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READING DEVELOPMENT IN CHILDREN: AN ELECTROPHYSIOLOGICAL INVESTIGATION

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Abstract

This study utilized event-related potentials (ERPs) to explore reading development in children and the role of orthographic and phonological processing. Standardized tests were administered to two 11-year olds. The two subjects also participated in an ERP session where they performed a lexical decision task on a computer. The lexical decision task included word triplets consisting of real words (e.g., CLAP), pseudohomophones (PHs, e.g., KLAP), and pseudowords (PWs, e.g., BLAP). During the lexical decision task the children had to decide if the stimulus item presented was a real word or a non-word. It had been hypothesized that children would read relying much more on phonological codes and eventually would shift their reliance to orthographic information. This study attempted to determine if subjects who should be past the initial stages of reading development, but still developing as readers, show differences in ERP waveforms in the lexical decision task. Other studies have studied the pseudohomophone effects on reading in children but have not looked at ERP effects.

ERP differences were noted between the two subjects. Despite their waveforms being different, each child showed a sensitivity to the differences between real words and nonwords and showed a slight pseudohomophone disadvantage. It could be possible that these two subjects are still in the adaptive process of relying on phonology over orthography of the printed words. Future research is necessary to confirm the patterns displayed in this experiment and explore the varying strategies in children while reading.

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How children learn connections between sounds and letters, in order to read words, is a complex question. Reading is a skill to master, and the steps you take to extract meaning from letters or words can be debated. Different theories claim that different processes lead to masterful reading. Looking at these theories and exploring new methods of research can help us better understand the behavioral and neural relationships of reading in children who are past the initial stages of learning to read. Children are unique while looking at this relationship due to their developing lexicons and inexperience in reading. Attempting to identify how children read real words and pronounceable nonwords, which for children may be equivalent to new words, and the strategies they use can help us understand the acquisition of literacy and inform theories of language development.

For many years researchers have been interested in the question of whether words are read visually or phonologically. Do we go directly from spelling to meaning or is there an internal phonological code in between these two? Some theories suggest that these two processes work in parallel, with the meaning of a word being activated either from visual or phonological processes, depending on the individual's reading skill level. For example, Coltheart and colleagues have suggested that there is a "direct route" from orthography to semantics that skilled readers primarily rely on, while developing readers may use an "indirect route" via phonology (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). Howerver, Harm and Seidenberg (2004) have argued that both pathways (visual and phonological) always play a role in accessing the meaning of words. One process does not prevail over the other but they each contrinbute to activating the meaning of words. Whether the reader accessed the phonological or visual pathway could depend on a number of factors such as the amount of experience they had with the word as well as the spelling to sound consistency. The key to masterful reading according to this model is that both pathways work together to eventually increase the speed and accuracy with which meanings are computed. These competing theories not only inform our understanding of reading, but they also provide ways to think about how we should be teaching our children to read. As one theory versus another can be debated, the ways to teach children to read can too be debated. Some would focus on a phonics approach that would teach phonological mediation. Others support a “whole language” approach that focuses on sight word reading, going from orthography right to semantics (Hempenstall, 1997).

Debates about the ways in which people read may also be affected by the orthographic consistency of a language. English does not have direct mapping from the letters on the page to the sounds of the words. It is considered an orthographically deep language due to the inconsistency of its symbols and sounds. One letter can make many different sounds and one sound can come from many possible letters. A more consistent language such as Spanish does not have the same irregularities in the grapheme to phoneme correspondence and this is why it is considred an orthographically shallow language. Languages that are considered to be more orthographically consistent, such as German and Spanish, allow children to mainly use strategies of grapheme to phoneme decoding. On the other hand, less orthographically consistent languages such as English require children to use multiple strategies. They may use some grapheme-phoneme decoding but also must rely on knowing specific letter patterns and whole-word recognition. These strategies are used in children learning to read English due to the lack of reliability of grapheme to phoneme correspondences (Goswami, Ziegler, Dalton, & Schneider, 2001). However, regardless of the orthographic depth of a language, phonological skills play a significant role in learning to read. This pertains to every orthography, not just English. The phonological skills of the reader can determine the success they will have when reading a new word and the recoding strategies they put into effect (Goswami et al., 2001). Some researchers have argued that phonological mediation (accessing the phonology of a word on your way to the meaning) is a necessary task when seeing a word (Goswami et al., 2001).

One way that children's phonological recoding strategies can be looked at is by studying pseudohomophones (PH), made up words that sound like real words, such as *kandy* (Goswami et al., 2001). By studying pseudohomophone effects on reading performance, we may see how much orthography and phonology each contribute, since pseudohomophones have the phonology of a real word, but do not have the matching orthography. One method of doing this could be in a lexical decision task (LDT) in which the reader has to decide if a word is real or not. In a LDT, the time it takes to decide if a presented word is real or not is affected by the phonological similarity of that word to a real word (e.g., Besner & Davelaar, 1983). If a pseudohomophone is presented, it has been shown that the reader will take longer and be less accurate in a LDT than if a real word or a non-pseudohomophone pronounceable nonword had been presented. This could be evidence to show that phonological processing is occuring when reading printed words (Besner & Davelaar, 1983). In addition to a lexical decision task, naming tasks can also be done to look at the pseudohomophone effect. In a naming task, a pseudohomophone nonword would usually be read faster than a matched orthographic control. For example, *kandy* would be read faster than the word *landy* (McCann & Besner, 1987). Having prior experience with the phonological information (*kandy* for *candy*) improves reading the English nonwords (Besner & Davelaar, 1983).

Goswami et. al (2001) studied performance in both naming and lexical decision tasks with English and German children ages 7, 8, and 9. Pseudohomophones were made for the experiment that were phonologically the same as their real word, “basewords”, but orthographically different. In addition to the pseudohomophones, there were pseudowords that were orthographically and phonologically similar to the baseword but not identical. There was also an additional group of nonwords that were neither orthographically nor phonologically similar to the real words. In the naming task, the children were asked to read the words or nonwords as quickly and accurately as possible that were presented one at a time. The children were timed on their reading time and they were also recorded. Significant pseudohomophone effects were found in the English children but not in the German children. They read the pseudohomophone words significantly more accurately than the controls while the German children read the pseudohomophone words and controls at the same level of accuracy. This result showed that the English children were much more reliant on whole-word phonology and were less reliant on recoding strategies at the grapheme-phoneme level, since prior experience with a real word sharing the pseudohomophone’s phonology only helped the English-speaking children. In a second experiment, Goswami et. al used a lexical decision task to investigate the extent to which phonological information is used to access lexical information while reading. The children had to decide whether the presented word was a real word or a nonword as quickly and accurately as possible. In contrast to the first experiment, pseudohomophone effects were found in the German children but not in the English children. Results showed that the English children were making their lexical decisions more based on the orthographic familiarity while the German children had more phonological recoding which lengthened their reaction times. The pseudohomophone disadvantage that the German children displayed suggested a more efficient recoding process at the grapheme-phoneme level with their activation of phonological information being more automatic than the English children.

While Goswami et al. (2001) found evidence for differences in reading strategies by native language, other researchers have found evidence that different strategies may even be used within English speakers. In a study by Jared, Levy, and Rayner (1999), adult poor readers showed more evidence of using phonological mediation during reading over good readers. Jared et al. (1999) used eye-tracking and proofreading tasks in order to see the relative contribution of phonological versus a direct route to word meanings. The skill of the readers as well the experience they had with the presented words played a factor in the role of phonology. These results can be interpreted to suggest that poor readers may not have the ability to pass up phonology when reading, while good readers have this ability and can rely on the orthography alone. However, an alternate interpretation is also possible. Good and poor readers may both activate phonology, but the poorer readers may let the phonology interfere on their way to reaching the semantics of the word.

While studies such as Jared et al.'s (1999) have shown that adults that are poor readers experience larger phonological effects than good readers, smaller pseudohomophone effects are apparent with children compared to adults (Laxon, Masterson, Gallagher, & Pay, 2002). This can present a challenge when looking at children’s development of reading skills. In Laxon et al.’s (2002) study, children 8-9 years old and 9-10 years old were tested for pseudohomophone effects. They found that the pseudohomophones were read more accurately in the younger group of children than the 9-10 year olds. This could provide an age range in which children may move away from phonological mediation and onto a more direct route of reaching the meaning of words. Reading strategies could vary significantly based on the developmental level of the reader as well as their reading skill. In order to look at the development of the direct route more accurately, additional studies with children and beginning readers would be invaluable.

In Ehri’s (1991) theory of learning to read, Ehri discussed that when children learn to read they already have an extensive spoken vocabulary that they need to merge with the corresponding orthography. She emphasized that for beginning readers many words act like pseudohomophones because they match up to a phonological code but not to an orthographic code. Less familiar words that are not present in a child’s spoken vocabulary would act like the non-pseudohomophone pseudowords.

Since behavioral studies have been mixed with regard to the processes underlying developing and skilled reading, additional data may need to be sought out. An online measure such as event-related potentials (ERPs) can be used to provide information about the sequence of events involved during reading. The ERP technique is a form of electroencephalography (EEG), which measures electrical activity on the scalp by multiple electrodes placed on the subject. The electrical activity that is measured is due to the firing of groups of neurons. When the brain responds to motor, sensory, or cognitive stimuli the EEG reveals the electrical charges as continuous brainwave (Molfese, Molfese, and Kelly, 2001). The neural responses are time-locked to the onset of critical stimuli which allows for analysis of the effects of the stimuli as changes in the EEG (Molfese, Molfese, and Kelly, 2001). After a filtering and and signal averaging process the result is the ERP which shows the brain's processing specific to the events of interest (Molfese, Molfese, and Kelly, 2001).

The ERP waveforms are recorded onto a graph which allows important positive and negative peaks to be identified. The peaks are often referred to as "components" and specific labeling systems are used for these peaks. The peaks are often labeled in terms of when they occur in the waveform and their polarity (e.g., P1 would be the first positive peak in the waveform) (Molfese, Molfese, and Kelly, 2001). Peaks are also often labeled based on the milliseconds (ms) at which they occur after the onset of the stimulus (e.g., N400 is a negative peak that occurs 400 ms post-stimulus onset) (Molfese, Molfese, and Kelly, 2001). Analyzing the components in the ERPs allows us to investigate how individuals process information, for example while reading. Some of the most analyzed peaks are the N1, P2, N100, P300, N400, and P600 (Key, Dove, and Maguire, 2005).

One waveform that is very common in language ERP studies is the "N400". The N400 component is generated by words and pronounceable pseudowords (as well as other meaningful stimuli), and its amplitude tends to be larger for items which require more processing load. For example, a previous ERP study looked at the cognitive processing of words and pseudowords from large orthographic neighborhoods (i.e., which resemble a large number of real words) and these words showed a greater processing load according to the ERP data than pseudowords from small lexical neighborhoods. Namely, the pseudowords from the larger orthographic neighborhood words showed an increased N400 (Holcomb, Grainger, & O'Rourke, 2002). However, another previous ERP study by McPherson, Ackerman, Holcomb, & Dykman (1998) showed a reduced N400 when reading disabled adolescents processed phonological information. In general, then, we know that the N400 is sensitive to both orthographic and phonological information during reading. However, the relative significance of these variables and how they may change as the skill of readers differ remains in question.

Overview of the Current Study

The current study aims to look at patterns of ERP and behavioral data in two 11-year old readers during lexical decision task. It also will explore any relationships between standardized test scores and ERP data while reading. A goal of this study is to better understand the role of orthographic and phonological processing when children read. Children are unique while looking at this relationship due to their developing lexicons and inexperience in reading. It has been hypothesized that children would read relying much more on phonological codes and eventually would shift their reliance to orthographic information. This study will attempt to determine if subjects who should be past the initial stages of reading development, but still developing as readers, show differences in ERP waveforms in the lexical decision task. This type of research can aid in further developing theories of reading and to help promote the most appropriate form of literary instruction for typical and atypical children. The following research questions are being addressed:

1) Do the participants respond more quickly or accurately to the basewords, pseudohomophones, or pseudowords (i.e., do they show a behavioral pseudohomophone effect)?
2) Are there differences in the N400 response to the basewords, pseudohomophones, or pseudowords?
3) Do standardized test measures show a relationship to the performance on the LDT task based on behavioral performance and ERP waveforms?

Methods

Participants

The participants of the current study were two children, each age 11, recruited from the Language and Literacy Research Initiative at the Pennsylvania State University. A third child, age 8, enrolled in the study, but did not complete the lexical decision task and data from this child are not discussed further. The children were native speakers of English who did not learn any other language before age 5. Additional requirements included the children being right-handed, having normal or corrected-to-normal vision and hearing, and no history of neurological disorders. The families were compensated $10 per hour for their participation.

Overview of Experiment

The study received approval from the Penn State University Office for Research Protections. The children that participated had completed a battery of standardized tests assessing cognitive, language, and reading abilities previously and the testing data was in the LLRI database. This allowed the children to only attend one experimental session for the current study that lasted approximately 2 hours.

The following standardized tests were completed prior to this study: The Comprehensive Test of Phonological Processing (CTOPP) (Wagner, Torgesen, & Rashotte, 1999), Test of Word Reading Efficiency (TOWRE) (Torgesen, Wagner, & Rashotte), the Clinical Evaluation of Language Fundamentals (CELF-4) (Semel, Wiig, & Secord, 2003), and the Wechsler Abbreviated Scale of Intelligence (WASI) (Wechsler, 1999). The CTOPP subtests used were elision, blending words, and rapid letter naming. The TOWRE test included two subtests, the sight word efficiency subtest and the phonetic decoding subtest. These two subtests were compiled together to make one final total word reading score. The CELF-4 score that was used was the Core Language score. Finally, with the WASI, the scores that were used were the verbal IQ score, the nonverbal IQ score, and a full scale IQ score. For Subject A, a verbal IQ score was not available but nonverbal IQ and full scale IQ were computed for each child.

Before the experimental session a screening questionnaire was completed over the phone to ensure the participants met the experimental criteria. At the experimental session the children were asked to provide assent in writing, while parents provided written consent. During the experimental session, a participant questionnaire and reading and language questionnaire were completed by the parent. The first questionnaire requested demographic information, assessed handedness, and assured that the child met the inclusion criteria. The second questionnaire asked about the language and reading skills of the child and included a rating scale for their English language skills. A lexical decision task was administered in which the child had to decide whether or not the presented word was real or not, using a gamepad to respond. The presented word was either a real word, psuedohomophone, or pseudoword. ERPs and behavioral responses were recorded while the child completed this computerized task.

Stimuli

The stimuli were all based on English words, either monosyllable or bisyllable. The critical items consisted of groups of "triplets" with a real word "baseword", a matched pseudohomophone, and a matched pseudoword. The monosyllable basewords were 4-5 letter long nouns. Their pseudohomophones (PH) matched the baseword (BW) on pronunciation and differed fron the baseword by 1 or 2 letters. This criteria was used because Coltheart, Patterson, and Coltheart (1994) showed that the pseudohomophone effect only occurred with pseudohomophones that were orthographically very similar to their basewords, so the effect would be apparent with *kat* (for cat) but not for *phite* (for fight) (as cited in Coltheart & Rastle, 1994). The pseudowords (PW) were orthographic neighbors with the baseword, could rhyme with the baseword, and could differ from the baseword by 1-2 letters. As Coltheart et al. (1994) argued that the pseudohomophone effect only occurred with pseudohomophones that were similar orthographically to their base words, Seidenberg and McClelland (1989) proposed that the pseudohomophone effect was present due to the fact that pseudohomophones are just closer orthographically to real words than the non-pseudohomophone words. To rule out this possibility as an explanation for any observed pseudohomophone effects, the "pseudowords" in this experiment were kept orthographically similar to the baseword but were non-homophonic. All monosyllable stimuli items had regular spelling. The bisyllable words differed in that they could have irregular spelling, and spelling regularity was coded for. The bisyllable basewords were 4-6 letter long nouns. The pseudohomophones and pseudowords for the bisyllable words followed the same rules as the monosyllable words. In addition to these stimulus items, monosyllable and bisyllable filler words were presented during the task, so that equal numbers of real words and nonwords (including pseudowords and pseudohomophones) were presented during the experiment. Each child saw 280 total items during the experiment. There were 40 monosyllable words in each condition (baseword, pseudohomophone, pseudoword, filler) and 30 bisyllable words in each condition. Specific examples of the conditions are in Table 1.

Table 1. *Experimental conditions and stimuli examples from matched triplets. Note that items were counterbalanced across participants, so no participant saw more than one item from a given triplet.*

Condition	**Stimulus Example**	**Number**
mono baseword	CLAP	40
mono pseudohomophone	KLAP	40
mono pseudoword	BLAP	40
bi baseword	ACID	30
bi pseudohomophone	ASID	30
bi pseudoword	APID	30
mono fillers	ACHE	40
bi fillers	AGENT	30

For each stimulus item the age of acquisition, Kucera and Francis written frequency (K-F Frequency), and number of letters was found. The age of aquistion (AoA) was found from the MRC Database (http://www.psy.uwa.edu.au/mrcdatabase/uwa_mrc.htm), as well as from Bristol Norms (http://language.psy.bris.ac.uk/norms/BristolNorms30-08-05.txt). The MRC database AoA ratings come from the norms of Gilhooly and Logie (1980) and were multiplied by 100 to produce scores in the 100-700 range (100 x 1 [0-2 yrs] to 7 [13+]). The Bristol

Norms values were scaled to match the norms of Gilhooly and Logie. The K-F Frequency was found from the MRC Database as well (Kucera & Francis, 1967). Three orders were created which differed in whether they saw the baseword, pseudohomophone, or pseudoword of a "triplet". However, because there were only two participants in this study, only two orders were used. As shown in Table 2, the orders were well-matched on the stimuli's characteristics. On average, words used in the experiment had fairly low frequencies, but average age of acquisition ratings between 285 and 349, corresponding to an age range of approximately 4 to 6 years old.

Table 2. *Average number of letters, frequency (KFFRQ), and age of acquisition (AoA) for each stimulus list (order) across critical conditions.*

	Monosyllable Words			Bisyllable Words		
Order	# of letters	KFFRQ	AofA	# of letters	KFFRQ	AofA
1	4.39	11.41	338.3	3.86	15.60	285.0
2	4.59	13.45	314.2	5.01	17.58	279.3
Fillers	4.40	24.25	349.0	5.60	23.79	333.0

Experiment

After the questionnaires, consent, and assent were confirmed, participants were fitted with an electrode cap (see below). Once the cap was in place, the children completed one computer-based task that was split into four 5-minute blocks. Each experimental block had 70 stimulus items (words, pseudohomophones, and pseudowords) presented in a random order. The stimuli were presented on the computer screen in a sound-attenuated and electrically shielded room as the child sat in a comfortable chair.

The EEG activity was recorded as the children saw one word at a time on the computer screen. The words were either basewords, pseudohomphones, pseudowords, or filler words. A lexical decision task (LDT) was administered in which the child had to decide whether or not the presented word was real or not, using a gamepad to respond. The “red” button was pressed if the word was not real (PW and PH) and the “blue” button was pressed if the child thought the word was real (basewords and fillers). Practice trials were administered before the task to assure that the child understood the directions and to practice blinking at the desired times, as described below.

In the LDT task, each word was presented on the screen for 400 ms. There were six programmed screen shots in each trial (see Figure 1). The first screen consisted of a plus sign that allowed the child to know that focus needed to be on the center of the screen for the upcoming word and this lasted 500 ms. A blank screen followed for another 500 ms and then the word screen appeared. Another blank screen followed for 1100 ms in which the child responded during this time. The next screen had a symbol that resembled closed eyes and this was designated as the time blinking was allowed. Allowing a set time for blinking was necessary since eye movements create an electrical signal that could interfere with the desired brain recordings. The blinking screen lasted for 2000 ms and was finally followed by the last screen of the trial which was blank and lasted 500 ms.

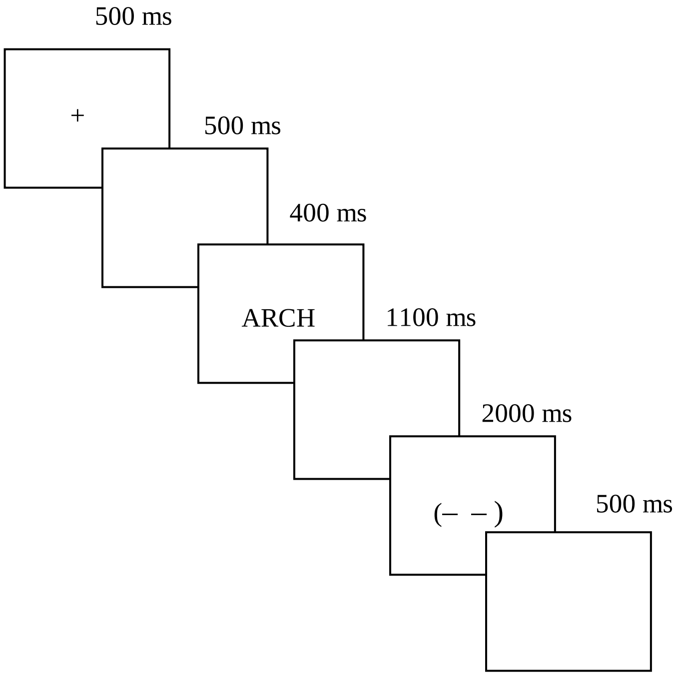

Figure 1. Time course and organization of stimuli from the onset of one critical item to the next.

EEG recording

The electrical activity of neurons in the brains was measured at the scalp of the participants using an electrode cap. The EEG was amplified and digitized following the capping procedure. The EEG was time-locked on the different stimulus items so it was possible to see the activity of the brain related to each stimulus item.

The cap consisted of 29 electrodes. In addition to these 29 electrodes, 4 surface electrodes were placed beneath the left eye, beside the right eye, and on each mastoid bone. The conduction between the scalp and electrode was allowed by injecting a small amount of conductive gel into each electrode. Before the task, impedances for scalp and mastoid electrodes were brought to below 5 kilo-ohms (kΩ) and the eye electrodes were reduced to less than 20 kΩ. The left mastoid electrode (A1) was the designated reference electrode. The left eye electrode (LE) recorded participant eye blinks while the right eye electrode (HE) measured horizontal eye movements.

For Subject A, all 33 of the electrodes were connected to an SA amplifier which allowed the signal to be amplified and analyzed at a later time. This amplifier had a bandpass of 0.1 to 40 hertz (Hz) and sampled the EEG continuously at 200 Hz during the experiment. Eleven of the electrodes were measured from the standard international 10-20 system. Electrodes were located on the midline at frontal (Fz), central (Cz), and parietal (Pz) sites. Eight more electrodes were found at each hemisphere frontal (F2/F4), temporal (T3/T4), central (C3/C4), and parietal (P3/P4). An additional ten electrodes were found based on the Modified Combinatorial Nomenclature system. There were two midline sites on the frontal pole (FPz) and the occipital pole (Oz), four left and right fronto-central sites (FC1/FC2, FC5/FC6), and four left and right centro-parietal sites (CP1/CP2, CP5/CP6). Eight additional modified 10-20 system sites were recorded from lateral positions that were 33% of the distance from FPz to T3/T4 (FP1’/FP2’), 67% of the distance from FPz to T3/T4 (F7’/F8’), 33% of the distance from Oz to T3/T4 (O1’/O2’), and 67% of the distance from Oz to T3/T4 (T5’/T6’). Subject B differed in that he only had 11 electrodes connected to the amplifier. Data from the following electrodes were collected for Subject B: Fz, Cz, Pz, FC1, CP1, FC2, CP2, A1, A2, LE, and HE. The full 33-channel montage is presented in Figure 2.

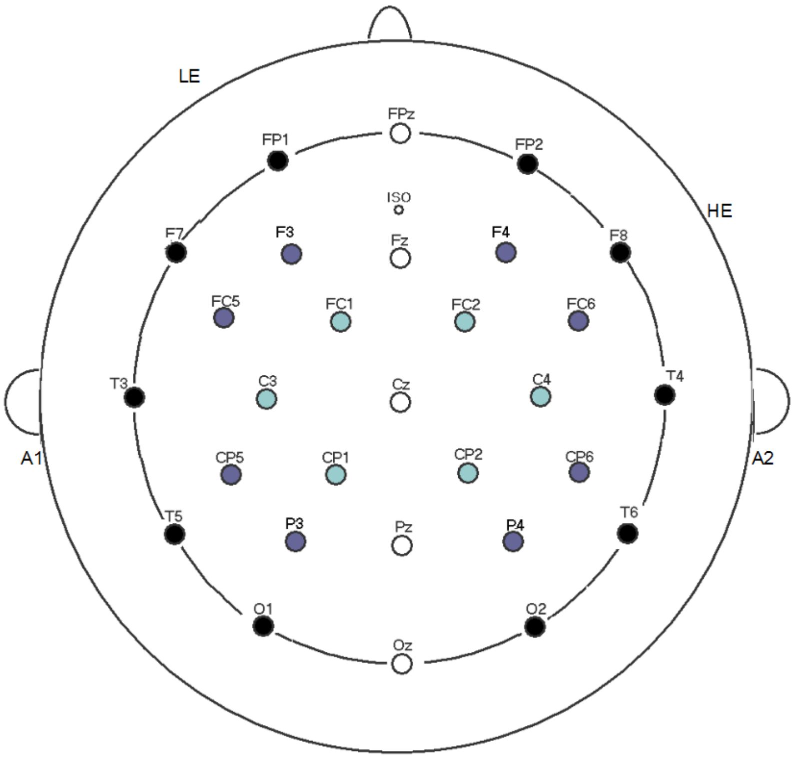

Figure 2. 32-channel electrode montage.

Data analysis

Electrophysiological measures were evaluated for the baseword, PW, and PH processing by the children. At the completion of the experiment the neural activity was averaged to form event-related potentials (ERPs). ERPs were analyzed for each subject for each condition (BW, PH, PW) at the Fz, Cz, and Pz electrode sites. The EEG waveforms began with a 100 ms baseline before the stimulus word onset and were assessed until 900 ms post-stimulus word onset. An automated artifact rejection algorithm was applied to the data to eliminate any muscle artifacts and eye blinks that could affect the averages. The EEG was rechecked visually to assure that no artifacts were missed, and the artifact algorithm was adjusted to best fit each child's data. Trials with unrecoverable eye blinks or muscle movements were not included in the averages.

Based on visual inspection of the EEG waveforms, components of interest were apparent when looking at the words versus pseudohomophones and pseudowords. Differences appeared at two peaks, one approximately at 200 ms and another at approximately 400 ms. The behavioral data (button presses) was also evaluated in addition to the ERP results. Mean reaction times and the percent correct were calculated for the real words (basewords and fillers) and non-words (PH and PW) for each participant.

Results

In the current study words, pseudohomophones, and pseudowords were presented during a lexical decision task. The ERP data gathered during the task was evaluated to look at how the orthographic or phonological properties of the critical items might impact different ERP components. The following three electrodes were evaluated for both participants: Fz, Pz, and Cz.

Standardized Test Measures

Subject A and Subject B completed a battery of standardized tests as part of the LLRI and their scores are presented in Table 3.

Table 3: *Standardized test scores for Subjects A and B.*

	Subject A	*Subject B*
WASI verbal IQ	119	N/A
WASI nonverbal IQ	104	117
WASI full scale IQ	113	124
CELF core language	123	121
TOWRE sight word efficiency	125	114
TOWRE phonetic decoding	106	112
TOWRE total word	119	116
CTOPP elision	10	13
CTOPP blending words	13	12
CTOPP rapid letter naming	12	10

Subject A's full scale IQ score placed him in the 81st percentile while Subject B's score placed him in the 95th percentile. Their core language scores were similar with Subject A falling in the 94th percentile and Subject B in the 92nd percentile. Another comparable test score was the TOWRE total word score with Subject A in the 89th percentile and Subject B in the 85th percentile. Based on these scores both children were typical readers and learners.

Behavioral Results

The reaction times and accuracy for Subject A are presented in Table 4. Subject A never responded that a nonword was presented. Thus he only responded correctly to monosyllable and bisyllable real words as well as fillers (conditions 1,4,7,8). All pseudohomophones and pseudowords if responded to were then incorrect. The participant was more likely to fail to respond to pseeudohomophones and pseudowords than to real words. However, even if no responses are treated as correct responses for the two types of nonwords, accuracy was low for this participant on the PHs and PWs.

Table 4: *Reaction times and percent errors for Subject A.*

	Correct Response Time (ms)	*% correct*	*Incorrect Response Time (ms)*	*% incorrect*	*% no response*
Mono BWs	522.63	95.0%	---	---	5.0%
Mono PHs	---	---	414.62	65.0%	35.0%
Mono PWs	---	---	472.62	52.5%	47.5%
Bi BWs	554.63	90.0%	---	---	10.0%
Bi PHs	---	---	405.24	70.0%	30.0%
Bi PWs	---	---	400.00	56.7%	43.7%
Mono Fillers	487.63	100%	---	---	---
Bi Fillers	593.45	96.7%	---	---	3.3%

In contrast to Subject A, Subject B did respond when he thought a nonword was presented. The reaction times and accuracy for subject B are presented in Table 5. Subject B showed high accuracy to all types of items.

Table 5: *Reaction times and percent errors for Subject B.*

	Correct Response Time (ms)	*% correct*	*Incorrect Response Time (ms)*	*% incorrect*	*% no response*
Mono BWs	749.17	90.0%	746.25	10.0%	---
Mono PHs	776.71	95.0%	812.50	5.0%	---
Mono PWs	785.51	97.5%	---	---	2.5%
Bi BWs	802.88	86.7%	791.67	10.0%	3.3%
Bi PHs	812.04	90.0%	867.50	10.0%	---
Bi PWs	789.64	93.3%	765.00	6.7%	---
Mono Fillers	766.63	100%	---	---	
Bi Fillers	710.29	96.7%	---	---	3.3%

As the tables show, the subjects responded significantly differently from each other. On average Subject A responded to critical items 481.35 ms post-onset whether correct or incorrect. Subject B responded 782.75 ms post-onset stimulus. Subject A took on average 129.66 ms less time to respond to PHs than BWs and 26.38 ms less time to respond to PHs than PWs, but all of these responses were incorrect. However, Subject B took 56.04 ms more time to respond to PHs than BWs and 37.14 ms more time to respond to PHs than PWs. Monosyllable words were responded to 13.9 ms faster than bisyllable words for Subject A. Subject B responded to monosyllable words 18.5 ms faster than bisyllable words as shown in Table 7.

Table 6: *Reaction times averaged for both monosyllabic and bisyllabic critical items.*

	Subject A	*Subject B*
BWs	539.585	761.1483
PHs	409.93	817.1875
PWs	436.31	780.05

Table 7: *Average reaction times for both subjects in terms of word length.*

	Mono	*Bi*
Subject A	474.4	488.3
Subect B	772.8	791.3

The mean percentage of errors are listed below in Table 8. Subject A had the fewest errors for the real words, followed by pseudowords, and finally pseudohomophones. Subject B differed slightly with the real word errors and pseudohomophone errors being relatively similar. Subject B had overall many fewer errors than Subject A, but the two cannot be directly compared due to the way each subject's errors were calculated. For Subject A, responses were considered correct in the two nonword categories if there was no response, even though a no response was considered incorrect for Subject B.

Table 8: *Mean percentage of errors for Subjects A and B in terms of word length and word type.*

		words	*PH*	*PW*
Subject A	Mono	2.5%	65%	52.5%
	Bi	6.7%	70%	56.7%
Subject B	Mono	5%	5%	2.5%
	Bi	5%	10%	6.7%

Patterns observed in ERP Waveforms

The averaged ERP data of each subject was analyzed visually to compare the processing of the basewords, pseudohomophones and pseudowords presented during the lexical decision task. The electrode sites Fz, Cz, and Pz were specifically looked at. Subjects A and B differed in some of the components shown. For both subjects, the decision was made to look at all items together, regardless of the accuracy of the response, since Subject A's behavioral responses made it difficult to identify a large enough subset of "correct" responses for each category. However, it is possible that the ERPs would be sensitive to knowledge that is not revealed behaviorally. For example McLaughlin, Osterhout, & Kim (2004) found evidence that ERPs can reveal lexical knowledge in second language learners that behavioral performance does not reflect. Although Subject B was more accurate in the task and it would have been possible to evaluate only correct responses for this subject, analyses for this participant focused on all items, as with Subject A, in order to make the waveforms more comparable.

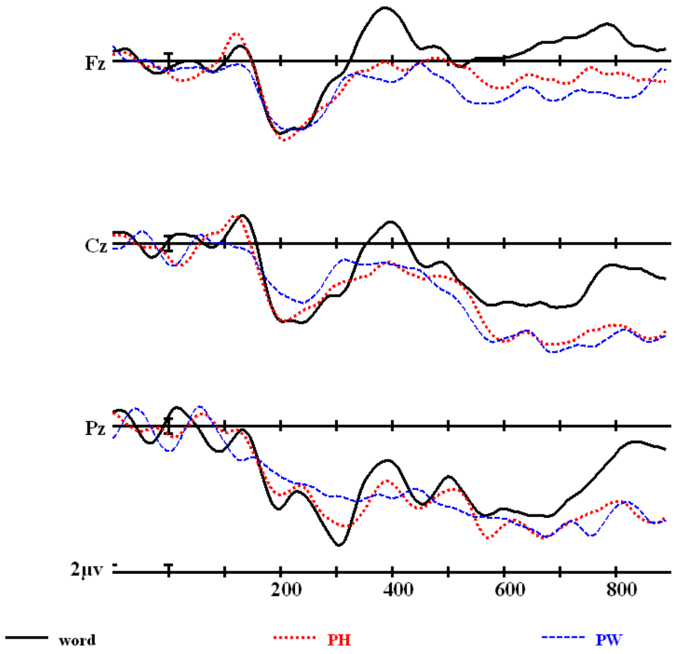

Figure 3: ERP waveforms at Fz, Cz, and Pz electrode locations for words, PHs, and PWs for Subject A.

For Subject A, the processing of all words, pseudohomophones, and pseudowords was evaluated and the waveforms are shown in Figure 3. The following components of interest were identified: a positive peak approximately at 200 ms (P200), followed by a negative peak approximately at 400 ms (N400). The waveforms are similar from the stimulus onset until 150 ms where the word and PH waveforms then form a small negative peak before making a positive peak at 200 ms (P200). The amplitude of the PW P200 peak was not as positive as that for the basewords, but the PH amplitude was similar to that for the words. From 200 ms until 400 ms the waveforms act similarly until all three waveforms make a negative peak, the word condition being the most robust. The N400 peak was more prominent in at the Fz and Cz electrode sites than the Pz site. At N400 the amplitude is significantly larger for the BW than the PH and PW conditions at the Fz and Cz sites and slightly more negative at the Pz site. From 400 ms on, the word waveform lies above the other two (more negative) until the end of the epoch at 900 ms.

Subject B’s processing of all words, pseudohomophones, and pseudowords appeared differently from Subject A’s and are shown in Figure 4. The ERPs showed the following components: a negative peak approximately at 170 ms (N1), followed by a positive peak approximately at 300 ms (P200), and another negative peak around 400 ms (N400).

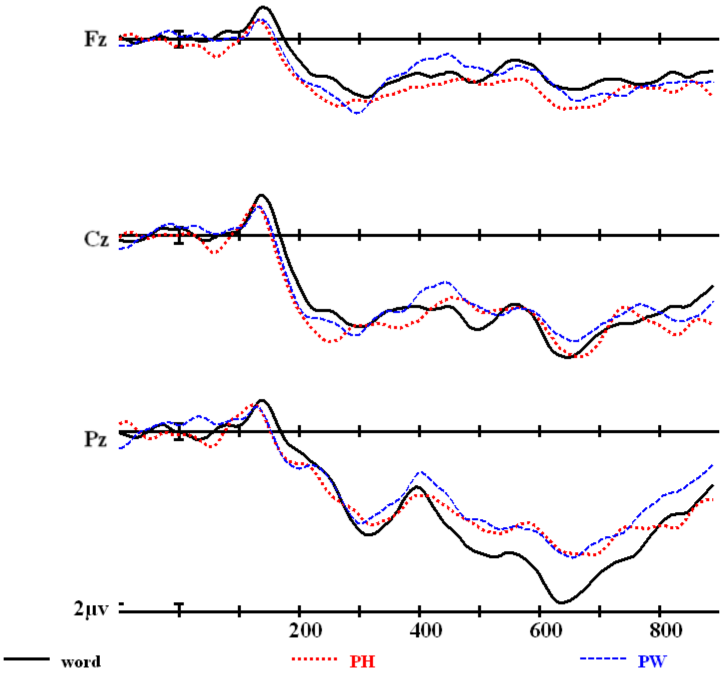

Figure 4: ERP waveforms at Fz, Cz, and Pz electrode locations for words, PHs, and PWs for Subject B.

The waveforms are similar from the stimulus onset until 150 ms where all three conditions formed a small negative peak, which is slightly larger for words than the other two conditions. All three waveforms dip down after 200 ms to form a more broad positive peak approximately at 300 ms, which may be a somewhat delayed P200.

Following this component, all three become more negative around 400 ms with the Pz site showing the most distinct N400 peak. Unlike Subject A, for Subject B the PW waveform was the most negative around the 400 ms marker. Following 400 ms, all three waveforms act relatively the same with very small positive and negative peaks. The only large change in amplitude following 400 ms is at the Pz site where the real words waveform forms a positive peak, below the PH and PW waveforms, at 600 ms.

Discussion

The study's aim was to better understand the role of orthographic and phonological processing when children read by analyzing behavioral measures and ERPs. ERPs were used to measure each child's processing patterns while reading real words, pseudohomophones (PHs), and nonhomophonic pseudowords (PWs) in a lexical decision task. One of the main foci of this study was to evaluate how real words, PHs, or PWs affect ERP components at the Fz, Cz, or Pz electrode locations.

The two participants in this study were 11-year old males with typical language development. Before the ERP data was evaluated, it was noted that there were no significant differences in the standardized test scores of the two subjects that could better explain differences in their reading abilities while performing the ERP task. Behaviorally, however, the two subjects differed in their responses to the stimuli presented during the lexical decision task. Something of interest is Subject A's behavior of not responding "no" to any of the made up words. Whether a real or made up word, if there was a response it was always the "yes" response, meaning he thought it was a real word. Since Subject A and B performed so differently on this task, their errors had to be computed differently. Subject A never pressed "no" to distinguish that a word was not real. Since there could not be any incorrect responses to real words, his lack of answering was considered to be his “no” response. In the “nonword” categories, his lack of response was therefore considered to be correct.

In Table 8 the mean percentage of errors are listed. One can see that in Subject A, there is a PH disadvantage compared to the other nonword category (PW). He was more likely to classify the PH stimuli as words than the PW stimuli, showing that he could possibly be using more phonological recoding strategies than basing his judgments on orthography alone. The activation of the phonological information may be automatic and hard to hinder. As Goswami et al. (2001) stated, if phonology is a primary constraint during silent reading, then it should be harder to reject PHs like BRANE than controls like BRATE. In other words, there should be more errors in the PH condition than the PW condition. Although he did not make as many errors as Subject A, Subject B too shows more errors in the PH category than the PW category. Both subjects are making more errors in the PH category than the PW, showing that there is some pseudohomophone disadvantage during the lexical decision task. Subject B also showed slower responses to pseudohomophones than other pseudowords in the LDT, which is consistent with finding a behavioral pseudohomophone effect. The phonological automaticity can also be supported by the word length effect when looking at monosyllables versus bisyllables. Both subject A and subject B took longer to respond to the bisyllable items (both words and nonwords) than the monosyllable items (see Table 7). Word length effects such as this can persist in skilled adult reading (Goswami et al., 2001).

These children differed from the English children in Goswami et al.’s (2001) study who showed no PH disadvantage during the lexical decision task. This meant that they were making their lexical decisions based on orthographic familiarity. They found the orthographically unfamiliar PH words easy to reject. They had more difficulty rejecting the orthographic controls than the other types of nonwords. In terms of reaction times in Goswami et. al’s (2001) study, there were no differences in speeds between the different nonword types. The only real difference was that the German children took longer at making lexical decisions. The two subjects in this experiment differed in the amount of time they took to respond to all stimuli. Subject B behaved much more like the German children in Goswami et al.’s (2001) study by having such slower reaction times than Subject A. This could be evidence that subject B is using more phonological recoding during the processing of the printed words than subject A. However, his slower reaction times could also be the reason for fewer errors than Subject A, and may not reflect an underlying difference in the reliance on phonology. Allowing more time to process the words may have allowed Subject B to make more accurate decisions than Subject A.

In evaluating the subjects’ ERP data some differences were noted. In Subject A’s ERP data, there is a clear pattern that shows a difference between words, PHs, and PWs. At the Fz and Cz electrode sites especially, there is a clearly different response to the real word critical stimuli at 400 ms. Earlier in the waveform, the words and PHs seem to be responded to in the same manner. This could be seen as the child not seeing a difference between the words and nonwords that sounded like real words. However, the real words created an N400 effect showing that the child knew that the words were different from the other two categories. Despite what the child's response was, the brain distinguished between the real words and nonwords in this child.

Subject B did not have the same type of waveforms as Subject A in response to the three stimulus categories. Interestingly, at 400 ms Subject B responded to the pseudowords differently than the words and pseudohomophones. This makes sense also when looking at the error percentages of this subject. He made a similar amount of errors with the real words and pseudohomophones but made fewer with the pseudowords. Subject B must have found the orthographic controls easier to reject than the pseudohomophones, and it is possible that the presence of the pseudohomophones in this task also made him less sure of how to categorize the real words. His sensitivity to the differences between the items that sounded like real words (words and PHs) and the non-homophonic pseudowords is shown by the difference in his waveform at 400 ms.

Since English is an orthographically inconsistent language, a pseudohomophone disadvantage was not expected considering that English children would be expected to rely more on orthography than the phonology. English children often rely on whole word phonology strategies and specific orthographic units that correspond to rimes (Goswami et al, 2001). English children can use grapheme-to-phoneme strategies as children in shallow orthographies might, but this would be highly inefficient in the English language. Due to this inefficiency, children learning to read English form orthographic recognition units for whole words and for larger sequences of letters (Goswami et al., 2001). This is a developmental and adaptive process. Due to the characteristics of the English orthography, children's reliance on whole-word recognition increases their reading accuracy. It could be possible that these two subjects are still in the adaptive process of relying on phonology over orthography of the printed words. It is also possible that current emphases on using phonics approaches in teaching reading may have lead the children in the current study to rely on different strategies than those children in Goswami et al.'s (2001) study. However, because Goswami et al. did not provide data about the method of reading instruction used for their participants, and no data about instructional methods are available for the children in the current experiment, this suggestion is only speculative.

In future studies more children would be included to better characterize the processes at this stage of reading development. As these results have shown, children have very different strategies for this task and their ERP patterns also differed significantly, even though they appeared to be at similar levels of reading proficiency. Having a larger group of children could patterns of behavioral and neural responses in children at this age and reading level.

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