Developmental Neuropsychology

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/hdvn20

Neurophysiological Correlates of Reading Difficulties in Elementary School Children

Huilin Sun, Qinxin Shi, Saeedeh Pazoki, Yajun Jia & Steven Woltering

To cite this article: Huilin Sun, Qinxin Shi, Saeedeh Pazoki, Yajun Jia & Steven Woltering (2023) Neurophysiological Correlates of Reading Difficulties in Elementary School Children, Developmental Neuropsychology, 48:6, 259-279, DOI: 10.1080/87565641.2023.2225664

To link to this article: https://doi.org/10.1080/87565641.2023.2225664

Published online: 26 Jun 2023.

DEVELOPMENTAL NEUROPSYCHOLOGY
2023, VOL. 48, NO. 6, 259–279
https://doi.org/10.1080/87565641.2023.2225664

Routledge
Taylor & Francis Group

Check for updates

Neurophysiological Correlates of Reading Difficulties in Elementary School Children

Huilin Sun[a], Qinxin Shi[b], Saeedeh Pazoki[c], Yajun Jia[d], and Steven Woltering[c]

[a]Department of Psychology, Syracuse University, Syracuse, NY, USA; [b]Department of Psychology, University of Utah, Salt Lake City, UT, USA; [c]Department of Educational Psychology, Texas A&M University, College Station, TX, USA; [d]School of Social Work, Columbia University, New York City, NY, USA

ABSTRACT

The present study examined the event-related potentials (ERPs) and reading-language skills of elementary school children with and without reading difficulties. Typically developing children showed an N400 effect characterized by significantly larger N400 amplitudes elicited by nonwords than real words. Their meaning processing shown by the N400 systematically differed by lexicality. On the other hand, the N400 effect was absent in children with reading difficultiesExploratory analyses were conducted with the N1 and Late Positive Component. Additionally, the relationships between ERPs and reading-language skills were examined; sight word efficiency and phonemic decoding efficiency accounted for significant variance in the N400 effect

ARTICLE HISTORY
Received 6 January 2023
Revised 28 April 2023
Accepted 11 June 2023

Introduction

As reading becomes increasingly essential to participate in school and society, children with reading difficulties experience significant challenges in academic, career, and socioemotional arenas (Livingston et al., 2018). Functional reading depends on a number of skills or processes such as decoding, word recognition, vocabulary, oral language, executive functions, background knowledge and use of strategy (Cutting & Scarborough, 2006; Gough & Hoover, 1990). Children with reading difficulties may have trouble with phonological-orthographic regularity knowledge which has implications for their reading fluency and accuracy (Araújo et al., 2012; Ballan et al., 2023; Ehri, 1994). Phonological-orthographic regularity knowledge in English involves understanding how letters are typically arranged, letter positional frequency, and permissible letter sequences (Kaefer, 2016). It can be acquired from statistical learning when children implicitly take in common letter patterns as they read (Ballan et al., 2023). It is also acquired through instruction when children are taught common letter patterns and encouraged to notice them in new words; as such, it continues to develop through elementary school (Ehri, 1994; O'Brien, 2014). With insufficient phonological-orthographic regularity knowledge, children have lower fluency in reading known words as well as learning new words because they may rely heavily on letter-by-letter decoding or guessing instead of drawing upon common letter patterns to read by analogy (Ehri, 1994).

Understanding the underlying mechanisms of reading difficulties helps advance the early identification and intervention of reading difficulties (Noordenbos et al., 2013; Shaywitz et al., 2006). In addition to the end-product of reading captured by a test score, neurophysiological methods such as Electroencephalography (EEG) can record the underlying, ongoing processes of reading (Henderson et al., 2011; Perfetti & Stafura, 2013). EEG measures neural activity by recording changes in voltages on the scalp. Brain–behavior relationships can be established by observing

CONTACT Steven Woltering swolte@tamu.edu Texas A&M University

brain activity elicited by time-locked stimuli. Brain activity patterns that correspond systematically to cognitive activities are identified as Event-Related Potentials or ERPs (Luck, 2014). ERPs shown by typically developing readers and those with reading difficulties can be compared to identify group differences and thus potential biomarkers of reading difficulties.

Neurophysiological correlates of reading

N400

The N400 waveform is an ERP component conceptualized as an indicator of meaning processing (Kutas & Federmeier, 2011; Lau et al., 2008). The N400 waveform is a negative-going waveform that peaks around 400 ms post-stimulus onset. The N400 effect was first found in a garden path sentence (a sentence with incongruous final words) reading in adults. N400 amplitudes elicited by the incongruous final words are systematically different from N400 amplitudes elicited by congruous final words whilst reading typical sentences (Kutas & Hillyard, 1980). Specifically, N400 amplitude differs by semantic anomaly (Lau et al., 2008). The N400 effect refers to a systematic difference in the N400 waveform by experimental condition (Kutas & Federmeier, 2011; Lau et al., 2008). Although theoretical interpretations of the N400 effect vary, the N400 effect is often utilized to understand how meaning processing differs systematically by conditions such as word properties or population characteristics.

In proficient readers, the N400 effect is sensitive to lexicality or phonological-orthographic regularity (Fonseca et al., 2006; Y. Tzeng et al., 2017; Wang & Yuan, 2008). In lexicality tasks, proficient readers show different N400 amplitudes viewing real words and nonwords (Bentin et al., 1999; Coch & Holcomb, 2003; Gao et al., 2022; Laszlo et al., 2012; Nobre & McCarthy, 1994). A nonword is defined as a string of letters in violation of the phonological-orthographic regularity of a writing system (Coch et al., 2012; Ziegler et al., 1997). Proficient readers' N400s elicited by words tend to have larger amplitudes than their N400s elicited by nonwords or false fonts (Bentin et al., 1999; Coch & Mitra, 2010). This N400 effect reflects how real words (e.g., back) are processed more efficiently than other word-like stimuli such as nonwords (e.g., kcba). Proficient readers recognize that nonwords violate phonological-orthographic regularity, which means that they are less likely to be real or meaningful. Thus, proficient readers avoid activating or completing meaning retrieval or meaning construction, reducing the N400 amplitude to nonwords (Coch, 2015, Nobre & McCarthy, 1994; Y. L. Tzeng et al., 2018).

The N400 effect on lexicality has unique theoretical implications; it reflects how phonological-orthographic knowledge modulates meaning-processing. Successful integration of phonological, orthographic, and meaning processing skills has been theorized as a prerequisite for proficient reading (Perfetti, 2007). As the N400 indicates meaning processing, looking at N400s elicited by lexicality differences provides information on the connection between lexicality, an orthographic-phonological processing aspect, and meaning processing. When a "word" violates phonological-orthographic regularity, does the reader recognize the violation and thus process the stimulus differently than words? Furthermore, does the reader recognize it soon enough to inhibit attempts to process its meaning or does the reader activate meaning processing regardless? Proficient readers show a word superiority effect in that real words are processed differently and more efficiently than nonwords (Coch et al., 2012; Reicher, 1969). The absence of an N400 effect may be related to insufficient phonological-orthographic regularity knowledge or inadequate connections between phonological, orthographic, and meaning processing (Coch & Benoit, 2015).

Less experienced readers often show a lack of N400 effect. All word-like stimuli, including nonwords and false fonts, are processed similarly to real words, eliciting similar N400 amplitudes (Coch & Holcomb, 2003; Coch et al., 2002). Children may treat all unknown words like new words outside of their vocabulary regardless of phonological-orthographic regularity; this is considered a word humility bias (Coch et al., 2002). This is consistent with behavioral findings that children's discrimination between real words and nonwords is emergent in the first grade, and it matures through elementary school (van Viersen et al., 2022). Also, it is possible that children read in a letter-by-letter fashion, which partially activates the mental lexicon before nonwords are recognized (Coch et al., 2002).

Additionally, less experienced readers may show an N400 effect in the opposite direction than that of proficient readers. Some typically developing children showed an N400 effect characterized by a larger N400 amplitude to nonwords than words (Coch et al., 2012; Y. Tzeng et al., 2017; Y. L. Tzeng et al., 2018). Based on prior research, larger N400 amplitudes are usually interpreted as an indication of more effortful processing or higher interference (Coch et al., 2012; Friedrich & Friederici, 2005; López Zunini et al., 2020). For example, even proficient readers showed larger N400 amplitudes to "words" with transposed morphemes than real words (Coch et al. 2013). It is possible that the children find it more difficult to process or access the meanings of nonwords compared to real words (Coch et al., 2012). Overall, findings in children are less clear cut. For example, a cross-sectional study showed that while third and fifth graders showed an N400 effect characterized by smaller N400 amplitudes to nonwords than words, fourth graders had no N400 effect (Coch et al., 2012). Little can be generalized about the developmental trajectory of the N400 effect in word-nonword reading at this time.

The N400 effect has the potential to be a biomarker for reading difficulties seeing as it differs by reading proficiency (Coch, 2015; Rüsseler et al., 2007). Very few studies have focused on the N400 effect on lexicality in children with reading difficulties. In two studies comparing typically developing children and children with reading difficulties in Chinese-speaking environments, typically developing children showed an N400 effect differentiating between real words and nonwords, but children with reading difficulties showed non-significant differences in amplitudes elicited by real words and nonwords (Chung et al., 2012; Y. L. Tzeng et al., 2018). Still, findings from a non-alphabetic orthography may not be generalizable to English readers. Some studies, however, found no significant group differences (Bonte & Blomert, 2004; Hasko et al., 2013; Kemény et al., 2018; Rüsseler et al., 2007). In two studies in German-speaking environments, both typically developing children and those with reading difficulties lacked an N400 effect differentiating between word types (Hasko et al., 2013; Kemény et al., 2018). On the other hand, another study that examined lexicality within a priming design found no group differences in that both German-speaking children who are average readers and those with reading difficulties showed an N400 effect (Bonte & Blomert, 2004). Still, findings from an alphabetic orthography with higher transparency and consistency may not be generalizable to English readers. Because the number of studies comparing children with reading difficulties to average readers is small, it may be premature to interpret convergences and divergences in findings. Discrepant findings from various studies may be understood with reference to language context, task demand, age, reading proficiency and ERP methodology (Henderson et al., 2011). Additional research would help clarify the N400's potential as a biomarker of reading difficulties.

N1

In addition to the N400, two more ERPs associated with reading were explored. The N1 component is the first negative-going peak occurring around 120-290 ms post-stimulus onset (Eberhard-Moscicka et al., 2015, Maurer et al., 2006). As an early occurring ERP, it is conceptualized to reflect visual-perceptual processes specialized for word reading (Kast et al., 2010; McCandliss et al., 2003). The N1 effect has been found lateralized in the occipital and occipito-temporal regions (Bentin et al., 1999, Eberhard-Moscicka et al., 2015; Kast et al., 2010). In proficient readers, the N1 amplitude is larger for orthographic stimuli such as real letters compared to non-orthographic stimuli such as letter-like symbols or false fonts (Bentin et al., 1999). The same pattern has been found amongst 7-year-olds categorized as high-ability readers but not their same-aged peers who were considered low-ability readers (Zhao et al., 2014). The N1 effect becomes fine-tuned with reading experience (Maurer et al., 2007). Findings related to the N1 effect in children with reading difficulties are mixed (Araújo et al., 2012; Eberhard-Moscicka et al., 2015; Kast et al., 2010). A longitudinal study showed that children with reading difficulties showed no growth when the N1 effect emerged between kindergarten and second grade for typically developing children (Maurer et al., 2007). However, others reported that children with reading difficulties and typically developing children both showed an absence of N1 effect differentiating between word types (Bakos et al., 2018; Hasko et al., 2013; Kast et al., 2010). Still, both Kast et al. (2010) and Bakos et al. (2018) found that children with reading difficulties showed overall smaller N1 amplitudes than typical readers. The absence of N1 effect in children may reflect a lack of print specialization at the visual perceptual level.

LPC

The LPC or the Late Positive Complex is an ERP component observed between 400 and 900 ms post-stimulus onset (Bakos et al., 2018; Coch & Holcomb, 2003; Hasko et al., 2013; Kemény et al., 2018). It has been conceptualized as an indicator of recognition or retrieval, showing systematic differences in amplitudes between known words and unknown words; for proficient readers, known words generate larger and earlier LPCs over parietal brain regions, which are stronger over the left parietal electrode sites (Bakos et al., 2018; Hasko et al., 2013). The LPC is sensitive to phonological and orthographic regularity (Hasko et al., 2013; Kemény et al., 2018). Various studies reported that typically developing children showed an LPC effect but children with reading difficulties did not (Hasko et al., 2013; Kemény et al., 2018). However, the direction of the LPC effect may be different from that in adult readers; for example, children showed larger amplitudes for nonwords than words (Kemény et al., 2018). The absence of an LPC effect may be related to insufficient phonological orthographic regularity knowledge which leads to undifferentiated processing of words and nonwords.

Brain–behavior relationship

Exploring the associations between ERPs and performance on standardized measures can further our understanding of brain–behavior relationships of reading. While ERPs capture reading-language processes, standardized testing is also an evidence-based approach to measure reading skills. Little is about the extent to which these methods tap common processes. Significant associations between N400 and reading-language skills measured by standardized tests have been found in the limited number of studies that utilized standardized measures. However, the mechanism of the relationship is unclear and the types of N400 data and standardized measures reported vary across studies. As N400 broadly reflects meaning processing and vocabulary skills are related to word meanings, significant negative correlations between vocabulary and N400 amplitudes elicited by real words (but not nonwords) have been reported (Coch & Benoit, 2015; Khalifian et al., 2016). In addition to meaning-related skills like vocabulary, associations between word reading and N400s have been found. Coch and Holcomb (2003) found a negative correlation between sight words and decoding skills and N400 amplitude elicited by real words. Coch et al. (2012) reported a negative correlation between word reading and N400 averaged peak amplitude. On the other hand, Henderson et al. (2011) reported no significant correlations between vocabulary and N400 amplitudes across conditions. Theoretically, it is unclear why N400 amplitudes elicited by a particular condition or extracted by a particular method should be associated with a reading-language skill whereas other N400 values are not. However, existing studies point to a positive association between reading-language skills and the size of the N400 effect (amplitude difference between words and nonwords). This is consistent with the theoretical understanding that stronger readers have better phonological-orthographic regularity knowledge which allows for more highly differentiated processing of words and nonwords.

The present study

In the present study, we aim to compare the ERPs shown by children with reading difficulties and typically developing children and explore associations between ERPs and reading-language performance. First, we hypothesized a group difference in N400 effect between children with reading difficulties and typical readers, i.e., the N400 effect is shown by typical readers but absent in children with reading difficulties. Second, we hypothesized significant associations between ERP and reading-language measures, i.e., positive correlations between the N400 effect (difference wave) and standard scores on word reading, reading comprehension, and vocabulary based on the idea that proficient readers tend to have larger N400 effects. Additionally, exploratory analyses were conducted with two additional ERPs (N1 and LPC) found to be associated with reading skills. A distinction is made between planned N400 analysis and exploratory N1 and LPC analyses because the study was designed and powered based on hypotheses and a priori analysis plan for the N400 effect, whereas N1 and LPC analyses were conducted post-hoc after the data was collected, processed, and analyzed for the N400 effect.

Method

Participants

Fifty-two children participated in the present study. Participants in the control group included 32 children (female = 15, male = 17; mean age = 8.90 years, SD = 1.38, min = 7.1, max = 11.53). Participants in the reading difficulties group included 20 children (female = 7, male = 13; mean age = 9.46 years, SD = 1.28, min = 7.44, max= 11.89). Children were recruited through a university listserv e-mail looking for child participants in reading neuroscience research as well as collaboration from a university-based reading clinic; four participants in the reading difficulties group were recruited through the university reading clinic and scheduled to begin reading intervention after their lab visit. The age requirement was set as 7–11. All participants (parents) who responded to the recruitment calls were contacted for a phone screening. Children with any psychological or neurodevelopmental disorder diagnoses other than specific learning disorder, children receiving special education for reasons other than learning disability in reading, as well as children who were unavailable to participate in a 3-h lab visit were not invited for data collection. As a result of convenience sampling, the numbers of children in the control and reading difficulties group and their gender distributions were different.

Determination of reading difficulties grouping was based on the concurrence between parent report and child performance on standardized reading measures of sight word reading efficiency, decoding efficiency, and reading comprehension. Children were assigned to be in the control group if their parents reported them to have no reading difficulties, and they scored in the Average range or above (standard scores) on two or more reading measures. Definitions for standard score ranges, such as Average or Below Average, came from the manuals of the published standardized measures (Dunn & Dunn, 2007; Torgesen et al., 2012; Woodcock, 2011). Children were assigned to the reading difficulties group if their parents reported them to have reading difficulties and they scored in the Below Average range on two or more standardized measures. Parent reports of reading difficulties were based on children's special education eligibility and participation, 504 dyslexia services for students with reading difficulties who do not meet the criteria for special education (Zirkel, 2020), psychological diagnoses, communication with children's teachers, or parents' subjective observations. Therefore, it was necessary to check concurrences between parent reports and children's performance on standardized measures. Regarding discrepancies between parent report and child performance, one participant was reported to have reading difficulties, but their performance on all standardized measures was in the Average or Above Average range, which led to our decision to reassign them to the typical reader group. It should be noted that the alternative strategy of assigning groups by diagnostic label has similar drawbacks due to the disagreements and variations amongst professionals regarding methods of diagnosing reading problems. Children with reading difficulties often present a divergent score profile on standardized psychoeducational tests; divergences between child performance and parent report are common as well. Clinical judgment by individual psychologists is heavily implicated in interpreting divergent data to make diagnoses. As such, some recent articles are using "reading difficulties" instead of a diagnostic label to define a group (Psyridou et al., 2019).

Informed consent and assent were obtained from guardians and children, respectively, prior to beginning the experiment. Each child completed a 3-h lab visit involving rating scales, ERP tasks, eye tracking tasks (Lee et al., 2022), and standardized reading-language measures. Breaks were provided throughout. All children received $30 and small prizes at the end of the session. The study was approved by the Institutional Review Board of a university in a southwestern state in the United States (IRB2017–0007D).

Demographic information was reported by parents or legal guardians of the participating children. All participants were native speakers of English; 22% of them were bilingual. Participants' racial-ethnic identities included 59% Caucasian, 18% Hispanic, 14% Asian/Pacific Islander, 2% African-American, and 6% "others." Regarding parental educational attainment, 51% reported a graduate degree, 41% reported a 2-year or 4-year college degree, 6% reported a high school degree, and 2% reported not having obtained a high school degree. By self-report and observation, one child was left-handed. All children had normal or corrected-to-normal vision based on parent-report and a test with the standard Snellen chart (20/40 or better).

ERP task

In the ERP task, individual words appeared on the screen one at a time; children were to press a button each time they saw an animal word. The task included two test blocks; each block had 124 trials with 57 real words, 57 nonwords, and 10 animal words. The same words and nonwords were presented in both blocks in randomized order. Each trial began with a 0–200 ms jitter of a black screen, followed by a 500 ms fixation screen (white plus sign surrounded by a red rectangle). The stimulus word surrounded by a red rectangle then appeared for 600 ms. After that the fixation screen appeared again for 800 ms, followed by a black screen with a number sign (#) for 2400 ms. The fixation screen prompted children to look at the center of the screen to minimize eye movements. The number sign (#) signaled to children that it was the designated time to blink or rest their eyes whereas they were to minimize eye movement during other times. The task was programmed and delivered through EPrime software (Psychology Software Tools, Inc.). The task is depicted in Figure 1.

In the real word condition, 57 words were selected from the Fry Words List which categorized words by grade levels (Fry, 2000); 38 words were selected from Grades K to 1, Grades 2 to 3, and Grades 4 to 5 words, respectively. In the nonwords condition, another 114 words were selected in the same manner and then arranged into letter strings that were phonologically and orthographically illegal. Numbers of letters, syllables, and phonemes were recorded. To rule out word length as a confounding factor, a one-way ANOVA confirmed that words from the 3 difficulty levels did not differ on number of letters or number of phonemes (all p's > .05). In the animal word condition, 20 animal words were included as catch trials. The ERP task was adopted from three studies (Coch, 2015; Coch & Benoit, 2015; Coch & Holcomb, 2003).

The ERP task began with a teaching block with 3 stimuli (a real word, a nonword, and an animal word). During the teaching block, the examiner explained the rules of the task with a standardized script; items were presented at an untimed pace controlled by the examiner. The researcher provided children with a story of being a zookeeper whose animals have escaped; children were to press a button each time they saw an animal word to capture the animal. In addition to promoting engagement, the button-press task provided a semantic context encouraging children to process words at the meaning level in addition to decoding-word recognition (Coch & Holcomb, 2003). During the teaching block, the research assistant also showed the child's continuous EEG while instructing the child to blink and move their eyes to explain how blinking and eye movements would affect the brain waves. Children

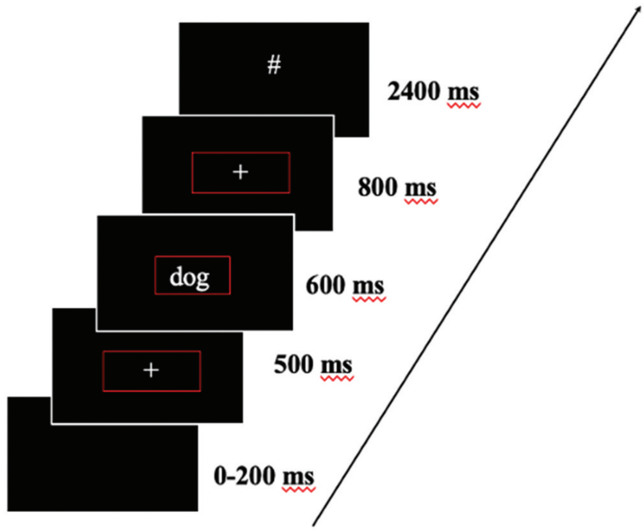

Figure 1. Depiction of the ERP task.

were encouraged to look toward the center of the screen, avoid eye movements, and blink during a designated number sign (#) screen. After the teaching block, children completed a practice block with 10 stimuli (5 real words, 3 nonwords, and 2 animal words) presented at the same pace as stimuli in the test blocks. The researcher started the testing blocks once children's practice block performance showed adequate understanding of task requirements.

Electrophysiological data acquisition

During the ERP task, continuous EEG was recorded with a 129-electrode high-density Geodesic Sensor Net (EGI-Magstim) with Cz as reference. EEG was digitized at an online sampling rate of 1000-Hz. A 0.01-highpass filter and 100-Hz lowpass filter were applied online. Impedance was checked to be below 50 kΩ. Eye blinks were monitored with electro-oculogram (EOG) at eye electrode sites. The ERP task was completed in a sound-proof, well-lit room maintained at a cool temperature of around 65 degrees Fahrenheit (Kappenman & Luck, 2010). Children sat 50 cm from the computer screen. Children were accompanied by a research assistant in the room who explained task instructions and monitored children's comfort level. At the same time, children's continuous EEG data and a video of the testing room were monitored by another research assistant outside the room.

EEG data preprocessing

The data were filtered with a 0.1–30 Hz bandpass filter. An epoch was defined as a 1200 ms segment beginning at 200 ms pre-stimulus onset (baseline) and ending at 1000 ms post-stimulus onset. Segmented data was screened for artifacts (eye blink, eye movement, drift) first using the Net Station software artifacting tool based on the following settings and then visually inspected. An eye blink was defined as a maximum-minimum amplitude difference exceeding 120 µV in the vertical eye channels within a 160 ms moving time window given a 20 ms moving average smoothing algorithm. An eye movement was defined as a maximum-minimum amplitude difference exceeding 120 µV in the horizontal eye channels within a 200 ms window. To address drifts, a bad channel was defined as a maximum-minimum amplitude difference exceeding 200 µV with a moving average of 80 ms. Bad channels were replaced with a statistically weighted interpolation from the full channel set. A segment was rejected if it contained an eye blink, an eye movement, or

Table 1. Reading-language scores.

	Reading Difficulties *n* = 20		Typical Readers *n* = 32	
Reading skills	Mean	SD	Mean	SD
TOWRE-2 Sight Word Efficiency (SS)**	80.85	11.47	109.10	10.75
TOWRE-2 Phonemic Decoding Efficiency (SS)**	80.60	10.27	100.16	11.70
WRMT-III Reading Comprehension (SS)**	84.40	13.45	111.53	12.00
PPVT-IV Receptive Vocabulary (SS)*	100.25	17.94	111.75	17.97

more than 30 bad channels. Finally, EEG data was visually inspected by 3 well-trained researchers (Brooker et al., 2019). Data were re-referenced to an average reference montage. Preprocessing was conducted within the Netstation (EGI-MAGSTIM) software environment with which research assistants were trained.

In data analysis, the reading difficulties group included 18 children (7 girls, 11 boys; mean age = 9.01, *SD* = 1.40) and the typically developing group included 29 children (15 girls, 14 boys; mean age = 9.54, *SD* = 1.27). Five children's ERP data were excluded from analyses due to data quality issues. The a priori requirement for ERP data was 45 trials per condition after artifact rejection. Two children in the reading difficulties group and two children in the typically developing group showed low signal quality and high artifact rate resulting in below 45 trials in one or both conditions after artifact rejection. One child in the typically developing group had unretrievable data to technical difficulties. The 1.5 IQR outlier analysis method was used and verified that children with low trial counts had extreme amplitude values. The two groups of children had a comparable number of trials in each condition after artifact rejection. They had a mean of 150 out of 228 trials after artifact rejection or 66%. No effect of group [$F(1, 46) = 0.22$, $p = .64$], word type by word difficulty level [$F(5, 230) = 0.38$, $p = .86$], or the group–condition interaction [$F(5,230) = 0.25$, $p = .94$] was found. The numbers of included trials by group and condition are summarized in Table 5.

Sites and time window for ERP components were planned a priori based on a review of the literature and later a visual inspection of the grand averaged waveform and topo plot by three researchers (Brooker et al., 2019). The N400 component shows a frontal-central-parietal topography in children (Coch, 2015; Friedrich & Friederici, 2005; Henderson et al., 2011; Rämä et al., 2013; Y. Tzeng et al., 2017). The N400 sites include eight electrodes around the C3 and F3 according to the 10–20 system; on the 128-site Geodesic Sensor Net, the eight electrodes were numbered 28, 29, 30, 34, 35, 36, 40, and 41 (marked by red circles, EGI-Magstim). No significant differences were found amongst the values extracted from the eight electrodes. The N400 component time window was defined as 250–550 ms post-stimulus onset. N400 amplitude was defined as the average of the eight electrodes' recorded minimum amplitude during the 250-550 ms epoch.

Sites and time windows for the N1 and LPC were also determined a priori based on a review of the literature and confirmed with a visual inspection of the grand averaged waveforms of all participants. The N1 is the first negative peak deflection with an occipital topography (Bentin et al., 1999; Eberhard-Moscicka et al., 2015; Kast et al., 2010). The N1 was computed from averaged electrodes numbers 66, 70, 71, 75, 76, 83, and 84 (marked by blue circles) on the 128-site EGI net which are equivalent to electrodes around O1 (electrode numbered 70) and O2 (electrode numbered 83) on the 10–20 system between 170 ms and 270 ms post-stimulus onset. The LPC was a positive deflection with a parietal topography (Hasko et al., 2013). The LPC was computed from averaged electrodes 31, 36, 37, 41, 42, 54, and 55 (marked by green circles) which are equivalent to electrodes around C3 (electrode numbered 36) and Cz (reference electrode) on the 10–20 system between 500 and 800 ms post-stimulus onset. A visual depiction of electrode sites is presented in Figure 2.

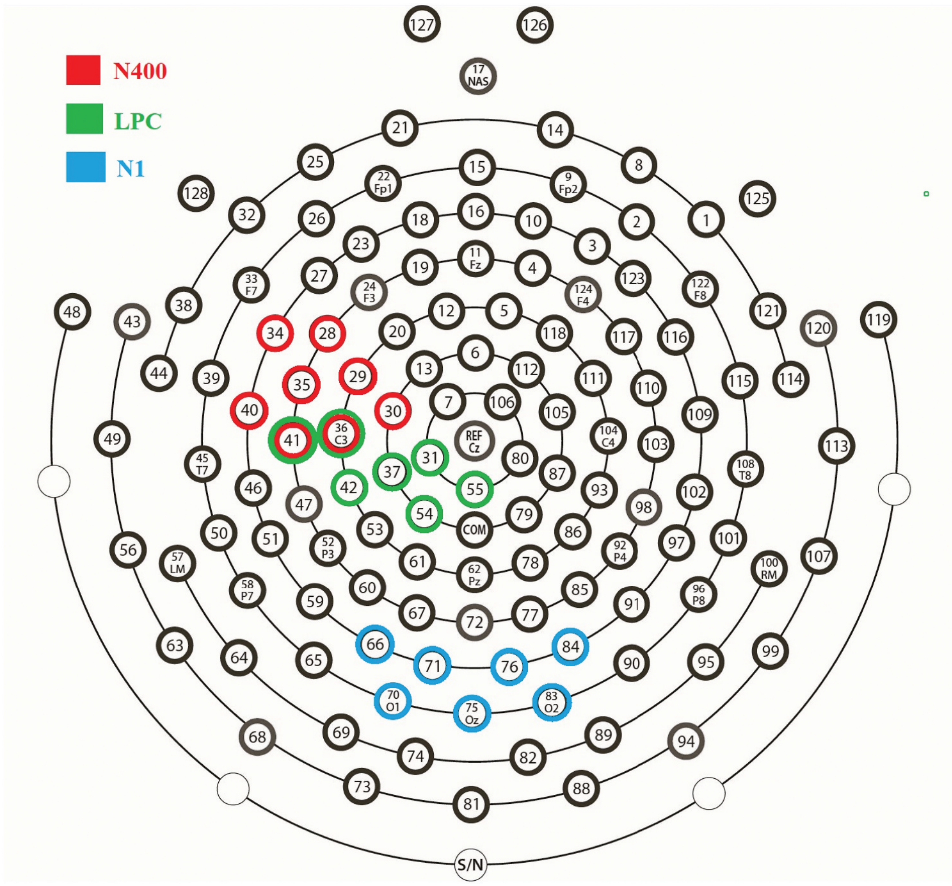

Figure 2. Electrode site map.

Reading and language

Word reading

Word reading was assessed using the Test of Word Reading Efficiency-2 (Torgesen et al., 2012). The test required children to read as many words as possible from a list arranged in an increasing level of difficulty, in a span of 45 s. The first list with real words measured sight word recognition efficiency and the second list with pseudowords measured phonemic decoding efficiency. Children received one point for each word read correctly. Raw scores were converted into standard scores based on age. Both Sight Word Efficiency (Cronbach's alpha = 0.98) and Phonemic Decoding Efficiency (Cronbach's alpha = 0.95) showed good reliability in the present sample. Good reliability and validity were reported for individuals aged 6 through 24 (Torgesen et al., 2012).

Vocabulary

Vocabulary was assessed using the Peabody Picture Vocabulary Test-4 (Dunn & Dunn, 2007). Children were presented with four pictures and were asked to select the picture that matched the vocabulary word read aloud by the examiner. Testing terminated when children missed 8 out of 12 items in a set. Children received one point for each item correctly answered. Raw scores were converted into standard scores based on age. This test showed good reliability and validity for individuals aged 2.5 through 90 (Dunn & Dunn, 2007) as well as the present sample (Cronbach's alpha = 0.96).

Reading comprehension

Reading comprehension was assessed using the "passage comprehension" subtest of the Woodcock Reading Mastery Test-III (Woodcock, 2011). It was a cloze task in which children read a sentence or passage and come up with a word to fill in the blank. Earlier items were supplemented with pictures and items had an increasing level of difficulty based on length, vocabulary, and complexity. Children received one point for every correct answer, and testing terminated with three consecutive incorrect answers. Raw scores were converted into standard scores based on age. The test showed good reliability and validity for individuals aged 4.5 through 79 in prior research (Woodcock, 2011) as well as good reliability in the present sample (Cronbach's alpha = 0.90). A cloze task without direct questions was selected to reduce guessing and use of prior knowledge. This task was chosen over paragraph-reading tasks to reduce frustration for children with reading difficulties, as earlier items consisted of single sentences with pictures.

Analysis

EEG and behavioral data were exported to Stata version 16.1 for analysis. To test for group differences on reading-language skills between children with reading difficulties and typical readers, one-way Analysis of Variance (ANOVA) was run on sight word efficiency, phonemic decoding efficiency, reading comprehension, and receptive vocabulary. Additionally, one-way Analysis of Variance (ANOVA) was run on accuracy scores on the task to verify successful completion of the ERP task by both groups of children. To test the first hypothesis that typical readers showed the N400 effect while children with reading difficulties did not, a repeated measure ANOVA was conducted with group (reading difficulties, typical readers) as between subject factor and word type (real words, nonwords) as within subject factor. To test the second hypothesis regarding the associations between ERPs and reading-language skills, Pearson correlation analyses were run on N1, LPC, and N400 effects and amplitudes elicited by word and nonword conditions and all reading-language measures with Bonferroni correction for multiple comparisons. Additionally, to examine if reading-language skills account for significant variance in the N400 effect, a hierarchical regression was run with age and gender as covariates. Receptive vocabulary, sight word efficiency, phonemic decoding efficiency, and reading comprehension were added to the predictive model respectively. The sequence of adding predictors to the model was based on theories of reading development (Ehri, 1994; Gough & Hoover, 1990; Grigorenko et al., 2020; Perfetti, 2007; Ziegler & Goswami, 2005). Receptive vocabulary precedes word reading (Grigorenko et al., 2020; Perfetti, 2007). In word reading, children first learn to recognize sight words as wholes and then learn individual letter-sound correspondences to decode pseudowords (Ziegler & Goswami, 2005). Also, oral skills (receptive vocabulary) and word reading are considered foundation to reading comprehension (Gough & Hoover, 1990).

Results

Behavioral results

Reading-language skills

Standard scores for reading-language measures are summarized in Table 1. Children with reading difficulties scored significantly lower than typical readers on sight word efficiency, phonemic decoding efficiency, reading comprehension, and receptive vocabulary. Additionally, all standardized measures generated standard scores which allow comparison to the norm. Based on the standard score interpretation guide stated in test manuals, mean scores for typical readers' sight word efficiency, phonemic decoding efficiency, and reading comprehension were in the Average range whereas mean scores for children with reading difficulties were in the Below Average range. On receptive vocabulary, both groups of children scored in the Average range.

Table 2. N1 amplitudes (μV).

	Reading difficulties n = 18		Typical readers n = 29	
Amplitudes	Mean	SD	Mean	SD
N1 Real words	−10.95	8.85	−12.24	7.51
N1 Nonwords	−9.60	8.68	−12.02	7.59
N1 Effect (difference)	−1.35	2.66	−0.22	2.57

Behavioral scores suggest a significant group difference in reading skills between children with reading difficulties and typical readers. Although the two groups also showed significant difference in receptive vocabulary, they both scored in the Average range compared to the norm. This result is consistent with the notion that vocabulary is an oral language skill that is related to but distinct from reading (Cavalli et al., 2016; Ehri, 1994).

Accuracy on ERP task

Accuracy scores on the ERP task helps verify children's task engagement and the appropriateness of task difficulty level, ruling out the possibility that group differences in ERPs could be attributed to children not reading the stimuli. The ERP task included 20 catch trials in which an animal word appeared, and children were to press a button each time they saw an animal word. Correct trials (out of 20) did not show a significant group difference between children with reading difficulties ($M = 11.17$, $SD = 5.25$) and typical readers ($M = 13.43$, $SD = 5.47$), $t(44) = 1.39$, $p = .17$, two-tailed. Although children with reading difficulties showed significantly lower performance on the standardized reading measures, they were able to complete the reading required in the ERP task at a level comparable to typical readers.

ERPs

N400

To test the first hypothesis that typical readers would show an N400 effect while children with reading difficulties would not, a repeated measure analysis of variance (RM-ANOVA) was conducted with group (reading difficulties, typical readers) as the between subject factor and word type (real words, nonwords) as the within subject factor. The interaction between group and word type was significant, $F(1, 45) = 4.13$, $p = .048$, $\eta^2 = 0.08$. The main effect of word type was significant, $F(1, 45) = 7.58$, $p = .009$, $\eta^2 = 0.14$. The effects remained significant when covariates including age (continuous) and gender (categorical) were added to the model. The main effect of group was insignificant, $F(1, 45) = 0.12$, $p = .27$.

To further understand the N400 effect, post-hoc t-tests were conducted using Bonferroni adjustment for multiple comparisons. For typical readers, nonwords elicited significantly more negative N400 amplitudes ($M = -7.13$, $SD = 2.11$) than real words ($M = -5.94$, $SD = 1.72$), $t(28) = 4.02$, $p = .0004$, two-tailed. On the other hand, in children with reading difficulties, N400 amplitudes elicited by nonwords ($M = -5.94$, $SD = 2.91$) and real words ($M = -5.75$, $SD = 2.43$) were not significantly different, $t(17) = 0.44$, $p = .66$, two-tailed. Real words elicited comparable N400 amplitudes in children with reading difficulties and typical readers. However, nonwords elicited significantly larger N400 amplitudes in typically developing readers than children with reading difficulties. Difference waves were computed by subtracting N400 amplitude elicited by nonwords from N400 amplitude elicited by real words. To visualize the N400 effect, N400 waveforms and difference waves by group and condition are represented in Figure 3.

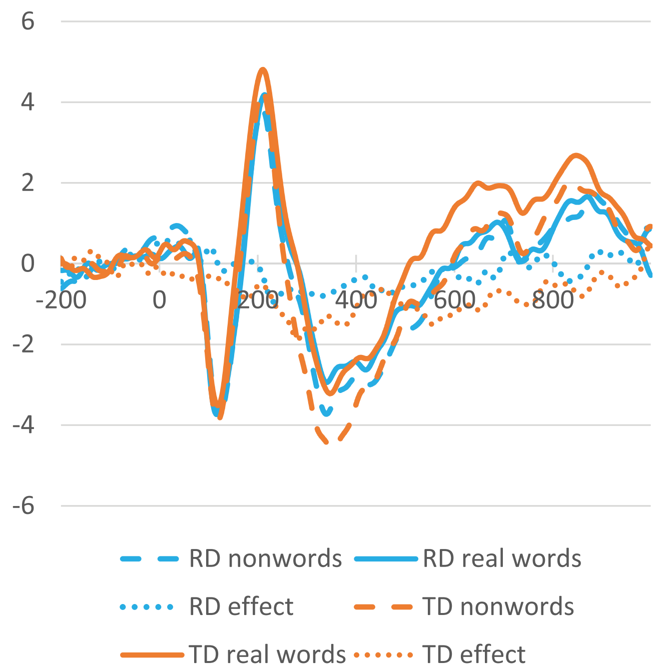

Figure 3. Stimulus-locked, grand average waveforms of the Reading Difficulties group (RD) are in blue and Typically Developing group (TD) in orange. Solid lines represent waveforms elicited by real words. Dashed lines represent waveforms elicited by nonwords. Dotted lines represent difference waves computed by subtracting nonwords from real words. Voltage (μV) is represented on the vertical axis and time (ms) is represented on the horizontal axis.

Table 3. LPC amplitudes (μV).

	Reading difficulties $n = 18$		Typical readers $n = 29$	
Amplitudes	Mean	SD	Mean	SD
LPC Real words	3.90	2.62	4.92	2.96
LPC Nonwords	3.13	2.43	3.82	2.11
LPC Effect (difference)	0.77	1.71	1.09	2.59

N1

N1 amplitudes are summarized in Table 2. Exploratory analyses with the N1, an indicator of print specialization at the visual perceptual level, was conducted. A repeated measure analysis of variance (RM-ANOVA) was conducted with group (reading difficulties, typical readers) as between subject factor and word type (real words, nonwords) as within subject factor. The main effect of word type, $F(1, 45) = 4.05$, $p = .0503$, the main effect of group, $F(1, 45) = 0.60$, $p = .44$, and the interaction effect between word type and group, $F(1, 45) = 2.09$, $p = .16$, were insignificant. Post-hoc t tests showed no significant N1 effect in either group of children. The same results were found with age and gender included as covariates.

LPC

LPC amplitudes are summarized in Table 3. A repeated measure analysis of variance (RM-ANOVA) was conducted with group (reading difficulties, typical readers) as between subject factor and word type (real words, nonwords) as within subject factor. The main effect of word type was significant, $F(1, 45) = 7.23$, $p = .01$, $\eta^2 = .14$. The main effect of group, $F(1, 45) = 1.56$,

Table 4. Correlation matrix between ERPs and reading-language measures.

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.
1. N400 real words	1												
2. N400 nonwords	.73*	1											
3. N400 effect	.11	−.60*	1										
4. N1 real words	.00	.12	−.16	1									
5. N1 nonwords	−.01	.08	−.13	.95*	1								
6. N1 effect	.06	.08	−.08	.15	−.18	1							
7. LPC real words	.02	−.18	.28	−.33	−.26	−.21	1						
8. LPC nonwords	.03	−.05	.11	−.25	−.17	−.25	.62*	1					
9. LPC effect	−.00	−.17	.24	−.17	−.17	−.01	.64*	−.29	1				
10. Sight Word Efficiency	−.02	−.24	.32	−.09	−.17	.24	.43	.35	.19	1			
11. Phonemic Decoding Efficiency	.03	.02	.00	−.09	−.12	.11	.36	.33	.12	.74*	1		
12. Reading Comprehension	−.07	−.21	.22	−.19	−.24	.15	.31	.36	.04	.73*	.53*	1	
13. Receptive Vocabulary	−.10	−.15	.11	−.22	−.17	−.15	.25	.44	−.12	.26	.24	.56*	1

$p = .22$ and the interaction effect between group and word type, $F(1, 45) = 0.22$, $p = .64$ were insignificant. Post-hoc analyses suggested that for typical readers, nonwords elicited significantly smaller LPC amplitudes ($M = 3.82$, $SD = 2.10$) than real words ($M = 4.92$, $SD = 2.96$), $t(28) = 2.27$, $p = .03$. For children with reading difficulties, nonwords elicited similar LPC ($M = 3.13$, SD = 2.43) as real words ($M = 3.90$, $SD = 2.62$), t(17) = 1.90, $p = .07$. However, LPC difference wave did not show a significant group difference, $F(1, 43) = 0.22$, $p = .64$. The findings remained consistent with age and gender as covariates.

Brain–behavior relationship

Bonferroni corrected Pearson correlations are summarized in Table 4. No significant association was observed between ERPs and reading-language measures. No significant association was observed between N1, N400, and the LPC. Reading measures (phonemic decoding efficiency, sight word efficiency, reading comprehension) were significantly associated with each other; receptive vocabulary was significantly associated with reading comprehension.

A hierarchical multiple regression was conducted to examine if reading-language skills accounted for variance in the N400 effect controlling for age and gender. On step 1, age and gender did not significantly account for variance in the N400 effect, F(2, 44) = 0.11, $p = .90$. On step 2, receptive vocabulary was added but the predictors did not explain significant variance in N400 effect, F(3, 43) = 0.32, $p = .81$; R-squared change = 0.017, F(1, 43) = 0.734, $p = .40$. On step 3, sight word efficiency was added and the predictors did not explain significant variance in N400 effect, F(4,42) = 1.29, $p = .29$. However, there was a statistically significant improvement from the previous model, R-squared change = 0.088, F(1, 42) = 4.127, $p = .046$. On step 4, pseudoword efficiency was added. The model explained significant

Table 5. Number of included trials after artifact rejection.

	Reading difficulties $n = 18$		Typical readers $n = 29$	
Condition (Grade level)	Mean	SD	Mean	SD
Real words				
Real words (K-1)	24.67	6.43	25.10	5.25
Real words (2–3)	24.89	4.99	24.66	5.01
Real words (4–5)	25.28	5.77	25.07	5.90
Nonwords				
Nonwords (K-1)	25.39	6.55	25	4.60
Nonwords (2–3)	25.44	6.43	25.03	5.28
Nonwords (4–5)	24.61	5.64	24.97	5.45

(17%) variance in the N400 effect, F(5, 41) = 2.91, p = .0246 with significant improvement from the previous model, R-squared change = 0.152, F(1, 41) = 8.462, p = .006. On step 5, adding reading comprehension did not explain additional variance in N400 effect, R-squared change = 0.000, F(1, 40) = 0.002, p = .96. Overall, the predictors explained a significant amount of variance (15%) in the N400 effect, F(6, 40) = 2.36, p = .0478. The unique contributions of sight word efficiency (p = .004) and pseudoword efficiency (p = .007) remain significant. Normality, linearity, and homoscedasticity assumptions were satisfied. Collinearity statistics were within acceptable range.

Discussion

The present study found that as hypothesized, typically developing children showed an N400 effect differentiating between words and nonwords, but the N400 effect was absent in children with reading difficulties. Exploratory analyses with the N1 and the LPC showed that typically developing children showed an LPC effect while children with reading difficulties did not; neither group showed an N1 effect. Regarding brain–behavior relationships, contrary to our hypothesis, ERPs were not significantly correlated with standardized measures of reading-language skills controlling for multiple comparisons. However, when the N400 effect was examined, sight word efficiency and phonemic decoding efficiency accounted for significant unique variance in the N400 effect but receptive vocabulary and reading comprehension did not.

The N400 effect

The present study provided evidence that the N400 effect differentiated between children with reading difficulties and average readers who performed at similar accuracy levels on the ERP task. The N400 effect provides clues on how word-level processes are connected to higher-level processes like meaning processing. At the word level, phonological-orthographic regularity knowledge facilitates reading by increasing reading automaticity for words with regular letter-sound patterns (Araújo et al., 2012; Coch & Holcomb, 2003; Lau et al., 2008). It also facilitates the efficiency of comprehension by selectively activating meaning processing for words with regular patterns and limiting meaning processing for words with irregular patterns (Kemény et al., 2018; Rämä et al., 2013). The group difference in the N400 lexicality effect suggests that the connection between word-level processes and meaning processing may be stronger in typically developing children. For typically developing readers, N400 amplitude differs between real words and nonwords; the difference suggests that word-level factors such as orthographic-phonological regularity modulated meaning processing. On the other hand, for children with reading difficulties, N400 amplitude did not differ significantly between words and nonwords, suggesting that word-level factors did not influence meaning processing. Another potential explanation is that the absence of the N400 effect in children with reading difficulties is related to insufficient phonological-orthographic regularity knowledge (Holcomb et al., 1992; Kaefer, 2016). It has been shown that given a task in which readers judged whether a word was real based on the phonological-orthographic regularity, children with reading difficulties were able to make judgments with comparable accuracy and reaction time as their typically developing peers (Kast et al., 2010). Still, neurophysiological processing differences may exist despite comparable behavioral performance.

The finding that typically developing children show larger N400 amplitudes to nonwords than words is consistent with some prior findings (Coch, 2015; Coch et al., 2002; Y. L. Tzeng et al., 2018). However, others reported that typically developing children, like proficient adult readers, showed smaller N400 amplitudes to nonwords than words because nonwords were meaningless, initiating less meaning processing (Chung et al., 2012; Coch et al., 2012; Khalifian et al., 2016). Processing demands of the tasks that elicited the N400 effect may be considered to understand the disparate findings. For example, some tasks required children to view stimuli and press buttons for catch trials that were their own names (Khalifian et al., 2016), make orthographic judgment in a Reicher-Wheeler paradigm (Coch et al., 2012), or make lexical judgment (Chung et al., 2012). The explicit meaning processing demand of these tasks may be relatively low. On the other hand, in the present study and others that found larger N400 amplitudes for nonwords than words, children completed a semantic judgment task in which they viewed stimulus words and pressed a button for words in a certain category, e.g., animals (Coch, 2015; Coch et al., 2002; Y. L. Tzeng et al., 2018). Children often utilize context to facilitate their reading; when both contextual effects and word-level effects are present, context effects may outweigh word-level ones (Kutas & Federmeier, 2011). Therefore, in the context of a semantic task where children are provided a story to judge whether a stimulus is an animal word, they may be predisposed to engage in meaning processing (Coch & Holcomb, 2003; Y. L. Tzeng et al., 2018). Nonwords would pose greater meaning processing demands than words because they are more difficult to fit into the story and task context, eliciting larger N400 amplitudes (Coch et al., 2012).

The number of studies targeting group comparison of the N400 effect in children is small. The present finding concurs with part of the literature (Chung et al., 2012; Y. L. Tzeng et al., 2018) and differs from others that did not identify a group difference (Coch & Holcomb, 2003; Mehlhase et al., 2020). Coch and Holcomb (2003) reported that 7-year-old readers with high and low reading abilities measured by Letter Identification, Word Identification, and Word Attack both showed a lack of the N400 effect distinguishing words and nonwords. Nevertheless, reading scores in their study revealed that both high and low ability groups scored above the population mean on all reading measures; a median split defined high and low ability groups (Coch & Holcomb, 2003). Mehlhase et al. (2020) found no difference between typical readers and children with reading difficulties around age 10. A methodological difference is that instead of defining nonwords as letter strings that are phonologically and orthographically illegal, Mehlhase et al. (2020) used consonant strings as nonwords and found that both groups of children showed an N400 effect differentiating consonant strings (smaller amplitudes) from other stimuli such as real words. Consonant strings are more distinguishable from real words than the nonwords used in the present study; the absence of vowels in an item is a conspicuous cue suggesting that the item is not a real word.

There are some challenges with synthesizing findings across studies conducted in different linguistic environments. Characteristics of reading difficulties differ across orthographies (Hasko et al., 2013; Landerl et al., 2022; Y. Tzeng et al., 2017). For example, amongst German readers with reading difficulties, relatively fewer readers struggle with word level decoding skills because orthographic-phonological correspondences tend to be more consistent with fewer exceptions, making orthographic-phonological regularities more readily acquired and applied (Landerl et al., 2022). Because the N400 effect elicited by lexical conditions taps knowledge about phonological-orthographic regularity, it likely varies across orthographies (Y. L. Tzeng et al., 2018). Previous studies suggest that differences in ERP patterns may be due to the differences in how written words in alphabetic and logographic orthographies are mapped onto meanings, how word sounds are accessed from written words, and how reading strategies differ by orthography (Bornkessel-Schlesewsky et al., 2011; Yum et al., 2011, 2014). Group differences in ERP between typical readers and individuals with reading difficulties were found in many orthographies; however, these differences occur at different time windows and in response to different stimuli. Due to the small number of studies, little is known about how or if orthography systematically moderates the relationship between reading difficulties and ERPs. Nevertheless, the present study, in conjunction with prior ones, suggests that in orthographies with inconsistent phonological-orthographic correspondences like English and Chinese, the N400 effect elicited by real words and nonwords differs between children with and without reading difficulties; this may not be the case for readers of consistent orthographies like German (Kemény et al., 2018). Although this cross-linguistic difference is consistent with theoretical conceptualizations of reading difficulties in opaque and transparent orthographies, additional cross-linguistic studies may be conducted to understand this pattern.

Exploratory analyses with N1 and LPC

Neither group of children showed a difference in N1 amplitude elicited by real words and nonwords. The words and nonwords in the present study are both made out of real letters, only differing by lexicality, reducing the likelihood of generating a marked N1 effect. Existing child studies often reported significant N1 effect by word-likeness (Maurer et al., 2006) but not by lexicality (Araújo et al., 2012; Eberhard-Moscicka et al., 2015; Kast et al., 2010). Developmentally, children first learn larger units to recognize words as wholes before becoming attuned to fine-grained, sub-lexical information (Ziegler & Goswami, 2005). Therefore, conditions with marked visual differences may generate an N1 effect when conditions with sub-lexical differences (words vs nonwords) may not.

Regarding the LPC, only children in the typical reading group showed an effect characterized by smaller LPC amplitude to nonwords than real words. The finding appears consistent with prior findings that average readers but not children with reading difficulties show an LPC effect differentiating familiar and unfamiliar words (Hasko et al., 2013; Kemény et al., 2018). The LPC has been associated with orthographic familiarity (Hasko et al., 2013). Children with typical reading skills may have developed stronger representations of the orthographic forms of words. As such, familiar or real words were processed differently than nonwords. The LPC effect group difference lends support to our findings regarding the N400 effect because the LPC reflects orthographic skills which also modulate the N400 in a word-nonword reading task.

Brain–behavior relationship

The hypothesized associations between N400 and meaning-related skills including receptive vocabulary and reading comprehension were not found. Although the N400 is considered an indicator of meaning processing, it was not associated with reading comprehension or receptive vocabulary in the present study. Amongst the handful of studies that examined this relationship, some reported significant correlations (Coch & Benoit, 2015; Khalifian et al., 2016) and others did not (Henderson et al., 2011). Significance was interpreted as a reflection of a common meaning processing construct shared by vocabulary and N400. In the present study as well as Henderson et al. (2011), vocabulary scores had limited variability compared to other scores. In Henderson et al. (2011) study, children ceilinged out on the vocabulary measure (mean = 96 out of 104, SD = 8) because instead of using a full standardized measure, 104 items were taken from a standardized measure based on children's grades. In the present study, children's vocabulary standard scores were negatively skewed (skewness = −1.05, kurtosis = 6.42). Many children with and without reading difficulties alike showed strong receptive vocabulary, consistent with the notion that oral language skills are important precursors of reading yet they are insufficient predictors for reading difficulties (Cavalli et al., 2016; Ehri, 1994; van Viersen et al., 2017). While reading comprehension also involves meaning processing which should overlap with the N400, previous studies suggested that in early elementary grades, reading comprehension may be more limited by word reading challenges than actual meaning processing challenges (Leach et al., 2003). Comprehension deficits independent of word reading may not emerge until late elementary grades when comprehension demands increase. As such, reading comprehension may not predict additional variance beyond word reading.

Word reading efficiency (sight words and decodable pseudowords) explained unique variance in the N400 effect controlling for age and gender. This finding corroborates the group difference found for the N400 effect where children with higher reading skills showed a larger N400 effect. Just as elementary school children's reading skills are more strongly influenced by word reading skills than meaning processing skills, their N400 effect is also more strongly associated with word reading than reading comprehension or vocabulary.

Significant associations between reading-language skills and N400s have been reported previously, but methodologies (i.e., selection of N400 measures) and results have been largely inconsistent across studies, leading to uncertainties about the mechanisms underlying these associations. Stronger word reading has been associated with smaller N400 amplitudes elicited by real words (Coch & Holcomb, 2003) and smaller N400 amplitudes across conditions (Coch et al., 2012; Henderson et al., 2011). However, other studies reported insignificant correlations (Coch & Benoit, 2015; Hasko et al., 2013). The present study diverges from the studies that reported significant associations in that amplitude measures (N400 amplitudes for real words or nonwords) were not significantly associated with reading-language skills.

The association between N400s and reading-language skills may be task-dependent because meaning processing is also task-dependent. Existing studies utilized different tasks with different requirements and cognitive demands to elicit the N400 component, e.g., congruency, repetition, rhyme judgment, orthographic judgment, semantic judgment, lexical judgment. N400s elicited by different tasks appear to show different patterns of association with different reading-language skills. For example, when an N400 effect was elicited by a picture-word judgment task where the picture and the word were either congruent or incongruent, the N400 effect was significantly associated with listening comprehension, which implicates meaning processing; however, the N400 effect was not associated with word reading or decoding (Henderson et al., 2011). Similarly, an N400 effect elicited in a word-nonword reading task may reflect the connection between orthographic-phonological processing and meaning processing, not meaning processing itself. Further, it has been suggested that the N400 may not represent a specific cognitive skill or stage in prominent theories (Khalifian et al., 2016; Kutas & Federmeier, 2011; Lau et al., 2008). The N400 does not follow a stagewise information processing theory in which word-level processes (e.g., decoding, sight word recognition) are first completed, followed by activation and selection of meaning in the mental lexicon, ending with successful comprehension. Instead, N400s represent an interactive, dynamic system supporting meaning processing (Kutas & Federmeier, 2011; Lau et al., 2008). Additionally, we might remain cautious about interpreting N400 or even standardized reading-language measures as "process-pure" constructs; successful integration of multiple skills is often needed to complete any given task (Khalifian et al., 2016).

Limitations and future directions

The present study has several limitations that may inform the directions for future research. First, our reading difficulties grouping was determined by the concurrence between a participant's parent report and standardized test scores on three standardized reading measures. The grouping challenge mirrors the ambiguity or lack of definitive cutoffs experienced by psychologists diagnosing specific learning disorder and educators determining special education eligibility for children with learning disabilities (Hale et al., 2010). Although some studies grouped participants by a diagnostic label, the diagnoses were made in a multi-method way, integrating parent-teacher reported information with standardized test scores (Flanagan & Alfonso, 2011; Grigorenko et al., 2020). Alternatively, some studies have grouped their participants into high and low reading abilities groups using a median split or utilizing "reading difficulties" as a group membership to avoid reliance on categorical diagnostic criteria (Grills et al., 2022; Psyridou et al., 2019). Nevertheless, future researchers may administer a comprehensive battery including academic and cognitive measures to determine how ERPs relate the cognitive-academic profiles of early readers. Second, although the present study focused on elementary school readers, participants varied in age. The youngest participants, 7-year-olds (with or without reading difficulties), were disproportionately excluded from ERP data analysis due to high artifact rate. For future research, over-sampling younger children or narrowing the age requirement may better account for the differences in children's reading process across levels. Third, to better isolate the lexicality effect, experimental stimuli may be expanded to represent various levels of lexicality (e.g., nonwords, pseudowords, regular words, irregular words).

Implications

The present study is focused on how ERPs differ between children with reading difficulties and typical readers on a word-nonword reading task. It is amongst the very few studies that examined this topic. First, typically developing readers showed an N400 effect and an LPC effect which were absent in children with reading difficulties. It shows that group differences exist on how children process orthographic information as well as the connection between orthographic-phonological processing and meaning processing; children with reading difficulties may be emergent in developing distinctions between how they process real words and nonwords. ERPs have the potential to be considered a biomarker of reading difficulties. However, integrating studies across linguistic environments, it appears that the N400 lexicality effect may differentiate between children with and without reading difficulties in opaque orthographies to a greater extent than it does readers of transparent orthographies. Second, the present study shows that word reading contributed unique variance to the N400 effect while vocabulary and reading comprehension did not. Just as children's reading is more limited by word reading skill than meaning processing skill in most elementary grades, the N400 effect is also more associated with word reading. Third, to understand mixed findings amongst N400 studies, it is important to note that N400 or meaning processing is context and task dependent whereas studies vary vastly in methodology and task demands. Specifically, the absence of an N400 effect elicited by lexicality may reflect inadequate connection between orthographic-phonological processing and meaning processing, but it may not indicate a deficit in meaning processing itself.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

Woltering S (PI) et al. (2018). Texas A&M University internal grant.

ORCID

Huilin Sun http://orcid.org/0000-0003-4132-0337

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*(2), 79–88. https://doi.org/10.1016/j.bandc.2012.02.010

Bakos, S., Landerl, K., Bartling, J., Schulte-Körne, G., & Moll, K. (2018). Neurophysiological correlates of word processing deficits in isolated reading and isolated spelling disorders. *Clinical Neurophysiology*, *129*(3), 526–540. https://doi.org/10.1016/j.clinph.2017.12.010

Ballan, R., Durrant, S. J., Manoach, D. S., & Gabay, Y. (2023). Failure to consolidate statistical learning in developmental dyslexia. *Psychonomic Bulletin & Review*, *30*(1), 160–173.

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. https://doi.org/10.1162/089892999563373

Bonte, M. L., & Blomert, L. (2004). Developmental dyslexia: ERP correlates of anomalous phonological processing during spoken word recognition. *Cognitive Brain Research*, *21*(3), 360–376. https://doi.org/10.1016/j.cogbrainres.2004.06.010

Bornkessel-Schlesewsky, I., Kretzschmar, F., Tune, S., Wang, L., Genç, S., Philipp, M., Roehm, D., & Schlesewsky, M. (2011). Think globally: Cross-linguistic variation in electrophysiological activity during sentence comprehension. *Brain and Language*, *117*(3), 133–152. https://doi.org/10.1016/j.bandl.2010.09.010

Brooker, R. J., Bates, J. E., Buss, K. A., Canen, M. J., Dennis-Tiwary, T. A., Gatzke-Kopp, L. M., Schmidt, L. A. (2019). Conducting Event-Related Potential (ERP) research with young children. *Journal of Psychophysiology*, *34*(3), 137–158. https://doi.org/10.1027/0269-8803/a000243

Cavalli, E., Casalis, S., El Ahmadi, A., Zira, M., Poracchia-George, F., & Colé, P. (2016). Vocabulary skills are well developed in university students with dyslexia: Evidence from multiple case studies. *Research in Developmental Disabilities*, *51*, 89–102.

Chung, K. K. H., Tong, X., & McBride Chang, C. (2012). Evidence for a deficit in orthographic structure processing in Chinese developmental dyslexia: An event-related potential study. *Brain Research*, *1472*, 20–31. https://doi.org/10.1016/j.brainres.2012.06.010

Coch, D. (2015). The N400 and the fourth grade shift. *Developmental Science*, *18*(2), 254–269. https://doi.org/10.1111/desc.12212

Coch, D., & Benoit, C. (2015). N400 event-related potential and standardized measures of reading in late elementary school children: Correlated or independent? *Mind Brain & Education*, *9*(3), 145–153. https://doi.org/10.1111/mbe.12083

Coch, D., & Holcomb, P. J. (2003). The N400 in beginning readers. *Developmental Psychobiology*, *43*(2), 146–166. https://doi.org/10.1002/dev.10129

Coch, D., Maron, L., Wolf, M., & Holcomb, P. J. (2002). Word and picture processing in children: An event-related potential study. *Developmental Neuropsychology*, *22*(1), 373–406. https://doi.org/10.1207/S15326942dn2201_3

Coch, D., & Mitra, P. (2010). Word and pseudoword superiority effects reflected in the ERP waveform. *Brain Research*, *1329*, 159–174. https://doi.org/10.1016/j.brainres.2010.02.084

Coch, D., Mitra, P., & George, E. (2012). Behavioral and ERP evidence of word and pseudoword superiority effects in 7- and 11-year-olds. *Brain Research*, *1486*, 68–81. https://doi.org/10.1016/j.brainres.2012.09.041

Cutting, L. E., & Scarborough, H. S. (2006). Prediction of reading comprehension: Relative contributions of word recognition, language proficiency, and other cognitive skills can depend on how comprehension is measured. *Scientific Studies of Reading*, *10*(3), 277–299. https://doi.org/10.1207/s1532799xssr1003_5

Dunn, L. M., & Dunn, D. M. (2007). *PPVT-4 manual*. NCS Pearson.

Eberhard-Moscicka, A. K., Jost, L. B., Raith, M., & Maurer, U. (2015). Neurocognitive mechanisms of learning to read: Print tuning in beginning readers related to word-reading fluency and semantics but not phonology. *Developmental Science*, *18*(1), 106–118. https://doi.org/10.1111/desc.12189

Ehri, L. (1994). Development of the ability to read words: Up- date. In R. Ruddell, M. Ruddell, & H. Singer (Eds.), *Theoretical models and processes of reading* (4th) ed., pp. 323–358. International Reading Association.

Flanagan, D. P., & Alfonso, V. C. (2011). *Essentials of specific learning disability identification*. John Wiley & Sons Inc.

Fonseca, L. C., Tedrus, G. M., & Gilbert, M. A. P. (2006). Event related potentials during the visual discrimination of words and pseudowords by children. *Arquivos de neuro-psiquiatria*, *64*(3A), 553–558. https://doi.org/10.1590/S0004-282X2006000400002

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*(11), 1785–1802. https://doi.org/10.1162/089892905774589172

Fry, E. (2000). *1000 instant words*. Teacher Created Resources.

Gao, F., Wang, J., Wu, C., Wang, M. Y., Zhang, J., & Yuan, Z. (2022). The neural dynamics associated with lexicality effect in reading single Chinese words, pseudo-words and non-words. *Cognitive Neurodynamics*, *16*(2), 471–481. https://doi.org/10.1007/s11571-021-09720-y

Gough, P. B., & Hoover, W. A. (1990). The simple view of reading. *Reading and Writing*, *2*(2), 127–160. https://doi.org/10.1007/BF00401799

Grigorenko, E. L., Compton, D. L., Fuchs, L. S., Wagner, R. K., Willcutt, E. G., & Fletcher, J. M. (2020). Understanding, educating, and supporting children with specific learning disabilities: 50 years of science and practice. *American Psychologist*, *75*(1), 37. https://doi.org/10.1037/amp0000452

Grills, A. E., Fletcher, J. M., Vaughn, S. R., & Bowman, C. (2022). Internalizing symptoms and reading difficulties among early elementary school students. *Child Psychiatry & Human Development*, *54*(4), 1–11. https://doi.org/10.1007/s10578-022-01315-w

Hale, J., Alfonso, V., Berninger, V., Bracken, B., Christo, C., Clark, E., Cohen, M., Davis, A., Decker, S., Denckla, M., Dumont, R., Elliott, C., Feifer, S., Fiorello, C., Flanagan, D., Fletcher-Janzen, E., Geary, D., Gerber, M., Gerner, M., & Wright, P.,Yalof, J. (2010). Critical issues in response-to-intervention, comprehensive evaluation, and specific learning disabilities identification and intervention: An expert white paper consensus. *Learning Disability Quarterly*, *33*(3), 223–236. https://doi.org/10.1177/073194871003300310

Hasko, S., Groth, K., Bruder, J., Bartling, J., & Schulte-Körne, G. (2013). The time course of reading processes in children with and without dyslexia: An ERP study. *Frontiers in Human Neuroscience*, *7*, 570. https://doi.org/10.3389/fnhum.2013.00570

Henderson, L. M., Baseler, H. A., Clarke, P. J., Watson, S., & Snowling, M. J. (2011). The N400 effect in children: Relationships with comprehension, vocabulary and decoding. *Brain and Language*, *117*(2), 88–99. https://doi.org/10.1016/j.bandl.2010.12.003

Holcomb, P., Coffey, S., & Neville, H. (1992). Visual and auditory sentence processing: A developmental analysis using event-related brain potentials. *Developmental Neuropsychology*, *8*(2–3), 203–241. https://doi.org/10.1080/87565649209540525

Kaefer, T. (2016). Integrating orthographic and phonological knowledge in early readers: Implicit and explicit knowledge. *Child Development Research*, *2016*, 1–7. https://doi.org/10.1155/2016/6036129

Kappenman, E. S., & Luck, S. J. (2010). The effects of electrode impedance on data quality and statistical significance in ERP recordings. *Psychophysiology*, *47*(5), 888–904. https://doi.org/10.1111/j.1469-8986.2010.01009.x

Kast, M., Elmer, S., Jancke, L., & Meyer, M. (2010). ERP differences of pre-lexical processing between dyslexic and non-dyslexic children. *International Journal of Psychophysiology*, *77*(1), 59–69. https://doi.org/10.1016/j.ijpsycho.2010.04.003

Kemény, F., Banfi, C., Gangl, M., Perchtold, C. M., Papousek, I., Moll, K., & Landerl, K. (2018). Print-, sublexical and lexical processing in children with reading and/or spelling deficits: An ERP study. *International Journal of Psychophysiology*, *130*, 53–62. https://doi.org/10.1016/j.ijpsycho.2018.05.009

Khalifian, N., Stites, M. C., & Laszlo, S. (2016). Relationships between event-related potentials and behavioral and scholastic measures of reading ability: A large-scale, cross-sectional study. *Developmental Science*, *19*(5), 723–740. https://doi.org/10.1111/desc.12329

Kutas, M., & Federmeier, K. D. (2011). Thirty years and counting: Finding meaning in the N400 component of the event-related brain potential (ERP). *Annual Review of Psychology*, *62*(1), 621–647. https://doi.org/10.1146/annurev.psych.093008.131123

Kutas, M., & Hillyard, S. (1980). Reading senseless sentences: Brain potentials reflect semantic incongruity. *Science (American Association for the Advancement of Science)*, *207*(4427), 203–205. https://doi.org/10.1126/science.7350657

Landerl, K., Castles, A., & Parrila, R. (2022). Cognitive precursors of reading: A cross-linguistic perspective. *Scientific Studies of Reading*, *26*(2), 111–124. https://doi.org/10.1080/10888438.2021.1983820

Laszlo, S., Stites, M., & Federmeier, K. D. (2012). Won't get fooled again: An event-related potential study of task and repetition effects on the semantic processing of items without semantics. *Language and Cognitive Processes*, *27*(2), 257–274. https://doi.org/10.1080/01690965.2011.606667

Lau, E. F., Phillips, C., & Poeppel, D. (2008). A cortical network for semantics: (De)constructing the N400. *Nature Reviews Neuroscience*, *9*(12), 920–933. https://doi.org/10.1038/nrn2532

Leach, J. M., Scarborough, H. S., & Rescorla, L. (2003). Late-emerging reading disabilities. *Journal of Educational Psychology*, *95*(2), 211.

Lee, S., Woltering, S., Prickett, C., Shi, Q., Sun, H., & Thompson, J. L. (2022). Exploring the associations between reading skills and eye movements in elementary children's silent sentence reading. *Reading Psychology*, *43*(1), 85–103. https://doi.org/10.1080/02702711.2021.2020189

Livingston, E. M., Siegel, L. S., & Ribary, U. (2018). Developmental dyslexia: Emotional impact and consequences. *Australian Journal of Learning Difficulties*, *23*(2), 107–135. https://doi.org/10.1080/19404158.2018.1479975

López Zunini, R. A., Baart, M., Samuel, A. G., & Armstrong, B. C. (2020). Lexical access versus lexical decision processes for auditory, visual, and audiovisual items: Insights from behavioral and neural measures. *Neuropsychologia*, *137*, 107305. https://doi.org/10.1016/j.neuropsychologia.2019.107305

Luck, S. J. (2014). *An introduction to the event-related potential technique*. MIT press.

Maurer, U., Brem, S., Kranz, F., Bucher, K., Benz, R., Halder, P., Steinhausen, H.-C., & Brandeis, D. (2006). Coarse neural tuning for print peaks when children learn to read. *NeuroImage*, *33*(2), 749–758. https://doi.org/10.1016/j.neuroimage.2006.06.025

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.

Mehlhase, H., Bakos, S., Bartling, J., Schulte-Körne, G., & Moll, K. (2020). Word processing deficits in children with isolated and combined reading and spelling deficits: An ERP-study. *Brain Research*, *1738*, 146811. https://doi.org/10.1016/j.brainres.2020.146811

Nobre, A. C., & McCarthy, G. (1994). Language-related ERPs: Scalp distributions and modulation by word type and semantic priming. *Journal of Cognitive Neuroscience*, *6*(3), 233–255. https://doi.org/10.1162/jocn.1994.6.3.233

Noordenbos, M. W., Segers, E., Wagensveld, B., & Verhoeven, L. (2013). Aberrant N400 responses to phonological overlap during rhyme judgements in children at risk for dyslexia. *Brain Research*, *1537*, 233–243. https://doi.org/10.1016/j.brainres.2013.09.018

O'Brien, B. A. (2014). The development of sensitivity to sublexical orthographic constraints: An investigation of positional frequency and consistency using a wordlikeness choice task. *Reading Psychology*, *35*(4), 285–311. https://doi.org/10.1080/02702711.2012.724042

Perfetti, C. A. (2007). Reading ability: Lexical quality to comprehension. *Scientific Studies of Reading*, *11*(4), 357–383. https://doi.org/10.1080/10888430701530730

Perfetti, C. A., & Stafura, J. (2013). Word knowledge in a theory of reading comprehension. *Scientific Studies of Reading*, *18*(1), 22–37. https://doi.org/10.1080/10888438.2013.827687

Psyridou, M., Tolvanen, A., Lerkkanen, M., Poikkeus, A., & Torppa, M. (2019). Longitudinal stability of reading difficulties: Examining the effects of measurement error, cut-offs, and buffer zones in identification. *Frontiers in Psychology*, *10*, 2841. https://doi.org/10.3389/fpsyg.2019.02841

Rämä, P., Sirri, L., & Serres, J. (2013). Development of lexical–semantic language system: N400 priming effect for spoken words in 18-and 24-month old children. *Brain and Language*, *125*(1), 1–10. https://doi.org/10.1016/j.bandl.2013.01.009

Reicher, G. M. (1969). Perceptual recognition as a function of meaningfulness of stimulus material. *Journal of Experimental Psychology*, *81*(2), 275–280. https://doi.org/10.1037/h0027768

Rüsseler, J., Becker, P., Johannes, S., & Münte, T. F. (2007). Semantic, syntactic, and phonological processing of written words in adult developmental dyslexic readers: An event-related brain potential study. *BMC Neuroscience*, *8*(1), 52. https://doi.org/10.1186/1471-2202-8-52

Shaywitz, S. E., Mody, M., & Shaywitz, B. A. (2006). Neural mechanisms in dyslexia. *Current Directions in Psychological Science*, *15*(6), 278–281. https://doi.org/10.1111/j.1467-8721.2006.00452.x

Torgesen, J. K., Wagner, R. K., & Rashotte, C. A. (2012). *Test of word reading efficiency*– (*Second Edition* ed.). Pro-Ed.

Tzeng, Y., Hsu, C., Huang, Y., & Lee, C. (2017). The acquisition of orthographic knowledge: Evidence from the lexicality effects on N400. *Frontiers in Psychology*, *8*, 433. https://doi.org/10.3389/fpsyg.2017.00433

Tzeng, Y. L., Hsu, C. H., Lin, W. H., & Lee, C. Y. (2018). Impaired orthographic processing in Chinese dyslexic children: Evidence from the lexicality effect on N400. *Scientific Studies of Reading*, *22*(1), 85–100. https://doi.org/10.1080/10888438.2017.1353996

van Viersen, S., Protopapas, A., Georgiou, G. K., Parrila, R., Ziaka, L., & de Jong, P. F. (2022). Lexicality effects on orthographic learning in beginning and advanced readers of Dutch: An eye-tracking study. *Quarterly Journal of Experimental Psychology*, *75*(6), 1135–1154. https://doi.org/10.1177/17470218211047420

Wang, Q., & Yuan, J. (2008). N400 lexicality effect in highly blurred Chinese words: Evidence for automatic processing. *NeuroReport*, *19*(2), 173–178. https://doi.org/10.1097/WNR.0b013e3282f3e3f2

Woodcock, R. W. (2011). *Woodcock reading mastery tests–third edition*. Pearson.

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*(7), 1910–1922. https://doi.org/10.1016/j.neuropsychologia.2011.03.018

Yum, Y. N., Law, S. P., Su, I. F., Lau, K. Y. D., & Mo, K. N. (2014). An ERP study of effects of regularity and consistency in delayed naming and lexicality judgment in a logographic writing system. *Frontiers in Psychology*, *5*, 315. https://doi.org/10.3389/fpsyg.2014.00315

Zhao, J., Kipp, K., Gaspar, C., Maurer, U., Weng, X., Mecklinger, A., & Li, S. (2014). Fine neural tuning for orthographic properties of words emerges early in children reading alphabetic script. *Journal of cognitive neuroscience*, *26*(11), 2431–2442.

Ziegler, J. C., Besson, M., Jacobs, A. M., Nazir, T. A., & Carr, T. H. (1997). Word, pseudoword, and nonword processing: A multitask comparison using event-related brain potentials. *Journal of Cognitive Neuroscience*, *9*(6), 758–775. https://doi.org/10.1162/jocn.1997.9.6.758

Ziegler, J. C., & Goswami, U. (2005). Reading acquisition, developmental dyslexia, and skilled reading across languages: A psycholinguistic grain size theory. *Psychological Bulletin*, *131*(1), 3. https://doi.org/10.1037/0033-2909.131.1.3

Zirkel, P. A. (2020). An updated primer of special education law. *TEACHING Exceptional Children*, *52*(4), 261–265. https://doi.org/10.1177/0040059919878671