon-Baudry & Bertrand, 1999; Tallon-Baudry, Bertrand, Delpuech, & Pernier, 1996). The stimulus-specific oscillations in the γ band have been shown to be category-specific (Engell & McCarthy, 2011). They are associated with synchronized neural activities in the visual system and are involved in the construction of coherent object representations through the use of elementary feature-binding processes (Singer & Gray, 1995; Tallon-Baudry & Bertrand, 1999). Studies have also demonstrated that binding-related 40 Hz oscillations emerge in an infant brain by around 8 months of age (Csibra, Davis, Spratling, & Johnson, 2000).

According to Galambos's classification (1992), there are spontaneous, induced and evoked gamma activities, which can be differentiated by the degree of phase-locking to the stimulus. Spontaneous gamma activity is completely uncorrelated with the experimental setting. For this reason, we do not focus on this type of activity in the present study. Induced activity is defined as being produced by the stimulus and occurs after each stimulus with varying onset time and/or phase jitter. Evoked gamma activity is phase-locked to the onset of an experimental condition across trials and can be extracted in the averaged evoked response. Here, to better describe the brain response evoked by words and faces within the N170 time window, we focused on the gamma activities evoked by different categories (i.e., faces vs. words). Albeit the gamma activities were most apparent at a frequency of 40 Hz; however, a broader range, between 30 and 50 Hz, was selected for analysis based on previous studies with young children (Csibra et al., 2000; Kaufman, Csibra, & Johnson, 2005).

It should be noted that the existing adult results regarding the lateralization of N170 for Chinese character are somewhat mixed comparing with that of alphabetic scripts. Both bilateral (Kim, Yoon, & Park, 2004; Zhang et al., 2011) and left-lateralized N170 effects were reported (Cao et al., 2011; Lin et al., 2011; Liu & Perfetti, 2003; Wong, Gauthier, Woroch, DeBuse & Curran, 2005). It is possible that both script-type and task demand contribute to the consistent results of N170 laterality in alphabetic scripts and the inconsistent results in Chinese characters. For example, there is different engagement of the left-lateralized phonological system in reading the two scripts. The phonological system is automatically activated and dominates other processes such as semantic processing in reading alphabetic scripts. It may contribute to a reliable left-lateralized N170 effect across tasks. However, Chinese character reading may not automatically involve in strong phonological processing (Perfetti et al. 2007; Zhou, Ye, Cheung, & Chen, 2009). Thus, task-demand is more important to modulate lateralization. The lateralization of N170 may be more prone to top-down task modulation for Chinese than for alphabetic scripts. Accordingly, Liu and Perfetti (2003) showed a left-lateralized N170 through a phonological task which

mainly activated the left hemisphere (Buchsbaum, Hickok, & Humphries, 2001). Kim et al. (Kim et al., 2004; Yum, Holcomb, & Grainger, 2011) found a bilateral N170 by using a semantic task which relies more on the right hemisphere (Bookheimer, 2002). Therefore, it is crucial to design a content-irrelevant task to allow us to minimize potential high-level linguistic (especially phonological) modulation and attentional biases across stimuli when examining N170 effect for Chinese characters. In the current study, we adopted the color-matching task which has been proved as a valid task in the studies on expertise in reading Chinese (Cao et al., 2011; Lin et al., 2011; Zhao et al., 2012). In those studies, we have found a robust left-lateralized N170 effect to Chinese characters.

2. Material and methods

2.1. Participants

Eighty-one children participated: 40 5-year-olds ($M_{\text{age}}=5.40$ years, $SD=0.05$, 19 males) and 41 6-year-olds ($M_{\text{age}}=6.15$ years, $SD=0.03$, 19 males). All children were monolingual native Chinese speakers. They had no formal schooling, no known disorders, and had normal vision.

We administered the Combined Raven's Test (CRT, Chinese version, 1991) to assess children's IQ and a 61-item Chinese word recognition test developed for preschoolers (Chow, McBride-Chang, Cheung, & Chow, 2008) to assess children's sight vocabulary. The words in the test were arranged in order of increasing difficulty, and children were asked to read each word aloud one by one. The possible maximum score for the task was 61. The maximum vocabulary score of our participants was 61 and the minimum was 1. We used the CRT age norms to derive children's IQ scores. Because the vocabulary test had no norms, we standardized children's sight vocabulary z-scores within the whole sample with z-transformations (henceforth referred to as vocabulary scores). Children's IQ (5 years: $M=115.48$, $SD=12.31$; 6 years: $M=115.58$, $SD=11.25$) and vocabulary scores (5 years: $M=-0.15$, $SD=1.0$; 6 years: $M=0.16$, $SD=1.0$) between the age groups were not significantly different ($t_{\text{IQ}}(79)=0.42$, $p=0.97$ and $t_{\text{vocabulary}}(79)=1.40$, $p=0.17$).

2.2. Materials

Faces and Chinese words were used as stimuli (Fig. 1a), and there were 30 different items for each category. The Chinese words were all common words. The faces were schematic face drawings that differed in the shape of their eyes and mouths. The schematic face drawings were matched to the physical format (spatial frequency and contrast) of the words. Each category had three colors: green, red, and yellow (10 each). The dimensions of each image were 2.38 cm \times 2.41 cm.

2.3. Procedure

Stim (Version 2, Compumedics Neuroscan) software was used to present the stimuli in the experiment. The stimuli were presented individually and randomly in one of the three colors on a gray background (Fig. 1a). Stimuli subtended 1.36° of the horizontal visual angle and 1.38° of the vertical visual angle from the participants' eyes. Each trial ran as follows: a grid appeared in one of the three colors for 200 ms, followed by a texture noise mask for 50 ms. After a 700 ms interval, a target stimulus appeared for 200 ms in one of the three colors. Following another 800 ms interval, a star appeared for 200 ms.

Children sat 100 cm away from the screen and compared the color of the stimulus with that of the preceding grid by pressing one of two buttons. The stimuli with different colors were presented randomly. Participants pressed the button only after they saw the star to minimize potential influence of button pressing on EEG signals. The number of same or different trials was equal. This color-matching task is content-irrelevant, which allowed us, more so than passive viewing, to minimize the effects of top-down modulations and attentional biases across stimuli. Also, it ensured to maintain children's attention to the screen. Children participated in either the schematic face drawings or word condition first, with the order of the conditions and button assignments counterbalanced between participants. Although color-matching is easy for children to perform, children were given practice trials to ensure that they understood the instructions and were able to perform the task prior to the start of the experiment. All the children reported enjoying playing the game. Child participants were also instructed to fixate on the center of the screen to achieve a high score. During the experiment, children had a break after every 60 trials and received a sticker for encouragement.

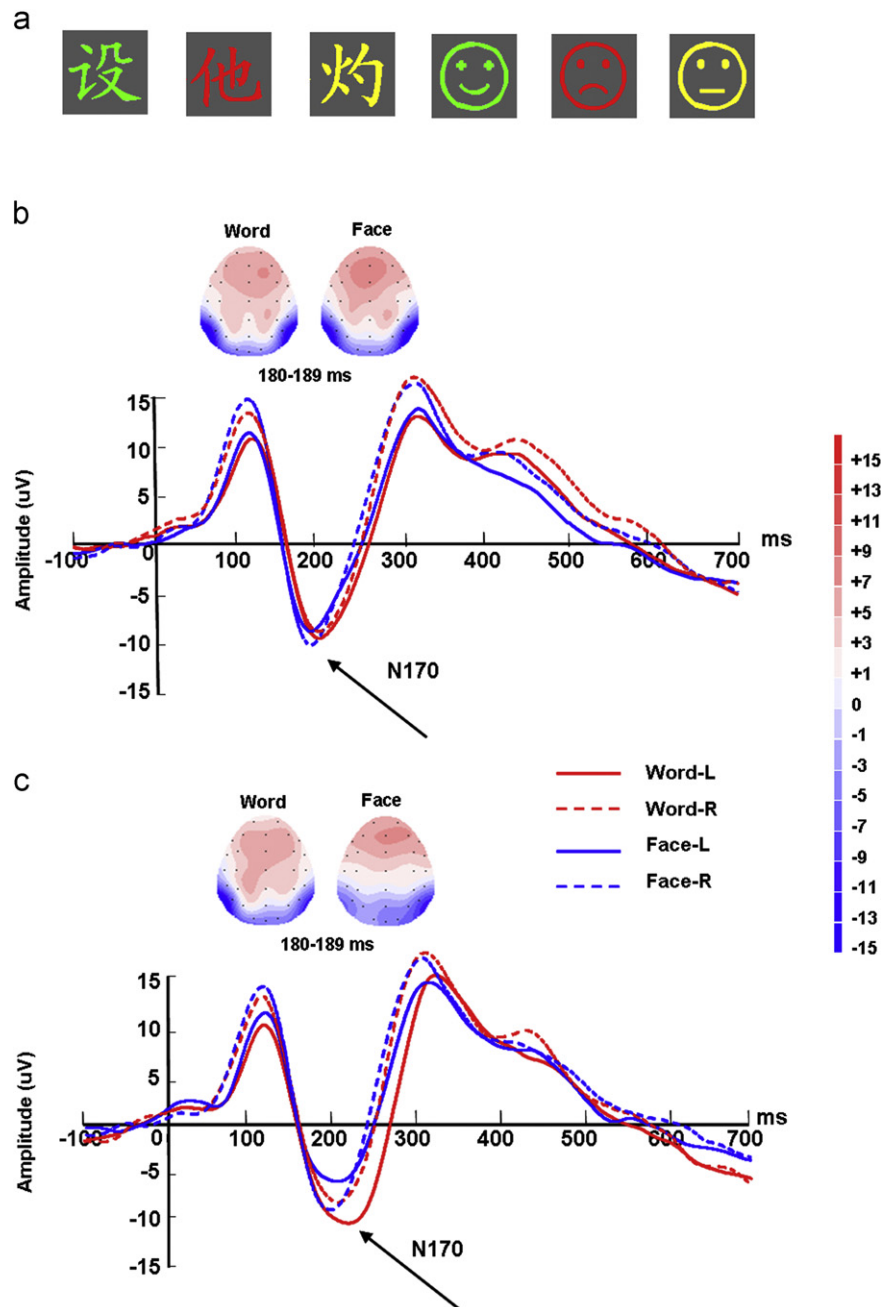


Fig. 1. (a) Examples of the two categories of stimuli used in the experiment. The left three images are Chinese words and the right three images are faces. (b) Grand average ERPs to the two categories of stimuli in the left and right hemispheres and the scalp voltage maps at 180–189 ms for children with low reading ability. (c) Grand average ERPs to the two categories of stimuli in the left and right hemispheres and the scalp voltage map at 180–189 ms for children with high reading ability. The two vocabulary groups (high vs. low) were divided according to the median of the word recognition task scores for all children. The solid red lines are ERPs for words in the left hemisphere. The solid blue lines are ERPs for faces in the left hemisphere. The dashed red lines are ERPs for words in the right hemisphere. The dashed blue lines are ERPs for faces in the right hemisphere.

2.4. EEG recording and analysis

EEG was recorded from 32 Ag/AgCl electrodes in an elastic cap (NeuroScan Inc., El Paso, TX, USA). Electrode placement was done according to the 10–20 international system. The horizontal EOG was recorded by a bipolar montage using two electrodes placed on the right and left external canthus. The vertical electrooculogram (EOG) was monitored with two electrodes above and below the left eye. Bilateral mastoids served as a reference and the GND between FPz and Fz electrodes as a ground (an average reference transformation was used in later data analyses). All channels were amplified with a band pass from DC to 100 Hz with 1000 Hz sampling rate. Electrode impedances were kept below 5 k Ω . Using Neuroscan 4.3 software, eye blinks were corrected and the data was digitally filtered by band-pass (0.5–30 Hz), segmented with epochs of 800 ms, including a 100 ms pre-stimulus baseline, regulated by the baseline correction (–100 ms to 0 ms). Trials with artifacts exceeding $\pm 100 \mu\text{V}$ were

rejected. Then, EEG signals of trials with correct responses were averaged to derive ERPs for words and schematic face drawings, respectively. At least 40 trials were averaged for each category for each child.

2.5. ERP analysis

One pair of channels on the occipito-temporal area was selected according to the topographic maxima in the negative field over both hemispheres (T5/T6). The peak values of amplitude and associated latencies on these channels for N170 segment were obtained between 100 ms and 250 ms after stimulus onset for minima. The time window was selected based on the previous developmental literature (Cao et al., 2011; Henderson et al., 2003; Maurer et al., 2006) and visual inspection of the individual waveform in our study. The N170 peaks for each trial

between 100 ms and 250 ms were checked for each electrode in each condition, and then the averaged N170 peak amplitudes were obtained for each stimulus category.

2.6. γ Band power spectrum analysis

A time-dependent power spectrum within the γ frequency band (30–50 Hz) was extracted from T5 and T6 based on the ERP data which was digitally filtered by band-pass (0.5–50 Hz). Eye movements were removed before analysis to avoid the potential effect of saccades on spectrum power. For each stimulus type, the averaged ERP epoch between 0 and 250 ms was divided into 251 overlapping 64 ms time-windows with a shift interval of 1 ms. After tapering with a Gaussian window, each window was converted to spectral power using a fast Fourier transformation. The fast Fourier transformation was used on the entire 0.5–50 Hz frequency band. This analysis provided the temporal patterns of the γ spectrum power for processing words and schematic face drawings. In the resultant power spectra, we only conducted correlation analyses against behavior variables using the 30–50 Hz frequency band (there was no additional filtering on the data).

3. Results

3.1. Behavioral results

The total number of correct same or different responses was divided by total number of trials to derive the accuracies for the word and face conditions. Latency data were not meaningful because children withheld their responses until the star appeared. A 2(word vs. face) \times 2(5 vs. 6 years) ANOVA showed no significant effects (5 years: $M_{\text{face}}=0.67$, $SD=0.12$, $M_{\text{word}}=0.67$, $SD=0.13$; 6 years: $M_{\text{face}}=0.68$, $SD=0.11$, $M_{\text{word}}=0.71$, $SD=0.12$).

3.2. N170 results

3.2.1. N170 peak amplitude

One-sample *t*-tests showed that in both the left and right hemispheres, word and face N170 peak amplitudes were significantly more negative than baseline ($t_{\text{word-left}}(80)=-6.42$, $p<0.001$; $t_{\text{word-right}}(80)=-2.01$, $p=0.05$; $t_{\text{face-left}}(80)=-5.39$, $p<0.001$; $t_{\text{face-right}}(80)=-4.42$, $p<0.001$). Thus, children showed the classic N170 responses to words and faces (Fig. 1).

We used the amplitude difference between the left and right hemispheres to index left-lateralization of word N170 and the amplitude difference between the right and left hemispheres to index right-lateralization of face N170. We correlated them with vocabulary scores and age (years). The word N170 left-lateralization was significantly related to vocabulary scores ($r=-0.27$, $p=0.01$; Table 1): the higher children's vocabulary score, the more left-lateralized word N170. Also, word N170 left-lateralization had a strong negative correlation with face N170 right-lateralization ($r=-0.51$, $p<0.01$; Table 1): the more left-lateralized word N170, the less right-lateralized face N170. The same results were found after controlling for age (Table 1).

Table 1

Correlations between word N170 left-lateralization, face N170 right-lateralization, vocabulary, and age.

Variables	Word N170 left-lateralization	Face N170 right-lateralization	Sight vocabulary	Age
Word N170 left-lateralization	–	–0.51** (–0.51**)	–0.27* (–0.26*)	–0.15
Face N170 right-lateralization		–	–0.11 (–0.12)	0.06
Sight Vocabulary			–	0.15

Note: Values in brackets are partial correlations between word N170 left-lateralization, face N170 right-lateralization, and vocabulary with age kept controlled.

* $p<0.05$.

** $p<0.01$.

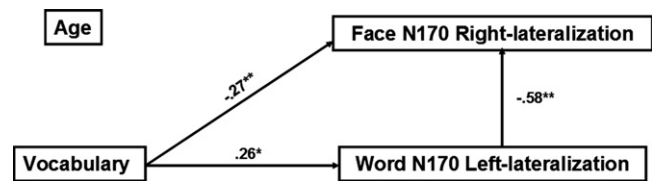


Fig. 2. Tested model of the effect of vocabulary and age on the left-lateralization of N170 for words and the right-lateralization of N170 for faces with the standardized path coefficients provided. * $p<0.05$. ** $p<0.01$.

Given the complex correlations among all the variables, we probed the directional relations among them with a path analysis. N170 left-lateralization for words and right-lateralization for faces were chosen as the observed endogenous variables, whereas vocabulary scores and age were the exogenous variables. We found that vocabulary had a direct effect on word left-lateralization ($p=0.04$; Fig. 2): the higher the vocabulary scores, the stronger the word left-lateralization. The word left-lateralization had a strong negative direct effect on the face right-lateralization ($p<0.01$): the greater the former, the less the latter. Vocabulary also had a direct negative effect on the face right-lateralization ($p<0.01$): the higher the vocabulary score, the less the face right-lateralization. Age did not show any significant direct effects. The model fit well with the data, $\chi^2(df=1)=1.83$, $p=0.18$. GFI (Goodness-of-Fit Index): 0.99, NFI (Normed Fit Index): 0.96, IFI (Incremental fit index): 0.98, TLI (Tucker–Lewis Index): 0.86, and CFI (Comparative Fit Index): 0.98. N170 peak latency showed no significant effects.

3.3. γ Band spectral power

We ran hierarchical regression analyses with the spectral power lateralization as the dependent variables and children's age as a predictor entered to the regression model first, and their vocabulary scores as another predictor in the second model. The word spectrum power left-lateralization was the left–right difference in the γ frequency spectrum power for words, and the face spectrum power right-lateralization was the right–left difference in the γ band for faces. The analyses were performed on every frequency of the gamma band (30 to 50 Hz) at each time point in the left and right hemispheres separately. Analyses produced Fisher-transformed part correlations (*z*-scores) between vocabulary scores and lateralization of the spectrum power, which allowed us to examine the extent to which children's vocabulary affected electrophysiological activities above and beyond the age effect (Fig. 3).

The left-lateralized word spectrum power significantly correlated with the face right-lateralized spectrum power in the opposite direction (Fig. 3a). The negative correlations were widespread, extending almost the entire γ band of 30–50 Hz. They were also wide ranging in time, covering the entire early visual processing time window (0–250 ms). Further, there were three main patches of significant negative correlations, with one patch occurring immediately after the stimulus onset to 100 ms, the second at 200 ms post-stimulus onset, and the third occurring between 150 ms and 200 ms. The first and second patches primarily involved the higher frequencies of the γ band (above 35 Hz), whereas the third patch was in the lower part of the γ band and notably in the time window where the N170 occurred.

In contrast to the above widespread and extensive negative correlations, Fig. 3b shows that the left-lateralized word spectrum power correlated positively with vocabulary scores. They were significantly positively correlated at 100 ms in the band of 46–50 Hz where the word P1 (the early positive ERP component which typically onsets 60–90 ms post-stimulus with a peak between 100 and 130 ms) occurred, and at approximately 140 ms in the

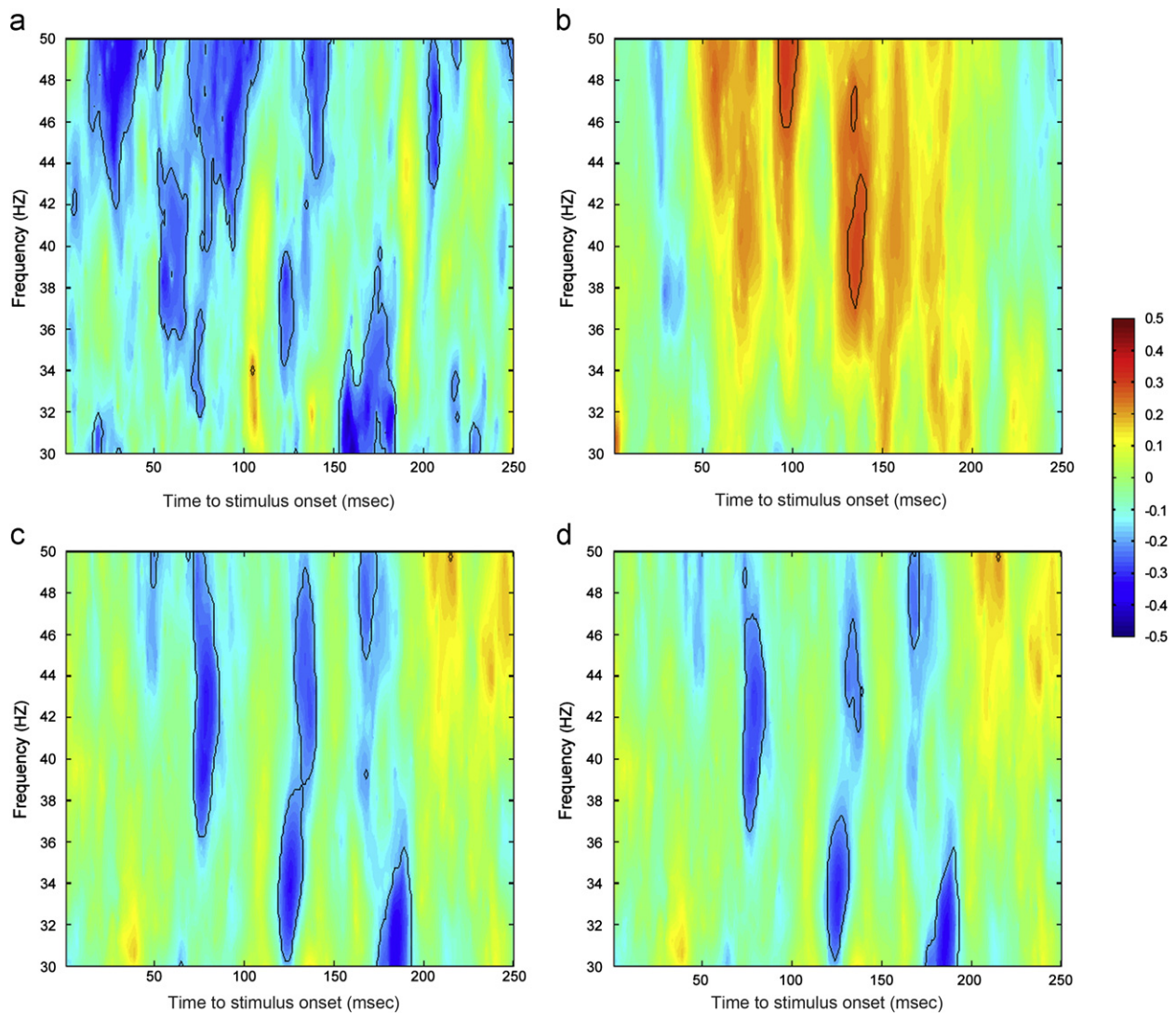


Fig. 3. Part correlations between the word left-lateralized power spectrum and the face right-lateralized power spectrum with age partialled out (a), between the word left-lateralized power spectrum and vocabulary with age partialled out (b), between the face right-lateralized power spectrum and vocabulary with age partialled out (c), and between the face right-lateralized power spectrum and vocabulary with age and word left-lateralized power spectrum partialled out (d). Areas with black contours indicated significant correlations ($p < 0.01$).

middle of the γ band between 36 and 46 Hz in the time-window where word N170 occurred.

A different pattern of correlations emerged between the right lateralized face spectrum power and the vocabulary scores (Fig. 3c). Immediately after the onset of the face stimulus, at around 70 ms, which was within the window of the face P1, vocabulary scores correlated significantly and negatively with the right lateralized face spectrum power in the 35–50 Hz range of the γ band. During the time window when the face N170 occurred, there were three significant negatively correlated patches. One occurred at about 125 ms extending almost the entire 30–50 Hz γ band. The second significant patch occurred at about 170 ms in the upper range of the γ band, and the third patch occurred between 170 and 200 ms in the lower range of the γ band. The above pattern of results remained even after the effects of age and the word spectrum power were partialled out (Fig. 3d).

4. Discussion

The current ERP study examined the effect of early exposure to reading on neural responses to both word and face processing in

Chinese preschool children who are learning to read logographic characters. We focused primarily on the lateralization of both N170 and spectrum power in the occipital–temporal sites. We specifically tested whether early word knowledge of logographic scripts facilitates or delays Chinese children's left lateralization of the electrophysiological responses to words and the right lateralization of the electrophysiological responses to faces, as both are neural markers of the mature responses to visual words or faces (Bentin et al., 1996; Lin et al., 2011; Maurer et al., 2005; Rossion et al., 2003).

4.1. Word knowledge and neural responses to words

We found that the left lateralization of both the word N170 and the spectrum power in the γ band were significantly influenced by Chinese children's word knowledge as indexed by their sight vocabulary scores. The greater children's word knowledge of logographic Chinese characters, the greater the left-lateralization of word N170 and γ spectrum power.

These results are expected given that the existing studies with older children who learn to read either alphabetic or logographic scripts have shown that the word N170 becomes increasingly

left-lateralized with increased age (Brem et al., 2006, 2009; Cao et al., 2011; Lin et al., 2011; Maurer et al., 2006; Spironelli & Angrilli, 2009). However, the existing literature is ambiguous regarding the extent to which this neural effect is the result of either reading experience or maturational factors. The present study showed, for the first time, that the neural effect emerges as early as 5–6 years of age and remains even after controlling for the effect of age, suggesting the important role that word knowledge plays in the left-lateralization of the neural responses to written words.

Two correlational results of the γ spectrum power are worth noting. One is the positive correlation of vocabulary and the time window at 100 ms in the upper range of the γ band when the word P1 typically occurs. As the word P1 is considered to be related to early processing of written word features (Hauk, Davis, Ford, Pulvermuller, & Marslen-Wilson, 2006a; Hauk et al., 2006b), this finding suggests that children's greater vocabulary engenders greater γ band powers for word stimuli during the initial stage of word processing. The second set of significant positive correlations occurred between 100 and 150 ms post-stimulus onset between 36 and 46 Hz. Note that this time was within the window used to extract the N170 amplitudes from the ERP signals. Thus, this result suggests that the middle frequency portion of the γ band might be responsible for the significant positive correlation between the word N170 left lateralization and vocabulary.

4.2. Word knowledge and neural responses to faces

Our data, also for the first time, allowed us to directly test several intriguing possibilities regarding the relations between preschool children's sight vocabulary of logographic Chinese characters and their neural responses to faces, namely the Facilitation Hypothesis, the Competition Hypothesis, and the Null hypothesis mentioned earlier. Overall, the Competition Hypothesis (Dehaene & Cohen, 2007) was supported by three major findings. First, the word N170 left lateralization was negatively correlated with the face N170 right lateralization. The more left lateralized the word N170, the less right lateralized the face N170. Second, the path analysis revealed that children's sight vocabulary had a direct negative effect on the face N170 right lateralization. This was revealed after the negative direct effect of the word N170 left lateralization on the face N170 right lateralization was controlled for. Third, the spectrum power analyses revealed that at about 70 ms, which is within the typical time window of face P1 (Rossion & Caharel, 2011; Rossion & Jacques, 2008), the face spectrum power in the middle range of the γ band was negatively correlated with children's vocabulary. This finding in particular suggests that children's word knowledge begins to negatively impact face processing at its earliest stages. Further, within the time window where the face N170 occurred (100–200 ms post-stimulus onset), children's sight vocabulary was negatively correlated with the spectrum power in various ranges of the γ band at different time points. These effects remained the same after the effects of age and the word spectrum power were controlled for. These results suggest that the activities associated with the γ band may be responsible for the direct effect of sight vocabulary on the face N170 right lateralization as revealed by the path analysis.

It is also worth noting that the correlation of vocabulary with the word spectrum power left lateralization (Fig. 3b) and that with the face power spectrum right lateralization (Fig. 3c) were located in similar ranges of the γ band at similar time points. As the γ band activities in the N170 time window have been suggested to reflect category-specific visual attention modulation and binding (Engell & McCarthy, 2011; Tallon-Baudry & Bertrand, 1999), this similarity indicates that these frequency ranges in

the γ band might be involved in feature-binding for both words and faces, leading to the interference effects seen in Fig. 3a. As children's word knowledge positively facilitated the word visual attention and feature binding in these specific frequency ranges in the γ band, it collaterally undermined the face visual attention and feature binding.

In summary, the results of the present study taken together revealed that young children's neural responses to words and faces are both influenced by their word knowledge. Above and beyond the influence of children's age, the greater children's word knowledge the more likely it was that children's neural responses to visual words resembled the mature pattern seen among expert readers. This finding suggests the facilitative role that early exposure to reading plays in the hemispheric specialization of neural responses to words. However, such a facilitative effect of early exposure to reading has a temporary cost in terms of the neural responses to faces. More specifically, early exposure to reading appears to be initially detrimental to children's neural responses to faces: the greater children's word knowledge, the less likely it was that children's neural responses to faces would resemble the mature pattern seen in adults. These findings taken together suggest that the neural development of visual word processing competes for neural resources with that of visual face processing during the preschool years. Thus, teaching young children to read early on may facilitate improved word processing, but delay the advancement of face processing abilities.

Our findings are in line with a major prediction based on the neural recycling hypothesis (NRH: Dehaene, 2009; Dehaene & Cohen, 2007). NRH suggests that written words are cultural products and recent human inventions (Olson, 1994; Wolf, 2008), and learning to read leads to the invasion of the evolutionarily older brain circuits originally used for processing natural objects. Thus, although literacy has positive impacts on certain perceptual-cognitive (e.g., Eskritt & Lee, 2007; Olson, 1994) and related neural functioning (Dehaene et al., 2010), due to competition between the new cultural ability and the evolutionarily older function in the visual cortex, certain negative consequences to the functioning in the latter may result. Indeed, using fMRI, Dehaene et al. (2010) found evidence of neural competition between the processing of words and that of faces in the ventral occipito-temporal cortex (VOT). Cantlon, Pintel, Dehaene and Pelphrey (2011), again using fMRI, found that 4-year-olds' proficiency in written symbol processing negatively correlated with the responses in the face-selective cortical region. This result hinted at the possibility that the neural responses of the face-selective region may be negatively affected by children's early exposure to written words. Our findings provide, for the first time, direct support for this suggestion.

Due to the fact that the present study is the first ERP study with preschool children to examine face and word processing concurrently, much additional research is needed to elucidate this competitive relationship in early childhood. Nevertheless, one can still make some educated speculations. One possibility may be that, although children have pervasive and extensive exposure to both faces and written words in their environment since birth, they are emphasized differently by caregivers. Caregivers explicitly teach children to discriminate and recognize words and create enriched environments at home and daycares to facilitate word learning. However, although faces are ubiquitous in children's environment and face recognition is one of the crucial tasks that children perform on a daily basis, caregivers hardly teach children explicitly about how to recognize faces. Such a difference in emphasis may induce children to devote more neural resources to processing words at the expense of the neural resources for face processing.

It should be noted that devoting more neural resources to the development of word processing does not necessitate competition

with neural developments in all other domains. For example, it does not compete with the neural development of motor skills and verbal language (Holowka & Petitto, 2002; Johnson, 2001; Mills, Coffey-Corina, & Neville, 1993; Mills et al., 2004; Serrien, Ivry, & Swinnen, 2006). Its competition with the neural development of face processing may be rooted in the similarities that exist between written words and faces as visual objects, despite clear differences between the two. Faces are products of evolution and have a biologically dedicated neural system to support their processing. In contrast, written words are cultural products and recent human inventions. However, faces and written words are also highly similar (Ge, Wang, McCleery, & Lee, 2006). For example, like faces, written words are seen in a canonical upright orientation. Also, like faces, they remain constant in identity regardless of changes in viewing angles (e.g., frontal vs. side view) and paraphernalia (e.g., hat, glasses), words remain the same regardless of changes in fonts and size. Furthermore, like face processing that requires the processing of both featural and configural information, to discriminate and recognize written words successfully, one must rely on both their features (e.g., letters in alphabetic language and strokes/radicals in Chinese) and the configuration between them. These similarities may have led children to initially use their face processing neural network for the processing of written words, resulting in competition for neural resources and the negative effect on the right lateralization of the neural responses to faces observed in the present study.

Some studies showed that the right hemisphere is more involved in reading Chinese, a logographic script (e.g., Tan et al., 2001). The competitive effects of visual word processing on face processing we found here may be partly due to the fact that the right hemisphere plays an important role in both face and logographic script processing. If this hypothesis is true, one may not observe a similar competitive effect in preschool children who learn to read alphabetic scripts, a possibility awaiting future investigation. Such comparative investigation to test this hypothesis is highly important because, if the hypothesis is true, it would suggest that the right, not the left, hemisphere is the site of the neural competition seen in the present study.

It is also valuable to examine the predictions of the Competition Hypothesis in atypically developmental children, such as children with dyslexia or SLI (Specific Language Impairment). Research has demonstrated that the initial development of reading skills and visual tuning for print progresses more slowly in children with dyslexia, than in their typically developing peers (Maurer et al., 2007), and children with dyslexia show impaired specialization for both print and orthography along the left VWF-system (van der Mark et al., 2009). According to our Competition Hypothesis, specialized face processing in dyslexic children could, intriguingly, develop earlier than in their typically developing peers. Children with SLI experience difficulty acquiring and processing oral language. Their problems are characterized by a protracted course of language development as well as difficulties with particular subcomponents of the language system, such as phonology, semantics, or syntax (Bishop & Adams, 1990; Thomas & Karmiloff-Smith, 2005). Although SLI children have difficulties with oral language, some studies have shown that the mean scores for the SLI group on tests of decoding, reading vocabulary, single-word reading, and spelling are also below the control mean (Conti-Ramsden, Botting, Simkin, & Knox, 2001; Tallal, Townsend, Curtiss & Wulfeck, 1991). Converging evidence from electrophysiological and fMRI studies suggests that decoding abilities play a causal role in the left-lateralized specialization of visual word processing (Brem et al., 2010; McCandliss & Noble, 2003). Therefore, if language development in SLI children diverges from that in typically developing children, then the right lateralization of face processing in SLI children may be less affected by their linguistic

experience and therefore may even develop relatively earlier than that of typically developing children.

Additional studies are also needed to address some theoretically important yet currently unresolved issues. First, due to our desire to control for task demand differences, our study did not allow for the assessment of the relations between children's word knowledge and performance in overt task-specific word or face processing, nor the relations between their word or face processing performance and the lateralization of ERP responses to words or faces respectively. To further test the prediction based on the NRH, future ERP studies should require that children perform category-specific tasks (e.g., reading words vs. recognizing faces). Additionally, since the children in our study had no formal schooling, they might lack exposure to a wide variety of faces, compared to children in schools. To address this issue, one could recruit young children of the same ages who, due to policy reasons, either receive or do not receive formal schooling.

Another issue relates to the age of children. As mentioned above, the present study focused on 5- to 6-year-olds because we intended to capitalize on the high variability of word knowledge among these children regardless of age, and in addition to controlling for the effect of formal schooling. As reviewed above, neural markers for word and face processing emerge in infancy and become increasingly lateralized with increased age, most notably during the preschool years. Such early developments might serve as a precursor to the neural competition findings observed in the present study, a possibility that requires empirical verification.

Also, future studies need to further trace the neurodevelopment of word and face processing into later childhood and adolescence to obtain additional evidence to test whether the neural competition hypothesis still holds. According to the neuroconstructivism view (Karmiloff-Smith, 2009), the neural development for word and that for face processing and the interaction between the two are not static, nor monotonic. Rather, they are dynamic processes. Word and face processing may be competitive for neural resources at an early stage of development when both skills are in the early stage of acquisition. However, later on, the competitive relationship may change to be facilitative as both skills become more specialized in the brain. Indeed, a recent behavioral study showed a positive correlation between reading competence and face lateralization in school-aged children and adolescents (Dundas et al., 2012). Thus, future studies with older children who have received formal schooling will allow for investigation into whether neural competition continues between face and word processing, and its short- and long-term consequences in terms of behavioral performance in reading and face recognition. As showed by a recent study, even after age of 30, our face processing ability continues to improve (Germin, Duchaine, & Nakayama, 2011). We can thus speculate that individuals including older children and adolescents still require a long period to develop the face processing ability after they have acquired fluent reading skills (Heering, Rossion, & Maurer, 2012). It is possible that the relation between word and face processing continues to undergo dynamic changes, perhaps from an interactive development (early competition and late facilitation) to a modularized development in adulthood when the two abilities become relatively independent from each other. Thus, future research needs to place the development of face and word specialization into an even longer time window of human development.

Yet another issue is related to the limitation of the ERP methodology, such that the exact loci of the neural responses to words and faces seen in the present study are unknown, although the existing evidence would suggest that these ERP activities may originate from the VOT (Brem et al., 2009; Cohen et al., 2000, 2002;

McCandliss et al., 2003; Puce et al., 1996). Future studies using MEG or fMRI methodologies similar to Cantlon et al. (2011), but with the addition of an assessment of children's reading and face processing abilities, are needed. Such studies would help determine the link between preschool children's reading/face processing abilities and neural responses to words and faces in the VOT as well as in the upstream of the neural network for processing written words (Schlaggar & McCandliss, 2007; Turkeltaub, Gareau, Flowers, Zeffiro, & Eden, 2003) or faces (Haxby, Hoffman, & Gobbini, 2000).

Evidence from these studies, we hope, will eventually answer the enigmatic question of why the neural development of both face and word processing undergoes a protracted course that is well into late adolescence despite their early onset (Booth et al., 2004; Brem et al., 2009; de Haan et al., 2002; Maurer et al., 2006; Mondloch, Geldart, Maurer, & Grand, 2003; Scherf, Behrmann, Humphreys, & Luna, 2007; Schlaggar et al., 2002; Taylor et al., 1999; for a review, see Lee, Anzures, Quinn, Pascalis, & Slater, 2011). More broadly, such studies will eventually elucidate the neural mechanisms underlying the dynamic interactions between different cognitive systems during development (Karmiloff-Smith, 1998).

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References

- 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(9), 2387–2399.
- Bentin, S., Allison, T., Puce, A., Perez, E., & McCarthy, G. (1996). Electrophysiological studies of face perception in humans. *Journal of Cognitive Neuroscience*, 8(6), 551–565.
- 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(3), 235–260.
- Bishop, D. V. M., & Adams, C. (1990). A prospective study of the relationship between specific language impairment, phonological disorders and reading retardation. *Journal of Child Psychology and Psychiatry*, 31, 1027–1050.
- Bookheimer, S. (2002). Functional MRI of language: New approaches to understanding the cortical organization of semantic processing. *Annual Review of Neuroscience*, 25, 151–188.
- Booth, J. R., Burman, D. D., Meyer, J. R., Gitelman, D. R., Parrish, T. B., & Mesulam, M. M. (2004). Development of brain mechanisms for processing orthographic and phonologic representations. *Journal of Cognitive Neuroscience*, 16(7), 1234–1249.
- 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*, 107(17), 7939–7944.
- Brem, S., Bucher, K., Halder, P., Summers, P., Dietrich, T., Martin, E., et al. (2006). Evidence for developmental changes in the visual word processing network beyond adolescence. *Neuroimage*, 29(3), 822–837.
- Brem, S., Halder, P., Bucher, K., Summers, P., Martin, E., & Brandeis, D. (2009). Tuning of the visual word processing system: Distinct developmental ERP and fMRI effects. *Human Brain Mapping*, 30(6), 1833–1844.
- Buchsbaum, B. R., Hickok, G., & Humphries, C. (2001). Role of left posterior superior gyrus in phonological processing for speech perception and production. *Cognitive Science*, 25, 663–678.
- Cantlon, J. F., Pineda, P., Dehaene, S., & Pelphrey, K. A. (2011). Cortical representations of symbols, objects, and faces are pruned back during early childhood. *Cerebral Cortex*, 21(1), 191–199.
- Cao, X., Li, S., Zhao, J., Lin, S., & Weng, X. (2011). Left-lateralized early neurophysiological response for Chinese characters in young primary school children. *Neuroscience Letters*, 492(3), 165–169.
- Carmel, D., & Bentin, S. (2002). Domain specificity versus expertise: Factors influencing distinct processing of faces. *Cognition*, 83, 1–29.
- Chow, B. W., McBride-Chang, C., Cheung, H., & Chow, C. S. (2008). Dialogic reading and morphology training in Chinese children: Effects on language and literacy. *Developmental Psychology*, 44(1), 233–244.
- Cohen, L., Dehaene, S., Naccache, L., Lehéry, S., Dehaene-Lambertz, G., Hénaff, M. A., et al. (2000). The visual word form area. *Brain*, 123(2), 291–307.
- Cohen, L., Lehéry, S., Chochon, F., Lemer, C., Rivaud, S., & Dehaene, S. (2002). Language-specific tuning of visual cortex? Functional properties of the Visual Word Form Area. *Brain*, 125(5), 1054–1069.
- Combined Raven's Test (CRT-Chinese version). (1991). Shanghai: Department of Psychology, East China Normal University.
- Conti-Ramsden, G., Botting, N., Simkin, Z., & Knox, E. (2001). Follow-up of children attending infant language units: Outcomes at 11 years of age. *International Journal of Language and Communication Disorders*, 36, 207–219.
- Csibra, G., Davis, G., Spratling, M. W., & Johnson, M. H. (2000). Gamma oscillations and object processing in the infant brain. *Science*, 290(5496), 1582–1585.
- de Haan, M., Pascalis, Olivier., & Johnson, M. (2002). Specialization of neural mechanisms underlying face recognition in human infants. *Journal of Cognitive Neuroscience*, 14, 199–209.
- Dehaene, S. (2009). *Reading in the brain: The science and evolution of a human invention*. New York, NY: Viking Penguin.
- Dehaene, S., & Cohen, L. (2007). Cultural recycling of cortical maps. *Neuron*, 56(2), 384–398.
- Dehaene, S., Pegado, F., Braga, L. W., Ventura, P., Nunes Filho, G., Jobert, A., et al. (2010). How learning to read changes the cortical networks for vision and language. *Science*, 330(6009), 1359–1364.
- de Heering, A., Rossion, B., & Maurer, D. (2012). Developmental changes in face recognition during childhood: Evidence from upright and inverted faces. *Cognitive Development*, 27, 17–27.
- Dundas, E. M., Plaut, D. C., & Behrmann, M. (2012). The joint development of hemispheric lateralization for words and faces. *Journal of Experimental Psychology: General*, <http://dx.doi.org/10.1037/a0029503> [August 6 Advance online publication].
- Engell, A. D., & McCarthy, G. (2011). The relationship of gamma oscillations and face-specific ERPs recorded subdurally from occipitotemporal cortex. *Cerebral Cortex*, 21(5), 1213–1221.
- Eskritt, M., & Lee, K. (2007). The impact of notation on cognition and its development: Theoretical perspectives and empirical evidence. In: L. Tolchinsky, & E. Teubal (Eds.), *The development of notational representations* (pp. 233–256). Rotterdam, NL: Sense.
- Galambos, R. (1992). A comparison of certain gamma band (40-Hz) brain rhythms in cat and man. In: E. Basar, & T. H. Bullock (Eds.), *Induced rhythms in the brain* (pp. 201–216). Boston, MA: Birkhauser.
- Ge, L. Z., Wang, Z., McCleery, J. P., & Lee, K. (2006). Activation of face expertise and the inversion effect. *Psychological Science*, 17, 12–16.
- Germine, L. T., Duchaine, B., & Nakayama, K. (2011). Where cognitive development and aging meet: Face learning ability peaks after age 30. *Cognition*, 118, 201–210.
- Halit, H., Csibra, G., Volein, A., & Johnson, M. H. (2004). Face-sensitive cortical processing in early infancy. *Journal of Child Psychology and Psychiatry*, 45, 1228–1234.
- Hauk, O., Davis, M. H., Ford, M., Pulvermuller, F., & Marslen-Wilson, W. D. (2006a). The time course of visual word recognition as revealed by linear regression analysis of ERP data. *Neuroimage*, 30(4), 1383–1400.
- Hauk, O., Patterson, K., Woollams, A., Watling, L., Pulvermuller, F., & Rogers, T. T. (2006b). [Q:] When would you prefer a SOSSAGE to a SAUSAGE? [A:] At about 100 ms. ERP correlates of orthographic typicality and lexicality in written word recognition. *Journal of Cognitive Neuroscience*, 18(5), 818–832.
- Haxby, J. V., Hoffman, E. A., & Gobbini, M. I. (2000). The distributed human neural system for face perception. *Trends in Cognitive Sciences*, 4(6), 223–233.
- Henderson, M., McCulloch, L., & Herbert, M. (2003). Event-related potentials (ERPs) to schematic faces in adults and children. *International Journal of Psychophysiology*, 51(1), 59–67.
- Herrmann, C. S., Mecklinger, A., & Pfeifer, E. (1999). Gamma responses and ERPs in a visual classification task. *Clinical Neurophysiology*, 110, 636–642.
- Herrmann, C. S., Munk, M. H., & Engel, A. K. (2004). Cognitive functions of gamma-band activity: Memory match and utilization. *Trends in cognitive sciences*, 8(8), 347–355.
- Holowka, S., & Petitto, L. A. (2002). Left hemisphere cerebral specialization for babies while babbling. *Science*, 297(5586).
- Itier, R. J., & Taylor, M. J. (2004). Face recognition memory and configural processing: A developmental ERP study using upright, inverted, and contrast-reversed faces. *Journal of Cognitive Neuroscience*, 16(3), 487–502.
- Johnson, M. H. (2001). Functional brain development in humans. *Nature Reviews Neuroscience*, 2, 475–483.
- Kanwisher, N., McDermott, J., & Chun, M. M. (1997). The fusiform face area: A module in human extrastriate cortex specialized for face perception. *The Journal of Neuroscience*, 17(11), 4302–4311.
- Karmiloff-Smith, A. (1998). Development itself is the key to understanding developmental disorders. *Trends in Cognitive Sciences*, 2(10), 389–398.
- Karmiloff-Smith, A. (2009). Nativism versus neuroconstructivism: Rethinking the study of developmental disorders. *Developmental Psychology*, 45(1), 56–63.
- Kaufman, J., Csibra, G., & Johnson, M. H. (2005). Oscillatory activity in the infant brain reflects object maintenance. *Proceedings of the National Academy of Sciences*, 102(42), 15271–15274.
- 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.
- Lee, K., Anzures, G., Quinn, P. C., Pascalis, O., & Slater, A. M. (2011). Development of face processing expertise. In: A. Calder, G. Rhodes, M. Johnson, & J. Haxby (Eds.),

- The *Oxford handbook of face perception* (pp. 753–778). New York, NY: Oxford University Press.
- Liu, Y., & Perfetti, C. A. (2003). The time course of brain activity in reading English and Chinese: An ERP study of Chinese bilinguals. *Human Brain Mapping, 18*, 167–175.
- Lin, S., Chen, H. C., Zhao, J., Li, S., He, S., & Weng, X. (2011). Left-lateralized N170 response to unpronounceable pseudo but not false Chinese characters—the key role of orthography. *Neuroscience, 190*, 200–206.
- Maurer, U., Brem, S., Bucher, K., & Brandeis, D. (2005). Emerging neurophysiological specialization for letter strings. *Journal of Cognitive Neuroscience, 17*(10), 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*(12), 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*(2), 749–758.
- 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*(7), 293–299.
- McCandliss, B. D., & Noble, K. G. (2003). The development of reading impairment: A cognitive neuroscience model. *Mental Retardation and Developmental Disabilities Research Reviews, 9*(3), 196–205.
- Mercure, E., Dick, F., Halit, H., Kaufman, J., & Johnson, M. H. (2008). Differential lateralization for words and faces: Category or psychophysics? *Journal of cognitive neuroscience, 20*(11), 2070–2087.
- Mills, D. M., Coffey-Corina, S. A., & Neville, H. J. (1993). Language acquisition and cerebral specialization in 20-month-old infants. *Journal of Cognitive Neuroscience, 5*, 326–342.
- Mills, D. L., Prat, C., Zangl, R., Stager, C. L., Neville, H. J., & Werker, J. F. (2004). Language experience and the organization of brain activity to phonetically similar words: ERP evidence from 14- and 20-month-olds. *Journal of Cognitive Neuroscience, 16*(8), 1452–1464.
- Mondloch, J., Geldart, Sybil, Maurer, Daphne, & Grand, Richard Le (2003). Developmental changes in face processing skills. *Journal of Experimental Child Psychology, 86*(1), 67–84.
- Olson, D. R. (1994). *The world on paper: The conceptual and cognitive implications of writing and reading*. Cambridge, England: Cambridge University Press.
- 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.
- Perfetti, C. A., Liu, Y., Fiez, J., Nelson, J., Bolger, J., & Tan, L. H. (2007). Reading in two writing systems: Accommodation and assimilation of the brain's reading network. *Bilingualism: Language and Cognition, 10*, 131–146.
- Puce, A., Allison, T., Asgari, M., Gore, J. C., & McCarthy, G. (1996). Differential sensitivity of human visual cortex to faces, letterstrings, and textures: A functional magnetic resonance imaging study. *The Journal of Neuroscience, 16*(16), 5205–5215.
- Rossion, B., & Caharel, S. (2011). ERP evidence for the speed of face categorization in the human brain: Disentangling the contribution of low-level visual cues from face perception. *Vision Research, 51*, 1297–1311.
- Rossion, B., & Jacques, C. (2008). Does physical interstimulus variance account for early electrophysiological face sensitive responses in the human brain? Ten lessons on the N170. *Neuroimage, 39*(4), 1959–1979.
- 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*(3), 1609–1624.
- Scherf, K. S., Behrmann, M., Humphreys, K., & Luna, B. (2007). Visual category-selectivity for faces, places and objects emerges along different developmental trajectories. *Developmental Science, 10*(4), F15–F30.
- Schlaggar, B. L., Brown, T. T., Lugar, H. M., Visscher, K. M., Miezin, F. M., & Petersen, S. E. (2002). Functional neuroanatomical differences between adults and school-age children in the processing of single words. *Science, 296*(5572), 1476–1479.
- Schlaggar, B. L., & McCandliss, B. D. (2007). Development of neural systems for reading. *Annual Review of Neuroscience, 30*, 475–503.
- Senkowski, D., & Herrmann, C. S. (2002). Effects of task difficulty on evoked gamma activity and ERPs in a visual discrimination task. *Clinical Neurophysiology, 113*(11), 1742–1753.
- Serrien, D. J., Ivry, R. B., & Swinnen, S. P. (2006). Dynamics of hemispheric specialization and integration in the context of motor control. *Nature Reviews Neuroscience, 7*, 160–167.
- Singer, W., & Gray, C. M. (1995). Visual feature integration and the temporal correlation hypothesis. *Annual Review of Neuroscience, 18*, 555–586.
- 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*(1), 35–45.
- Tallal, P., Townsend, J., Curtiss, S., & Wulfeck, B. (1991). Phenotypic profiles of language-impaired children based on genetic/family history. *Brain and Language, 41*, 81–95.
- Tallon-Baudry, C., & Bertrand, O. (1999). Oscillatory gamma activity in humans and its role in object representation. *Trends in Cognitive Sciences, 3*(4), 151–162.
- Tallon-Baudry, C., Bertrand, O., Delpuech, C., & Pernier, J. (1996). Stimulus specificity of phase-locked and non-phase-locked 40 Hz visual responses in human. *The Journal of Neuroscience, 16*(13), 4240–4249.
- Tan, L. H., Liu, H. L., Perfetti, C. A., Spinks, J. A., Fox, P. T., & Gao, J. H. (2001). The neural system underlying Chinese logograph reading. *NeuroImage, 13*, 836–846.
- Tarkiainen, A., Cornelissen, P. L., & Salmelin, R. (2002). Dynamics of visual feature analysis and object-level processing in face versus letter-string perception. *Brain, 125*(5), 1125–1136.
- Taylor, M. J., Edmonds, G. E., McCarthy, G., & Allison, T. (2001b). Eyes first! Eye processing develops before face processing in children. *Neuroreport, 12*(8), 1671–1676.
- Taylor, M. J., Itier, R. J., Allison, T., & Edmonds, G. E. (2001a). Direction of gaze effects on early face processing: Eyes-only versus full faces. *Cognitive Brain Research, 10*(3), 333–340.
- Taylor, M. J., McCarthy, G., Saliba, E., & Degiovanni, E. (1999). ERP evidence of developmental changes in processing of faces. *Clinical Neurophysiology, 110*(5), 910–915.
- Thomas, M., & Karmiloff-Smith, A. (2005). Can developmental disorders reveal the component parts of the human language faculty? *Language Learning and Development, 1*(1), 65–92.
- Turkeltaub, P. E., Gareau, L., Flowers, D. L., Zeffiro, T. A., & Eden, G. F. (2003). Development of neural mechanisms for reading. *Nature Neuroscience, 6*(7), 767–773.
- van der Mark, S., Bucher, K., Maurer, U., Schulz, E., Brem, S., Buckelmüller, J., et al. (2009). Children with dyslexia lack multiple specializations along the visual word-form (VWF) system. *Neuroimage, 47*(4), 1940–1949.
- Whitehurst, G. J., & Lonigan, C. J. (1998). Child development and emergent literacy. *Child Development, 69*(3), 848–872.
- Wolf, M. (2008). *Proust and the squid: The story and science of the reading brain*. New York, NY: Harper Perennial.
- 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.
- Yum, Y. N., Holcomb, P. J., & Grainger, J. (2011). Words and pictures: An electrophysiological investigation of domain specific processing in native Chinese and English speakers. *Neuropsychologia, 49*, 1910–1922.
- 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.
- Zhang, M. X., Jing, T., Mei, L. L., Yang, H. M., Chen, C. S., Xue, G., et al. (2011). It's a word: Early electrophysiological response to the character likeness of pictographs. *Psychophysiology, 48*, 950–959.
- Zhou, X. L., Ye, Z., Cheung, H., & Chen, H. C. (2009). Processing the Chinese language: An introduction. *Language and Cognitive Process, 24*, 929–946.