NEURAL CORRELATES OF PHONETIC AND LEXICAL PROCESSING IN CHILDREN WITH AND WITHOUT SPEECH SOUND DISORDER

by

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A Dissertation

Submitted to the Faculty of Purdue University

In Partial Fulfillment of the Requirements for the degree of

Doctor of Philosophy

Department of Speech, Language, and Hearing Sciences

West Lafayette, Indiana

August 2020

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ABSTRACT

Purpose: Children with speech sound disorder (SSD) mispronounce more speech sounds than is typical for their age and a growing body of research suggests that a deficit in speech perception abilities contributes to development of the disorder. However, little work has been done to characterize the neurophysiological processes indexing speech perception deficits in SSD. The primary aim of the current study was to compare the neural activity underlying speech perception in young children with SSD and typical development (TD).

Method: Twenty-eight children ages 4;1-6;0 participated in the current study. Event-related potentials (ERPs) were recorded while children completed a speech perception task which included phonetic (speech sound) and lexical (meaning) matches and mismatches. Groups were compared on their judgment accuracy for matches and mismatches as well as the mean amplitude of the Phonological Mapping Negativity (PMN) and N400 ERP components.

Results: Children with SSD demonstrated lower judgment accuracy across the phonetic and lexical conditions compared to peers with TD. The ERPs elicited by lexical matches and mismatches did not distinguish the groups. However, in the phonetic condition, the SSD group exhibited a more consistent left lateralized PMN effect and a delayed N400 effect over frontal sites compared to the TD group.

Conclusions: These findings provide some of the first evidence of a delay in the neurophysiological processing of phonological information for young children with SSD compared to their peers with TD. This delay was not present for the processing of lexical information, indicating a unique difference between children with SSD and TD related to speech perception of phonetic errors.

CHAPTER 1. INTRODUCTION

Speech sound disorder (SSD) is the most prevalent disorder treated by speech-language pathologists in pediatric settings (Mullen & Schooling, 2010). Children with SSD mispronounce more phonemes than expected for their age and this mispronunciation negatively affects their ability to be understood by others (ASHA, 1993). These children are also at risk for written language and reading disorders (Lewis, Freebairn, & Taylor, 2000; Stoeckel et al., 2013). There is no consensus on the causes of SSD (Munson & Krause, 2017); however, current classification systems agree on three subgroups including an articulation-based subgroup, a motor planning/programming subgroup, and a phonological subgroup (Waring & Knight, 2013). In addition, a growing body of research suggests that a deficit in speech sound perception contributes to development of SSD (Hearnshaw, Baker, & Munro, 2019; Rvachew & Grawburg, 2006). As defined in a recent systematic review of the SSD literature, speech perception is "the creation and processing of sound-based representations from detected acoustic input in tasks such as the discrimination, identification, recognition, and judgment of spoken sounds, syllables, and words" (Hearnshaw et al., 2019; Rvachew & Brosseau-Lapré, 2018). In SSD, a deficit in these speech perception skills is thought to lead to imprecise phonological representations, which underlie articulation of speech sounds as well as phonological awareness (e.g. Rvachew & Grawburg, 2006; Rvachew, Ohberg, Grawburg, & Heyding, 2003; Shiller, Rvachew, & Brosseau-Lapre, 2010). Although this deficit impacts communicative and educational skills, there have been few efforts to characterize the neurophysiological processes underlying this deficit. The goal of the current study was to characterize the underlying neural activity mediating speech perception in young children with SSD and typical development (TD) using a combined electrophysiological and behavioral approach.

1.1 Speech Sound Perception and Speech Sound Disorder

Through speech perception, children create phonological representations encompassing knowledge of how sounds are combined for communication, the acoustic features for words (acoustic-phonetic representation), and the articulatory features for words (articulatory-phonetic representation) (Preston & Edwards, 2010; Rvachew & Brosseau-Lapré, 2018). During development, the acoustic-phonetic representation forms a target for speech production and the development of the articulatory-phonetic representation (Shiller et al., 2010). As a child's vocabulary grows, phonological representations in the lexicon are thought to re-organize around similar sublexical units, such as syllables and phonemes (Metsala, 1997, 1999). Knowledge that words are made of these smaller parts is referred to as phonological awareness and this awareness is a building block of literacy (Claessen, Heath, Fletcher, Hogben, & Leitão, 2009). A speech perception deficit in children with SSD is thought to disrupt the development of well-specified phonological representations, and therefore speech production abilities as well as phonological awareness (Anthony et al., 2011; Preston & Edwards, 2010; Rvachew & Grawburg, 2006; Sayyahi, Soleymani, Akbari, Bijankhan, & Dolatshahi, 2017; Shiller et al., 2010). For example, Rvachew et al., (2003) showed that even with typically developing receptive language skills, 4-year-old children with SSD scored below their peers with TD on measures of phonemic perception and phonological awareness. Deficits in speech perception have been reported in children with SSD even when a variety of speech sounds are assessed, not only phonemes for which children produce errors (Edwards, Fox, & Isermann, 2002; Hearnshaw et al., 2019).

Typically, speech perception deficits in SSD have been studied through behavioral tasks such as speech sound discrimination and error detection (Hearnshaw et al., 2019). Although a variety of behavioral paradigms have been used, it is recommended that speech perception tasks require the child to compare acoustic input to their own internal representations (Hearnshaw et al., 2019; Locke, 1980). For instance, using the Speech Assessment and Interactive Learning System (SAILS) a child sees a picture, hears a word naming that picture from multiple talkers, and judges whether each production was a correct or incorrect example of the pictured word (Hearnshaw, Baker, & Munro, 2018; Rvachew et al., 2003). The picture sets an expectation for the upcoming word, which is based on a child's own internal representation, thereby assessing that child's phonological knowledge in comparison to the presented auditory input. Children who are more accurate in their judgments of the spoken words are considered to have more precise speech perception skills (Hearnshaw et al., 2018; Rvachew et al., 2003). It is important to consider that completion of behavioal speech perception tasks involve many steps, including decision making and response preparation processes, that occur between detecting the acoustic input and providing a judgment. Measures of neural activity may provide a more sensitive assessment of the internal processes underlying these tasks compared to judgment accuracy alone; however, there have been few research efforts to characterize the neural activity mediating speech sound perception in children with SSD, and to our knowledge no studies of children under the age of 8 years.

1.2 Neural Underpinnings of Speech Sound Disorder

Previous neuroimaging research of SSD has identified structural and functional differences between children with SSD and their typically developing peers (TD). Participants in these studies were older children ages 8-17 years who have a history of SSD residual speech sound errors (Luders et al., 2017; Preston et al., 2012, 2014; Tkach et al., 2011). Luders and colleagues (2017) found that the anterior third of the corpus callosum, a white matter tract which connects the left and right hemispheres of the brain, was thinner in 9-11-year-old children with a history of SSD, most with residual speech sound errors, compared to children with TD (Luders et al., 2017). The authors suggested that the thinner corpus callosum may reflect reduced left lateralization for speech and language in children with SSD (Luders et al., 2017). Preston et al., (2014) found that children with SSD aged 8-11 years had increased gray matter volume in the bilateral superior temporal gyri (STG) and left supramarginal gyrus. The authors suggested that this increase in gray matter could reflect reduced developmental synaptic pruning in areas related to perception of acoustic-phonetic detail, which may result in differences in speech perception between children with TD and SSD (Preston et al., 2014).

Using functional magnetic resonance imaging (fMRI), Tkach et al., (2011) compared brain activity that was associated with non-word repetition in adolescents with a history of TD and SSD. Non-word repetition tasks require a variety of processes such as speech perception, phonological memory, and speech production. Although both groups performed with high task accuracy, adolescents with a history of SSD demonstrated hypoactivation in the right medial temporal gyrus and right inferior frontal gyrus compared to their peers with TD. Decreased activation of these areas was thought to reflect deficits in speech perception and the maintenance stage of phonological working memory, respectively. The adolescents with a history of SSD also displayed hyperactivation in other brain areas involved in internal error monitoring (e.g. superior cerebellum), and semantic processing (e.g. angular gyrus). Areas of hyperactivation were thought to indicate increased cognitive effort or the adoption of alternative strategies for accurate non-word repetition given the hypoactivation of other components within the phonological working memory system (Tkach et al., 2011).

Functional brain activity utilizing fMRI measures has also been characterized for speech processing without overt speech production in children with SSD (Preston et al, 2012). In this speech perception task, 8-10-year-old children with residual speech sound errors and children with TD saw a picture (e.g. *tent*), and heard either the correct name, an incorrect name (e.g. "test"), or a non-word (e.g. "tert"). Groups did not differ in judgment accuracy or reaction time when indicating if the word and picture matched; however, there were differences in underlying brain activity. The SSD group demonstrated decreased activation compared to TD in the left middle temporal and inferior temporal gyri which are involved in acoustic-to-lexical processing. Increased activation was found in areas involved in auditory-motor processing (e.g. insula, STG) and perception of acoustic-phonetic information (e.g. right supramarginal gyrus, right postcentral gyrus). The authors suggested that children with SSD rely more heavily on articulatory-motor processing than lexical processing during speech perception (Preston et al., 2012).

These studies identify differences in brain structure and function underlying processes which are often discussed as disrupted in children with SSD, notably speech perception (Preston et al., 2012, 2014; Tkach et al., 2011). However, it is important to remember that the children in these studies were school age and that SSD is diagnosed and treated at younger ages (Campbell et al., 2003; Mullen & Schooling, 2010; Shriberg, Tomblin, & McSweeny, 1999). Differences in brain structure or function in older children with a history of SSD or residual errors compared to TD may reflect differences in neural development that occurred at younger ages (Luders et al., 2017; Preston et al., 2014). In addition, the effects of speech therapy or compensatory strategies on brain structure and function are not known (Tkach et al., 2011). Additional research is needed to understand how the brain functions for speech and language processing in younger children with SSD who are developing foundational language and literacy skills (Morgan, Bonthrone, & Liegeois, 2016).

1.3 Evaluation of Neural Activity Underlying Speech Sound Perception using Electrophysiological Methods

Event-related potentials (ERPs) are a measure of neural activity which is time-locked to the onset of a specific event or stimulus (Luck, 2014). The high temporal resolution of ERPs allows for the study of neural activity underlying speech sound and lexical processing in real-time (Federmeier, Kutas, & Dickson, 2015; Kutas & Federmeier, 2011). The current study focused on two ERP components known to index phonological and lexical aspects of word processing, the Phonological Mapping Negativity (PMN) and the N400.

The PMN is a negative component occurring 250-350ms after stimulus onset in a frontal and central scalp distribution (Connolly & Phillips, 1994; Desroches, Newman, & Joanisse, 2009). Left hemisphere brain areas including the superior temporal gyrus, supramarginal gyrus, and inferior frontal gyrus have been associated with generation of this component (D'Arcy, Connolly, Service, Hawco, & Houlihan, 2004; Kujala, Alho, Service, Ilmoniemi, & Connolly, 2004; Mody, Wehner, & Ahlfors, 2008; Trébuchon, Démonet, Chauvel, & Liégeois-Chauvel, 2013). The N400 is a negative potential peaking approximately 400ms after stimulus onset in a central parietal scalp distribution (Kutas & Federmeier, 2011; Kutas & Hillyard, 1980, 1983; Luck, 2014). This component has been associated with a variety of brain areas and may be better conceptualized as a series of activations across temporal and frontal areas than activation from a single source (Federmeier et al., 2015; Kutas & Federmeier, 2011; Swaab, Ledoux, Camblin, & Boudewyn, 2012).

Both the PMN and N400 are sensitive to word priming and display a smaller amplitude for primed, or expected items, and a larger, more negative amplitude for unprimed, or unexpected, items (Connolly & Phillips, 1994; Kutas & Federmeier, 2011; Newman, Connolly, Service, & McIvor, 2003). However, the mean amplitude of these components is modulated by different aspects of word stimuli. The PMN is sensitive to variations in expected phonology whereas the N400 is thought to index ease of lexical access and semantic integration (Connolly & Phillips, 1994; Federmeier et al., 2015; Kutas & Federmeier, 2011; Kutas & Hillyard, 1984). As a result, these components are also sensitive to different kinds of word stimuli. The N400 is sensitive to the lexicality of spoken stimuli, showing a lesser negativity to nonword than real word mismatches (both negativities increased relative to matches) (Newman & Connolly, 2009)**.** The PMN shows no differentiation for lexicality and demonstrates equally increased negativity relative to matches for both words and nonwords which violate phonological expectations (Newman & Connolly, 2009)**.** Furthermore, the mean amplitude of the PMN does not index degree of phonological mismatch from expectations, but instead seems to simply indicate detection of a phonological mismatch (Newman et al., 2003).

In a study of adults, Desroches, Newman, & Joanisse, (2009) investigated the PMN and N400 elicited by picture prime and spoken word pairs in conditions manipulating phonological and lexical expectations. In the word match condition, the picture prime and spoken word matched (picture cone, spoken “cone”). In the unrelated mismatch condition, the picture prime and spoken word differed both lexically and phonetically (picture cone, spoken “fox”). In the rhyme mismatch condition, the picture prime and spoken word differed in their onsets (picture cone, spoken “bone”), whereas in the cohort mismatch condition the picture prime and spoken word differed in their codas (picture cone, spoken “comb”). Due to differences in word-initial phonemes, the PMN was more negative for the unrelated mismatch and rhyme mismatch conditions compared to the word match condition. However, there was no significant difference in the PMN elicited by the cohort mismatch word and the match word, both of which shared an initial phoneme with the picture-primed word. The authors suggested that the PMN represented pre-lexical phonological processing, or comparison of the initial acoustic-phonetic information from the spoken stimulus to the activated phonological representation of the picture-primed word. This phonological processing indexed by the PMN was shown to influence later lexical processing indexed by the timing and magnitude N400. The N400 showed the largest amplitude increase, a greater negativity, in the cohort mismatch condition compared to the unrelated mismatch and rhyme mismatch conditions over a late time window (410-600ms). The authors suggested that greater negativity of the N400 elicited by the cohort mismatch condition in the late window represented increased effort in lexical activation after a phonological miscue. The PMN indicated initial acoustic-phonetic information matched expectations (initial phoneme /k/ in “comb”), but later information contradicted those expectations (final phoneme /m/ in comb vs /n/ in primed “cone”). Therefore, the N400 was more negative, indexing greater neural effort to accomplish correct lexical access to the cohort mismatch (“comb”), compared to other mismatch conditions (rhyme, unrelated) that did not share initial phoneme similarities. Although the PMN and N400 are modulated by phonological and lexical information respectively, the pre-lexical phonological processing of the PMN can influence later lexical access indexed by the N400 (Desroches et al., 2009).

The PMN and N400 ERP components have been used to index phonological and lexical processing in developmental language disorders. Two studies used the same method as Desroches and colleagues (2009) to compare the neural activity of school-age children (8-12 years) with dyslexia (Desroches, Newman, Robertson, & Joanisse, 2013) and specific language impairment (SLI; Malins et al., 2013) to their peers with TD. These studies contained the word match (e.g., picture *cone*, spoken "cone"), unrelated mismatch (e.g., picture *cone*, spoken "fox"), rhyme mismatch (e.g., picture *cone*, spoken "bone"), and cohort mismatch (e.g., picture *cone*, spoken "comb") conditions. In these studies, children with dyslexia and children with SLI showed similar PMN amplitudes compared to their peers with TD (Desroches et al., 2013; Malins et al., 2013). However, it should be noted that another study manipulating coarticulatory information found PMN differences between children with SLI and their peers with TD (Archibald & Joanisse, 2012). This study also reported group differences for the N100 component thought to index early auditory sensory processing (Näätänen & Picton, 1987). In younger 4-5-year old children, the N100 has not been as consistently elicited in studies using naturally spoken stimuli (e.g. Gerwin & Weber, 2020; Haebig, Leonard, Usler, Deevy, & Weber, 2018; Kreidler, Hampton Wray, Usler, & Weber, 2017).

Although the PMN did not differentiate groups in the studies by Malins and colleagues (2013) and Desroches and colleagues (2013), the N400s elicited by the rhyme mismatch conditions provided insight into differences in lexical access between groups. Unlike their peers with TD, children with dyslexia and SLI did not demonstrate a modulated N400 mean amplitude for the rhyming mismatch. In children with TD, the picture-primed word was thought to activate a network of related words, including words that rhyme. As a result, when the spoken rhyme mismatch word was presented, children with TD required less effort to access the word resulting in a modulated N400. Children with SLI and dyslexia may not as easily activate a network of phonologically related words resulting in a larger mean amplitude of the N400 elicited by the rhyme mismatch compared to children with TD (Desroches et al., 2013; Malins et al., 2013). This idea was supported in the study of children with dyslexia by the cohort mismatch condition (Desroches et al., 2013). In a later temporal window of the N400, children with dyslexia showed a larger cohort condition effect (mismatch – match) compared to the TD group. This group difference in the N400 effect in a later temporal window was thought to be indicative of difficulty resolving the cohort mismatch after an initial match in acoustic-phonetic information (Desroches et al., 2013). The authors suggested that children with TD activated the spoken cohort-mismatch word as part of a network based on the picture-prime word (e.g., comb is activated when picture of cone is presented). Therefore, the children with TD required less effort in lexical access to the cohort mismatch than children with dyslexia (Desroches et al., 2013). In these studies, the PMN and N400 elicited by phonological and lexical manipulations reveal subtle underlying differences in the spoken language processing of children with SLI and children with dyslexia compared to peers with TD.

1.4 The Current Study

Previous research has revealed evidence of structural and functional brain differences between children ages 8-17 years with residual speech sound errors or history of SSD and their peers with TD (Luders et al., 2017; Preston et al., 2012, 2014; Tkach et al., 2011). However, these differences may reflect neural development from younger ages, compensatory strategies, or effects of speech therapy. Although SSD is prevalent in children under the age of 8 years (Campbell et al., 2003; Mullen & Schooling, 2010; Shriberg, Tomblin, & McSweeny, 1999), to our knowledge there have been no studies investigating the neural activity underlying speech perception in these younger children with SSD. The current study used ERPs to examine the neural activity underlying lexical access/integration and speech sound processing in young children with TD and children with SSD ages 4;1 to 6;0. The speech perception task employed in the current study used picture primes to elicit lexical and phonological expectations about upcoming spoken words. On each trial the child was shown a picture (prime), followed by a spoken word (target), and was asked to judge if the spoken word matched the picture. We contrasted how SSD may be associated with processing of lexical (meaning) and phonetic (speech sound) matches and mismatches. This ERP study in young children with SSD was designed to increase our understanding of the neural indices of speech perception related to this disorder. Specifically, given that all participants had normal language abilities and because phonetic miscues were not included in the lexical task, we hypothesized that children with TD and SSD would show similar increases in amplitude of the PMN and N400 elicited by lexical errors (picture-spoken word mismatches) compared to correct lexical naming (picture-spoken word matches). We hypothesized that children with TD would exhibit the expected increased amplitude of the PMN, and N400 elicited by phonetic errors (picture-spoken word mismatches) relative to correct pronunciations (picture-spoken word matches). However, due to difficulties with speech perception and to evidence of structural and functional differences in brain areas (as reviewed above) that are known to be involved in both speech perception and generation of these

ERP components, we expected children with SSD would display deviations in the timing or amplitude of the PMN and N400 for phonetic errors relative to correct pronunciations (Mody et al., 2008; Preston et al., 2012, 2014; Trébuchon et al., 2013).

CHAPTER 2. METHODS

2.1 Participants

Twenty-eight children ages 4;1-6;0 participated in the current study with 14 in each of the TD and SSD groups. All children were native English speakers and passed a bilateral hearing screening at 500, 1000, 2000, 4000 Hz presented at 20 dB HL. They had normal or corrected-to-normal vision and no history of neurological or emotional disorders per parent report. They scored within normal limits on the Matrices subtest of the Kaufman Brief Intelligence Test - Second Edition (KBIT-2; Kaufman & Kaufman, 2004) as a screen for intellectual impairment. In addition, all children demonstrated language abilities within normal limits on the Expressive Vocabulary Test - Second Edition (EVT-2; Williams, 2007), Peabody Picture Vocabulary Test - Fourth Edition (PPVT-4; Dunn & Dunn, 2007), and Structured Photographic Expressive Language Test - Second Edition (SPELT–P2; Dawson, Eyer, & Fonkalsrud, 2005).

Participants were divided into groups based on a comprehensive assessment by a certified speech-language pathologist. This assessment included the aforementioned screenings, a case history including any prior diagnostic and treatment information, screening of the oral mechanism, standardized assessment of speech production, and a speech sample. Children with a standard score less than 85 on the Goldman-Fristoe Test of Articulation - 3rd Edition were considered SSD and children with a standard score equal to or above 85 were considered TD (GFTA-3; Goldman & Fristoe, 2015). One child with typical development was administered the Diagnostic Evaluation of Articulation and Phonology (DEAP; Dodd, Hua, Crosbie, Holm, & Ozanne, 2006) in place of the GFTA-3. Participants passed the Oral Speech Mechanism Screening Examination - Third Edition to rule out motor speech disorders (St. Louis & Ruscello, 2000).

The TD and SSD groups had similar age, $F(1, 26) = 0.958$, $p = .337$, and mother's highest level of education, $F(1, 26) = 1.382$, $p = .250$. Mother's level of education was used to estimate socioeconomic status on a scale where a score of 1 indicated highest education less than seventh grade and a score of 7 indicated graduate or professional training (Hollingshead, 1975). The TD group performed with higher accuracy than the SSD group on the assessment of speech production abilities (GFTA-3 or DEAP) confirming group classification based on the presence of

SSD, $F(1, 26) = 54.960$, $p < .001$. The groups demonstrated similar performance on the assessments of language, $F(1, 26) < 1.91$, $p > .29$. Table 1 displays information about participant gender and handedness, and group means for age, mother's level of education, and each standardized assessment of speech and language.

Table 1. Gender, handedness, age, mother's level of education and standard scores on speech and language assessments for TD and SSD participants.

Group	n (Female)	Handedness R (L)	Age in Months M (SE)	MLE M (SE)	PPVT-4 M (SE)	EVT-2 M (SE)	SPELT-P2 M (SE)	GFTA-3 or DEAP M (SE)
TD	14 (6)	11 (3)	63.36 (1.85)	6.14 (0.29)	117.36 (3.72)	112.00 (3.26)	113.86 (2.41)	94.36 (2.32)
SSD	14 (6)	12 (2)	60.93 (1.65)	5.64 (0.31)	112.50 (2.44)	111.21 (3.11)	111.86 (2.28)	61.43 (3.79)

Note. MLE = mother's highest level of education (Hollingshead, 1975); PPVT-4 = Peabody Picture Vocabulary Test – Fourth Edition (Dunn & Dunn, 2007); EVT-2 = Expressive Vocabulary Test – Second Edition (Williams, 2007); SPELT-P2 = Structured Photographic Expressive Language Test – Second Edition (Dawson, Eyer, & Fonkalsrud, 2005); GFTA-3 = Goldman-Fristoe Test of Articulation 3rd Edition (Godman & Fristoe, 2015); DEAP = the Diagnostic Evaluation of Articulation and Phonology (Dodd et al., 2006)

2.2 ERP Task Conditions and Stimuli

2.2.1. Conditions

Underlying neural activity and judgment accuracy were assessed for each child in two conditions: lexical and phonetic. The lexical condition involved the processing and judgment of meaning matches and mismatches, whereas the phonetic condition involved the processing and judgment of speech sound matches and mismatches. The experiment included an equal number of match and mismatch trials in each condition. Trials involved presentation of a visual-auditory stimuli pair. Each pair included a picture followed by a naturally spoken word or "non-word" label. In a lexical mismatch trial, the spoken word was pronounced correctly but did not name the presented picture (e.g. picture *wheel*, spoken "leaf"). In a lexical match trial, the spoken word accurately named the picture from the lexical mismatch condition and was pronounced correctly (e.g., picture *wheel,* spoken "wheel"). In a phonetic mismatch trial, the spoken word named the picture but contained a common phonetic error in the initial phoneme (e.g. picture *leaf*, spoken "weaf") creating a "non-word" label. In a phonetic match trial, the spoken word named the same picture as the phonetic mismatch condition, but was pronounced correctly (e.g. picture *leaf*, spoken "leaf,"). Examples of each trial type are presented in Table 2.

Table 2. Trial types and example stimuli in the phonetic and lexical conditions.

Trial Type:	Phonetic Match		Phonetic Mismatch		Lexical Match		Lexical Mismatch	
Correct Judgment:	Yes		No		Yes		No	
Stimulus:	Picture	Spoken Word	Picture	Spoken Word	Picture	Spoken Word	Picture	Spoken Word
s/t	soup	"soup"	soup	"toop"	tooth	"tooth"	tooth	"soup"
l/w	leaf	"leaf"	leaf	"weef"	wheel	"wheel"	wheel	"leaf"
r/w	rocket	"rocket"	rocket	"wocket"	wallet	"wallet"	wallet	"rocket"

2.2.2. Stimuli Selection

Words beginning with later developing sounds /s/, /l/, and /ɹ/ were used for the phonetic condition (McLeod & Crowe, 2018). These initial sounds were replaced by earlier developing sounds to form 3 common errors seen in typical development and in children with SSD; /w/

replaced /l/, /w/ replaced /ɹ/, and /t/ replaced /s/. The stimuli words for the lexical condition began with /t/ and /w/ in order to balance the number of times each sound was presented word-initially. Furthermore, the spoken word used in a phonetic match trial was used as the error word in the lexical mismatch trial. As a result, stimuli were balanced such that for a word pair formed in the lexical mismatch trial (e.g. leaf and wheel) the target phoneme and error phoneme were heard word-initially twice (e.g. /l/ and /w/), each picture was seen twice, and the response of yes or no was correct twice across trial types. An example of each error type and the balancing across trial types is shown in Table 2. Five word pairs were chosen for the lexical mismatch trial in the 3 error types (/t/ for /s/, /w/ for /l/, and /w/ for /ɹ/). These 15 pairs were used to generate the 4 trial types (phonetic match, phonetic mismatch, lexical match, and lexical mismatch) resulting in a total of 60 unique trials. Each trial was presented twice, once in the first half of the experiment and once in the second half, for a total of 120 trials.

A list of potential stimuli pairs were generated for this study based on the following criteria: 1) Words began with the phonemes of interest (/s/, /t/, /ɹ/, /w/, /l/); 2) All words had an age of acquisition less than 6 years (Kuperman, Stadthagen-Gonzalez, & Brysbaert, 2012); 3) Words modified for the phonetic mismatch condition did not form an English word, or the English word formed had an age of acquisition greater than 6 years; 4) Words paired in the lexical mismatch condition contained the same number of syllables; and 5) Words paired in the lexical mismatch condition had the same vowel after the initial phoneme. With these criteria, 60 potential words were generated, which formed 30 lexical mismatch pairs.

Photo-realistic images were chosen to represent each of the 60 words. In order to ensure pictures were easily recognized by participant group, we showed the 60 images to 3 children with TD and 1 child with SSD (ages 4-5 years) and asked each of them to name the pictures. We selected 30 pictures named with the highest accuracy for inclusion in the study. Twenty-five of the pictures were named with the intended word by at least 3 children, and 5 were named by 1-2 children. Overall, the 4 children named the 30 selected pictures with the intended target word on 86% of presentations.

The 30 stimulus words associated with the selected pictures had a mean age of acquisition of 4.47 years (*SD* = 0.96, range = 2.37-5.89) (Kuperman et al., 2012). The age of acquisition for the 5 pictures named by 1-2 children was compared to the remaining pictures named by at least 3 children. This comparison ensured age of acquisition did not influence naming accuracy. The five words (wheel, lick, ribbon, robber, and soup) had a mean age of acquisition of 5.01 years (*SD* = 0.63, range = 4.30-5.74), which was not significantly different from the other 25 stimulus words, $t(28) = -1.49$, $p = 0.15$. In 4 cases the phonetic mismatch condition formed a real English word (lick/wick, red/wed, sun/ton, and rain/wane). In these cases, the mean age of acquisition for the formed words was 8.93 years (*SD* = 3.09, range = 6.95-13.53). All words selected for the experiment are listed in Appendix A.

2.2.3. Semantic Relatedness and Association

In the lexical mismatch condition, paired words (picture prime and spoken target) were assessed for semantic relatedness and association to ensure the picture did not prime the paired spoken word. Semantic relatedness was assessed using the pairwise comparison application of the Latent Semantic Analysis @ CU boulder website (Laham, 1998). Latent semantic analysis provides an estimate of word similarity by comparing the contexts in which words do or do not appear (Landauer, Foltz, & Laham, 1998). “General Reading up to 3rd Grade” was selected as the topic space, or set of word context sources, because it was the closest match to the participant age-range (Laham, 1998). For each word pair in the lexical mismatch condition (e.g. wheel, leaf), a similarity score from -1 to 1 was returned as an estimate of their semantic relatedness. A similarity score of 0 indicates no semantic relatedness between the words. The 15 lexical mismatch word pairs had a mean semantic relatedness of 0.05 (*SD* = 0.07, range = -0.07 to 0.25) suggesting the lexical mismatch stimuli were not semantically related as intended.

In addition, the semantic association of the lexical mismatch word pairs was assessed using the University of Florida Free Association Norms website (Nelson, McEvoy, & Schreiber, 1998). These norms were created by providing participants with a cue word and asking them to provide “the first word that came to mind that was meaningfully related or strongly associated to the presented word” (Nelson et al., 1998). This resource was used to find words associated with each of the lexical mismatch stimuli. Twenty-eight of the thirty words were listed in this resource. “Seahorse” and “sailboat” were not available. None of the twenty-eight available words were associated with the paired word in the lexical mismatch condition. For example, when “leaf” was the cue word, “wheel” was not a listed associate, and when “wheel” was the cue word, “leaf” was not an associate. These measures confirmed that the lexical mismatch stimuli were not semantically related or associated. This means that the words presented in this condition should not prime one another and therefore a larger mean amplitude N400 elicited by the lexical mismatch compared to the lexical match condition was expected.

2.3 Procedures

2.3.1. Picture Familiarization

To ensure that the participants recognized the stimulus pictures, each child completed a picture familiarization task. In this task, the child had the opportunity to name each of the stimulus pictures. The child was given the following instructions, "We are going to look at some pictures and I want you to tell me what you think the picture shows. Sometimes I might give you another word for the picture and I will ask you to repeat the word after me. Let's start." If a child named a picture incorrectly, the experimenter provided the target label and requested an immediate repetition from the child. For instance, if a child says "ice cream" for the picture of lick, the experimenter might say, "You are right. He is eating ice cream. We lick ice cream. We will call this a picture of 'lick'. What are we naming this picture?" After all pictures were named once, incorrectly named pictures were presented again for naming. Picture naming was corrected, repeated, and presented up to 3 times per child; however, most pictures were named correctly between the initial presentation and first review of incorrectly named pictures. Of the 30 stimulus pictures, participants correctly identified an average of 18 on initial presentation and 9 on the first review. This procedure was audio recorded and each child's production of the 30 stimulus words analyzed by two trained raters for initial phoneme accuracy and whole word accuracy. Inter-rater reliability was 93% for initial phonemes and 87% for whole words.

2.3.2. ERP Task

For the ERP task, the child was comfortably seated in a sound booth and oriented toward an audio speaker and a 19-inch screen which presented the stimuli. The chair was approximately 76 inches from the monitor. Colored circles (2.8 inches) served as fixation points for each trial. The experimenter began trials with a button press on the response pad. There was a blank screen 150-350ms prior to the stimulus picture. The picture appeared on the screen alone for 650ms before the onset of the spoken stimulus word. The average spoken word duration was 560ms (*SD* = 100, range = 420-890). After the spoken word ended, the picture remained on the screen for an additional 1150ms. Then the decision prompt "Yes or No?" appeared on the screen to elicit the child's verbal response to the trial. The experimenter recorded the child's response with a button press on the response pad including options for "yes," "no," or "non-response" (e.g. child spoke through trial and missed stimuli). When the child was ready, the experimenter advanced to the next trial. The visual angle of the stimulus pictures was 3.77 degrees vertically and horizontally. The sequence and duration of stimuli events is illustrated below in Figure 1.

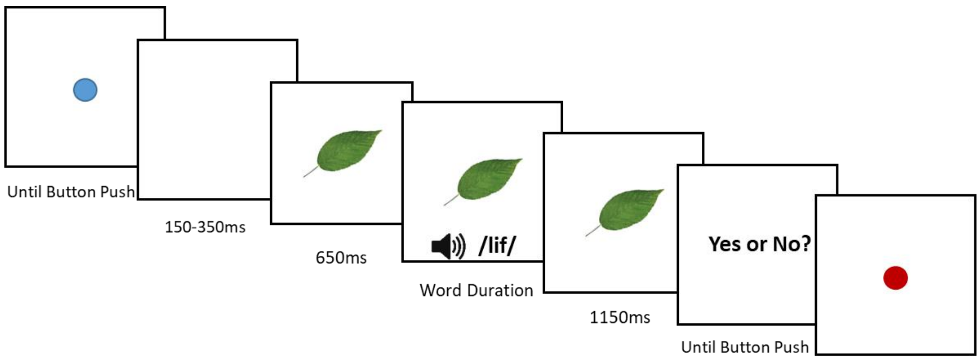

Figure 1. Sequence and duration of stimuli events in the ERP task. Leaf photo by Kelly Lacy from pexels.com.

The child was given the following instructions, "You will see pictures come up on this screen. When a picture comes up, you will hear a woman name the picture. Sometimes she says the name of the picture correctly and sometimes she does not. Listen carefully and tell me if the woman says the name of the picture or if she says something else. Let's practice." Four practice trials, one in each condition, were presented two times. The practice trials were formed using an earlier developing g/d initial phoneme contrast (McLeod & Crowe, 2018). If the child made an error during a practice trial, the experimenter provided feedback. For instance, if a child incorrectly judged a phonetic mismatch trial, the experimenter said, "Hmm goldfish starts with a guh sound and I heard a duh sound. That's not right. So you'd say 'no.' Let's try some more." After the practice trials, the child completed 8 experimental blocks each containing 15 trials. The experimenter provided breaks between each block to allow the child to stretch and participate in a rewarding activity (e.g. Legos, tic-tac-toe).

2.3.3. Trial Order

Trials were ordered such that each of the 4 trial types formed by a pair of lexical mismatch stimuli were distributed across the experiment (e.g. lexical match *picture* leaf, spoken "leaf" was separated from lexical mismatch *picture* wheel, spoken "leaf"). To ensure separation, the 60 trials were divided into 4 blocks of 15 trials each. Condition and error type were balanced across blocks. Each block was placed in the first and second half of the experiment on two separate lists. In list A, block order was 1, 2, 3, 4 in the first half and 2, 1, 4, 3 in the second half. List B had the halves reversed with 2, 1, 4, 3 in the first half, and 1, 2, 3, 4 in the second half. Within each block, trials were pseudorandomized such that there were no more than two consecutive trials of the same error type (s/t, r/w, l/w), no more than two trials of the same type (lexical match, lexical mismatch, phonetic match, phonetic mismatch), and no more than three consecutive trials with the same correct judgments (yes or no). List A and B were counterbalanced across participants and are included in Appendix B.

2.4 EEG Recording

Each child was fitted with an elastic cap with 32 embedded electrodes. The scalp positions of the electrodes correspond to the International 10-10 system including lateral (F7/F8, FC5/FC6, T7/T8, CP5/CP6, P7/P8), medial (FP1/FP2, AF3/AF4, FC1/FC2, F3/F4, C3/C4, CP1/CP2, P3/P4, PO3/PO4, O1/O2) and midline sites (FZ, CZ, PZ, OZ) (Sharbrough et al., 1994). The continuous electroencephalogram was recorded using the Biosemi ActiveTwo® system. Reference electrodes were placed on the participants' right and left mastoids. Additionally, electrodes were placed on the outer canthi of the right and left eyes to measure horizontal eye movements (HEOG) as well as on the inferior and superior orbital ridges to measure vertical eye movements (VEOG).

2.5 ERP Analysis

ERPs were time-locked to the onset of the spoken word in each trial. The spoken words were coded differentially for trial type and error type. The continuous electroencephalogram (EEG) was analyzed using EEGLAB (Delorme & Makeig, 2004) and ERPLAB (Lopez-Calderon & Luck, 2014), which are MATLAB® toolboxes (MathWorks, Natick, MA, USA). The EEG was down-sampled at a rate of 256Hz and band-pass filtered from 0.1 to 30Hz. Portions of the EEG associated with practice trials and "other responses" were removed from further processing. Independent component analysis (ICA), a statistical tool included in EEGLAB, was used to identify and remove eye artifacts, including blinks and eye movements.

The continuous EEG data was epoched from 200ms before the stimulus onset to 2000ms after the stimulus onset. Epochs were baseline corrected from -100ms to stimulus onset (0ms). An automatic artifact rejection algorithm with a 200ms window moving in 50ms increments was used to remove remaining artifact from all channels. Epochs were also inspected manually and removed if they contained any remaining artifact. Finally, the epochs were averaged to produce ERP waveforms elicited by phonetic matches, phonetic mismatches, lexical matches and lexical mismatches at each electrode site for each participant. Grand average ERPs of all artifact-free trials were computed for the TD and SSD groups. Although three sound contrasts (L/W, R/W, S/T) were included in the experiment for variety, there were not enough match and mismatch trials for each contrast to create reliable ERPs or conduct analyses based on contrast.

All trials, regardless of accuracy, were analyzed. Participants had at least 16 artifact-free trials, both correct and incorrect, in each condition. On average, the participants in each group had 21-22 artifact-free match and mismatch trials in each condition. The number of artifact-free match and mismatch trials in each condition did not distinguish the groups, $F(1, 27) < 0.23$, $p > .64$. The TD and SSD groups also had a similar number of correct match and mismatch trials in each condition, $F(1, 27) < 2.60$, $p > .12$.

Analyses focused on measuring the mean amplitudes of the PMN and N400 components elicited by target words in each condition in each individual's waveforms. Time windows and regions of interest (ROIs) were chosen for each component based on visual inspection of the waveforms and previous studies (e.g., Desroches et al., 2013; Haebig et al., 2018; Malins et al., 2013). A small PMN was present in the ERP waveforms from the phonetic condition only. This peak was most prominent in the SSD group; however, it was present in the individual waveforms of participants in both groups between 200 and 500ms. Measurement of the PMN in the phonetic condition was centered around the grand average peak from 300 to 380ms in an anterior ROI (F7/8, F3/4, FC1/2, FC5/6). The N400 was measured in both conditions across consecutive time windows in a posterior ROI (CP5/6, CP1/2, P7/8, P3/4, PO3/4, O1/2) and an anterior ROI (same sites as the PMN). In the posterior ROI, the central-parietal distribution of the N400 was measured between 400-600ms, 600-800ms, and 800-1000ms. In the anterior ROI, the frontal distribution of the N400 was measured between 600-800 and 800-1000ms. Figure 2 displays the scalp distribution of the electrodes included in the anterior and posterior ROIs.

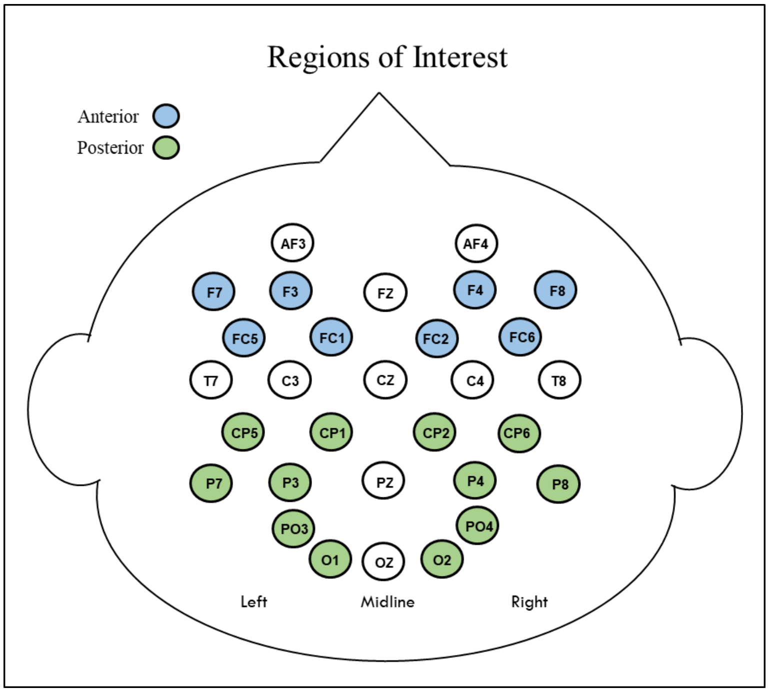

Figure 2. Scalp distribution of the electrodes included in the anterior and posterior regions of interest (ROI).

2.6 Statistical Analyses

Dependent variables were production accuracy for stimulus words (initial phoneme and whole word), judgment accuracy for the phonetic and lexical conditions in the ERP task, and measures of the mean amplitude of the PMN and N400 components elicited by the spoken words in each condition. Percent initial phonemes and whole stimulus words produced correctly were compared for the two groups using independent samples T-tests. For judgment accuracy, A' scores were calculated in addition to percent trials correct to account for response biases in the forced-choice (yes or no) judgment tasks (See Haebig et al., 2018 for procedure). Task accuracy (percent correct, A' score) was assessed across groups using a repeated measures ANOVA including a within factor of condition (lexical, phonetic) and contrast (L/W, R/W, S/T). The relationship between speech production abilities (standardized assessment, percent initial phonemes correct, and percent whole words correct) and percent phonetic judgment accuracy from the ERP task was assessed using Pearson's r correlation.

Separate repeated measures ANOVAs evaluated the mean amplitudes of each ERP component in each time-window and condition. These ANOVAs included a between factor of group (TD, SSD) and within factors of trial type (match, mismatch), hemisphere (left, right), and electrode. Huynh-Feldt corrected *p*-values are reported for effects with more than one degree of freedom in the numerator and significance was set to $p = .05$. Effect sizes (η_p^2) are reported for all significant effects. Only significant interactions involving group and condition are reported.

2.7 Additional ERP Analyses.

Additional ERP analyses were completed to address potential group differences arising from methodological decisions (e.g. including all artifact-free ERP trials vs. correct trials only). The results of these additional analyses were consistent with those of the planned analyses described above; therefore, results of the additional analyses are reported in the Appendices for succinctness. Appendix C includes an analysis of the ERP waveforms elicited by identical spoken word stimuli from the phonetic match (see leaf, hear "leaf") and lexical mismatch (see wheel, hear "leaf") conditions. The results of this analysis were consistent with comparisons between the lexical match (see wheel, hear "wheel") and lexical mismatch (see wheel, hear "leaf") conditions which involved presentation of different spoken words but the same picture primes. Appendix D describes an analysis of ERPs including only trials for which a participant provided a correct response. This analysis involved subgroups of the SSD and TD participants who achieved high ERP task judgment accuracy in both the lexical and phonetic conditions. Ten children with TD and 11 with SSD were included in the analysis. These children had at least 16 correct artifact-free match and mismatch trials in each condition.

CHAPTER 3. RESULTS

3.1. Speech Production Abilities for Stimulus Words

Consistent with the diagnosis of SSD, the SSD group showed lower accuracy in their production of the stimulus words compared to the TD group. This was true both for initial phoneme accuracy, $t(26) = 5.140$, $p < 0.001$, and whole word accuracy, $t(26) = 5.300$, $p < 0.001$. Children in the TD group accurately produced an average of 91.7% of initial phonemes and 79.0% of whole words whereas children with SSD accurately produced 68.4% of initial phonemes and only 43.6% of whole words.

Accuracy on each initial phoneme and types of errors were explored for individuals in both groups. Children named five stimulus pictures for each word-initial target phoneme /l/, /ɹ/, and /s/, and only one child with SSD produced all 15 initial phonemes correctly. Eight children with SSD produced initial /l/ correctly on all five attempts (two children produced /l/ → [w], two /l/ → [1, w], one /l/ → [l, j], one /l/ → [l, ∅]). One child produced initial /r/ correctly on all five stimulus words (twelve children produced /ɹ/ → [w] and one child /ɹ/ → [ɹ, w]). Four children produced initial /s/ consistently (one child produced /s/ → [t], one /s/ → [ʃ, ɬ], one /s/ → [d], one /s/ → [s̪], one /s/ → [h], one /s/ → [ʃ], one /s/ → [s, ʃ, ɬ], two /s/ → [s, s̪], and one /s/ → [s, ɬ]). Errors on the 15 initial /t/ and /w/ stimuli were less frequent as all children with SSD produced the initial /w/ correctly and 11 produced initial /t/ correctly (one child produced /t/ → [t, d, ∅], one /t/ → [d], and one /t/ → [t, s, s̪, ɬ].

Initial errors produced by children with TD were typical and developmental, meaning that the errors have been documented in children within the participants' age-range and are thought likely to remediate naturally (Smit, 1993). In the TD group, twelve children produced initial /l/ correctly on all five stimulus words (two children produced /l/ → [l, w]); nine children produced initial /ɹ/ accurately on all five attempts (four children produced /ɹ/ → [w], one child / ɹ / → [ɹ, w]); and eleven children produced initial /s/ accurately (two children produced /s/ → [s, s̪], and one produced /s/ → [s, ʃ]). All children with TD produced initial /t/ and /w/ accurately.

3.2. Judgment Accuracy for ERP Task

Groups achieved high lexical and phonetic judgment accuracy on the ERP task with all group averages over 84%. Table 3 includes group mean, standard error, and range of accuracy in each condition in the ERP judgment task. Across groups, accuracy for lexical judgments was higher than phonetic judgments, percent correct, $F(1, 26) = 12.588$, $p = .002$, $\eta_p^2 = .326$, A' scores, $F(1, 26) = 9.004$, $p = .006$, $\eta_p^2 = .257$. In addition, the TD group performed with higher accuracy overall compared to the SSD group, percent correct, $F(1, 26) = 6.184$, $p = .020$, $\eta_p^2 = .192$, A' scores, $F(1, 26) = 4.274$, $p = .049$, $\eta_p^2 = .141$. This group difference was significant for the lexical condition, $F(1, 26) = 6.185$, $p = .020$, A' scores, $F(1, 26) = 5.986$, $p = .021$, but not for the phonetic condition, $F(1, 26) = 3.546$, $p = .071$, A' scores, $F(1, 26) = 3.031$, $p = .093$. Group differences for phonetic judgment accuracy may not have reached significance because both groups showed a wider range of accuracy scores indicating greater variability in the phonetic condition compared to lexical condition.

There was an effect of sound contrast on overall accuracy, percent correct, $F(2, 52) = 7.724$, H-F $p = .001$, $\eta_p^2 = .229$, A' scores, $F(2, 52) = 8.184$, H-F $p = .002$, $\eta_p^2 = .239$, but the interaction between sound contrast and group was not significant, $F(2, 52) = 0.185$, $p = .827$, A' scores, $F(2, 52) = 0.422$, $p = .609$. Bonferroni-corrected pairwise comparisons (significance $p < .017$) revealed that percent judgment accuracy was similar for S/T and R/W contrasts, $t(55) = -1.491$, $p = .142$. However, judgment accuracy for L/W contrasts was lower than accuracy for S/T contrasts, $t(55) = -2.820$, $p = .007$, and R/W contrasts, $t(55) = -2.633$, $p = .011$. Figure 3 displays overall judgment accuracy for each contrast and indicates that the groups showed similar patterns of accuracy across the contrasts.

The relationship between judgment accuracy in the phonetic condition and speech production abilities was also investigated across all participants. There was a positive correlation between phonetic judgment percent correct and standard score on the GFTA-3/DEAP, $r = .424$, $p = .024$. Phonetic judgment accuracy was not significantly correlated with production of stimulus words measured as initial phoneme accuracy or whole word accuracy (ps > .298).

Table 3. Lexical and phonetic judgment accuracy of the TD and SSD groups

Group	Lexical Judgment Percent Correct		Phonetic Judgment Percent Correct	
	M (SE)	Range	M (SE)	Range
TD	96.7 (1.0)	87.7-100	91.5 (1.8)	76.7-100
SSD	92.3 (1.4)	78.0-100	84.2 (3.4)	50.0-95.0

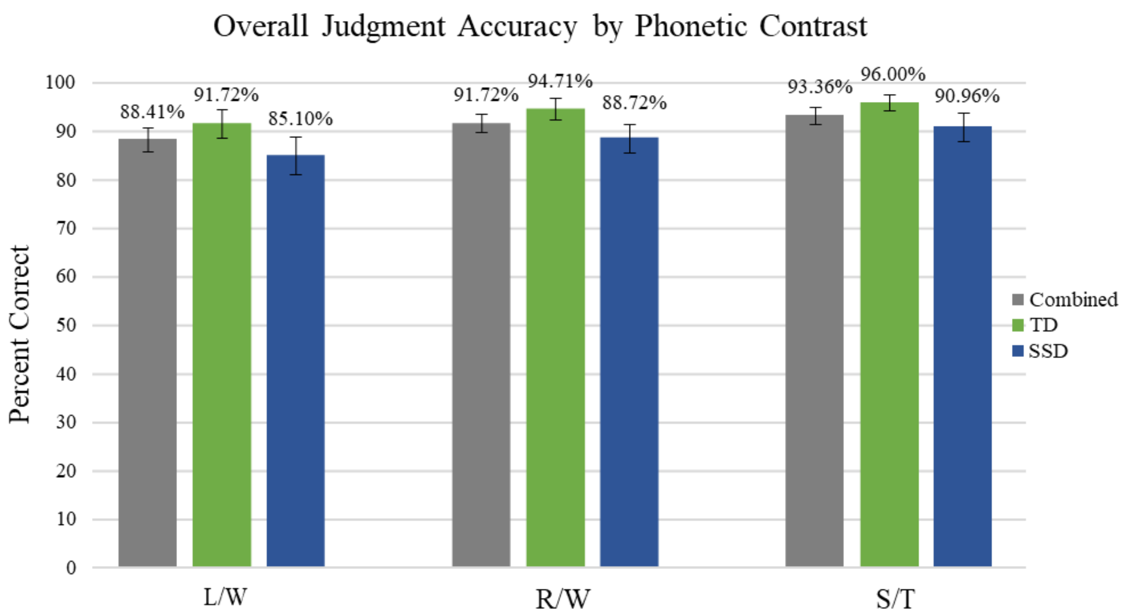

Figure 3. Average judgment accuracy by sound contrast for the groups combined and each group separately. Error bars represent the mean plus and minus the standard error.

3.3. ERPs Elicited by Lexical Matches and Mismatches

Waveforms elicited by the lexical matches and mismatches for the all trials analysis are displayed in Figures 4 and 5 in the anterior and posterior ROIs respectively.

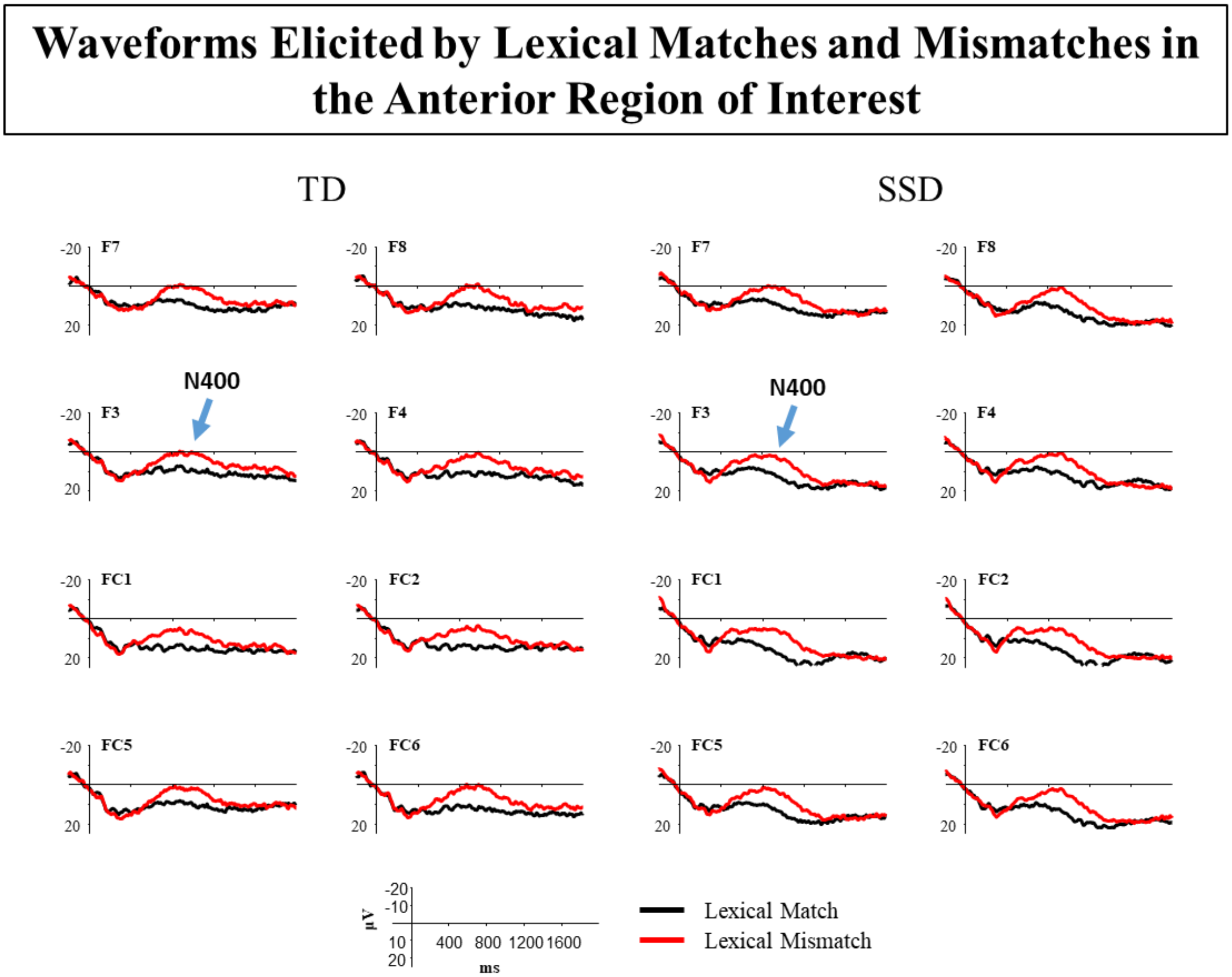

Figure 4. TD and SSD grand average waveforms elicited by lexical matches and mismatches in the anterior region of interest (ROI). Blue arrow point to the N400 component in each group, and negative potentials are plotted upward.

Waveforms Elicited by Lexical Matches and Mismatches in the Posterior Region of Interest

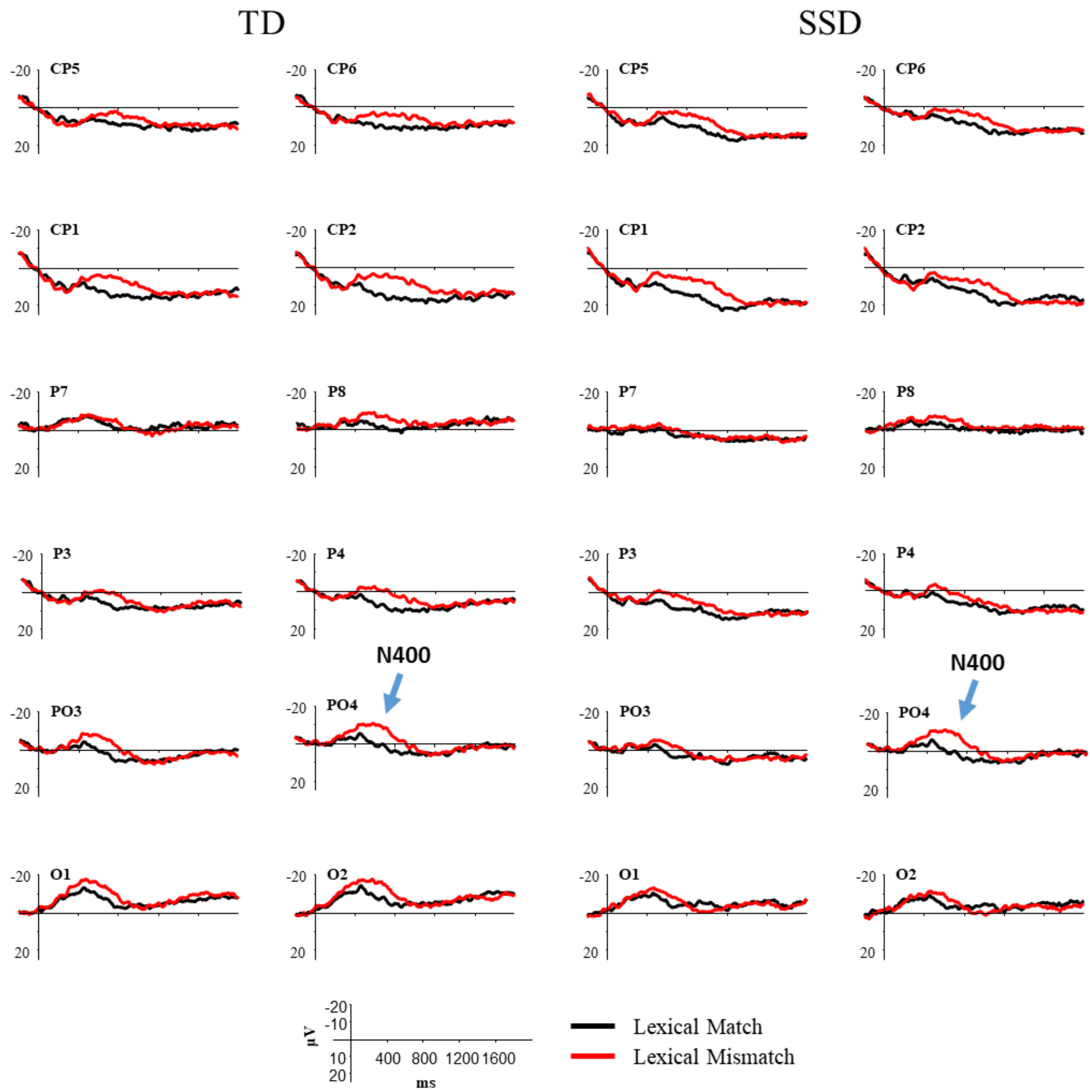

Figure 5. TD and SSD grand average waveforms elicited by lexical matches and mismatches in the posterior region of interest (ROI). Blue arrow point to the N400 component in each group, and negative potentials are plotted upward.

3.3.1. N400 Measures for the Anterior ROI

In the lexical condition, anomalous spoken labels (lexical mismatches) elicited a larger negative mean amplitude N400 compared to correct labels (lexical matches) in the frontal ROI between 600-800ms, $F(1, 26) = 16.745$, $p < .001$, $\eta_p^2 = .392$, and 800-1000ms, $F(1, 26) = 45.511$, $p < .001$, $\eta_p^2 = .636$. This match/mismatch effect did not distinguish the TD and SSD groups in either time window (trial type by group interactions, *p*s > .460).

3.3.2. N400 Measures for the Posterior ROI

There was a more negative mean amplitude N400 elicited for lexical mismatches compared to lexical matches in the posterior ROI across all time windows (400-600ms, $F(1, 26) = 13.647$, $p = .001$, $\eta_p^2 = .344$, 600-800ms, $F(1, 26) = 21.817$, $p < .001$, $\eta_p^2 = .456$, 800-1000ms, $F(1, 26) = 7.304$, $p = .012$, $\eta_p^2 = .219$). This match/mismatch effect did not distinguish the TD and SSD groups in any of the time windows (trial type by group interactions, *p*s > .092).

3.3. ERPs Elicited by Phonetic Matches and Mismatches

Waveforms elicited by the phonetic matches and mismatches for the all trials analysis are displayed in Figures 6 and 7 in the anterior and posterior ROIs respectively.

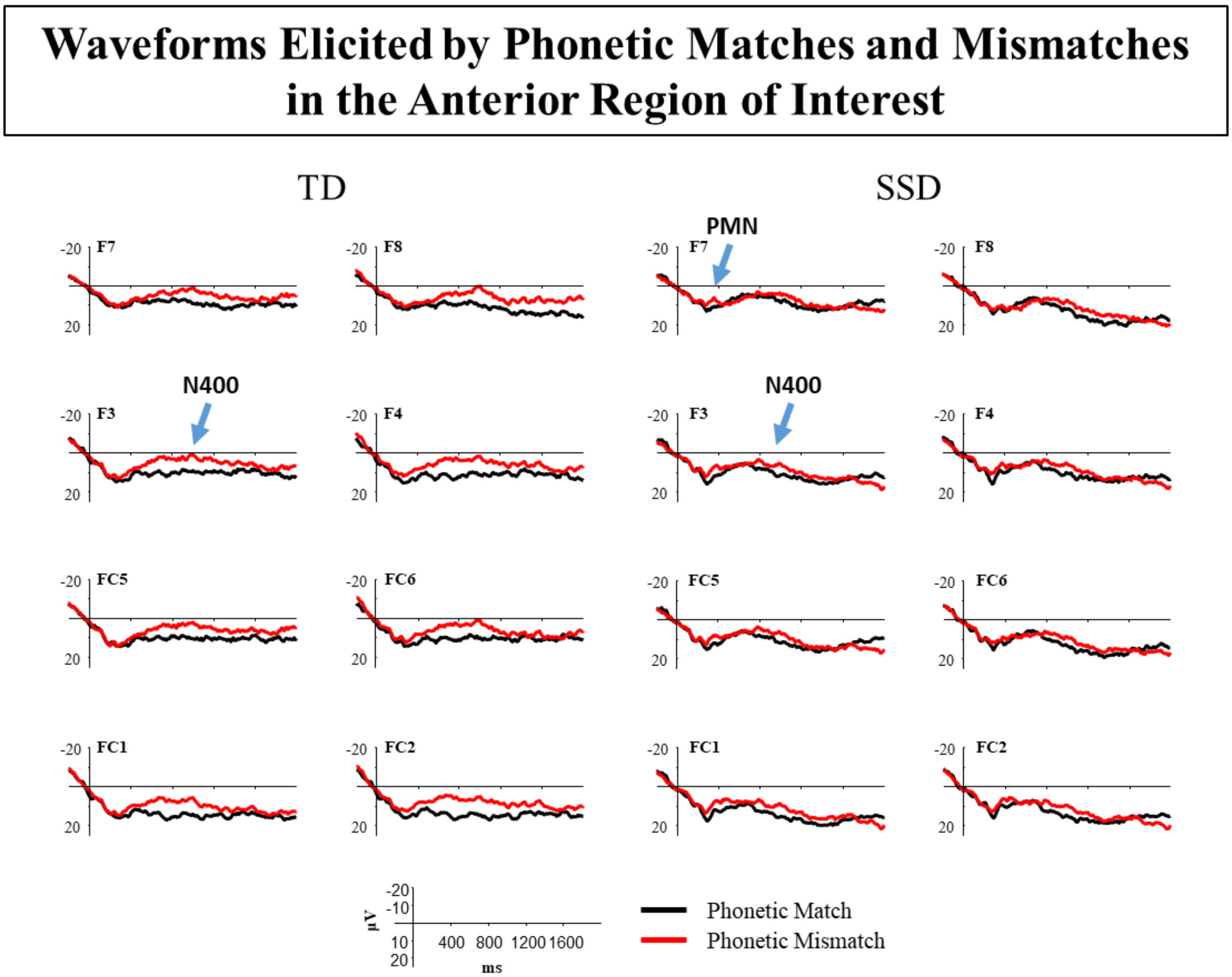

Figure 6. TD and SSD grand average waveforms elicited by phonetic matches and mismatches in the anterior region of interest (ROI). Blue arrows point to the PMN and N400 components, and negative potentials are plotted upward.

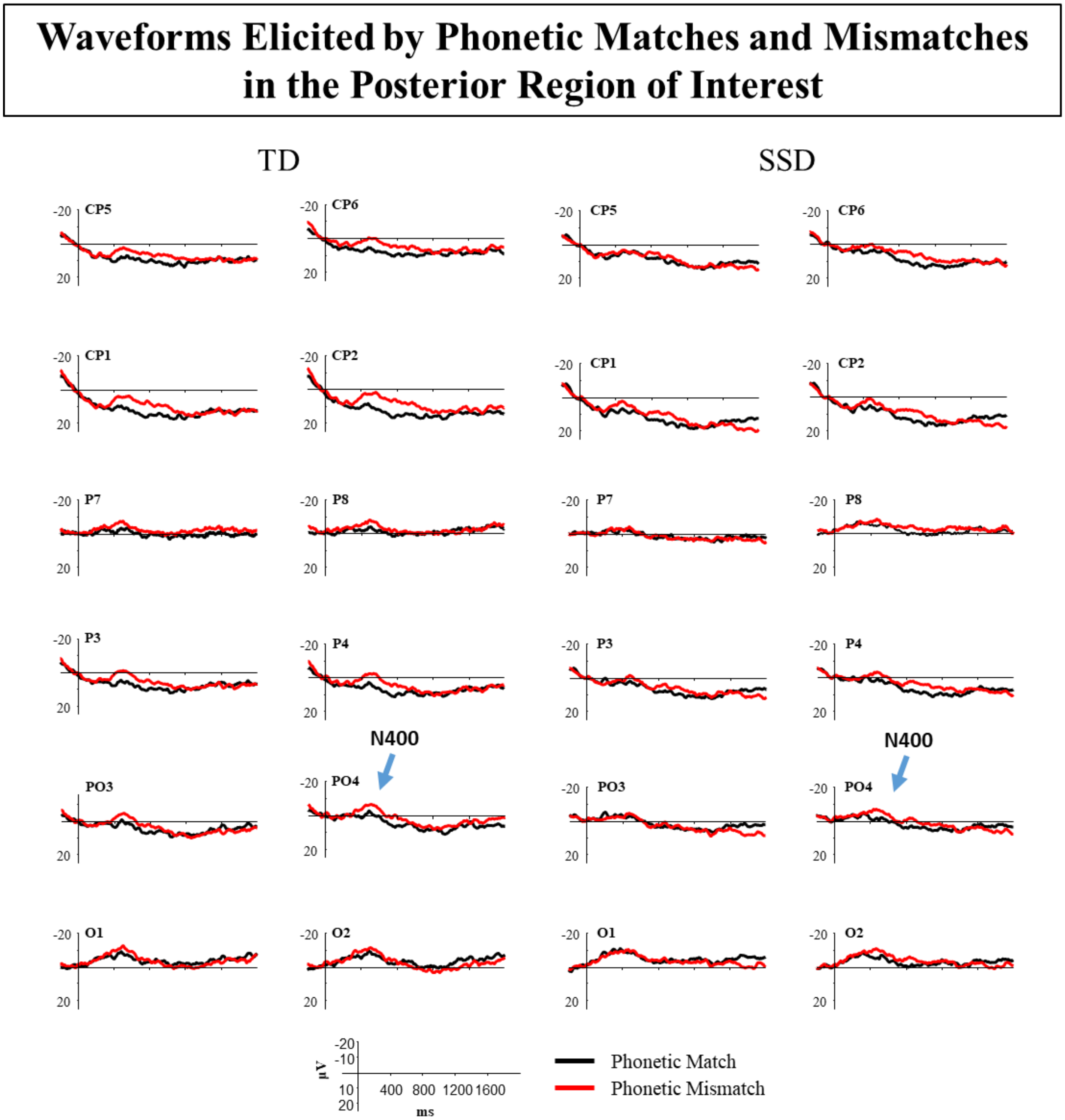

Figure 7. TD and SSD grand average waveforms elicited by phonetic matches and mismatches in the posterior region of interest (ROI). Blue arrows point to the N400 ERP component in each group, and negative potentials are plotted upward.

3.4.1. PMN

In the phonetic condition, a more negative mean amplitude PMN was elicited by words with initial phoneme errors (e.g., "weaf") compared to correct pronunciations (e.g. "leaf), main effect of trial type, $F(1, 26) = 6.970$, $p = .014$, $\eta_p^2 = .211$. An interaction of trial type (match/mismatch) by group by hemisphere, $F(1, 26) = 6.414$, $p = .018$, $\eta_p^2 = .198$, was explored to understand the nature of potential group differences. Figure 8 displays the mean amplitude of the PMN elicited by phonetic matches and mismatches for each group in each hemisphere of the anterior ROI. The PMN amplitudes for the TD and SSD groups were not significantly different when compared over the left and right hemispheres separately, (left, H-F *p*s > .366; right, H-F *p*s > .597). However, when the amplitude of the PMN was examined for each of the groups separately, the SSD group demonstrated a more reliable match/mismatch effect, $F(1, 13) = 5.540$, $p = .035$, $\eta_p^2 = .299$, that was lateralized over the left hemisphere (trial type by hemisphere, $F(1, 13) = 10.857$, $p = .006$ = .455, left hemisphere trial type effect, $F(1, 13) = 10.123$, $p = .007$, $\eta_p^2 = .438$). The increased PMN for phonetic mismatches was not reliable in the TD group, (trial type, $F(1, 13) = 2.341$, $p = .150$, interactions with trial type *p*s > .321). Although the PMN was not as robust in the TD group, eight children with TD and ten with SSD showed the effect in the 300-380ms time window. Figure 9 displays the individual patterns of mean amplitude for phonetic matches and mismatches in each group.

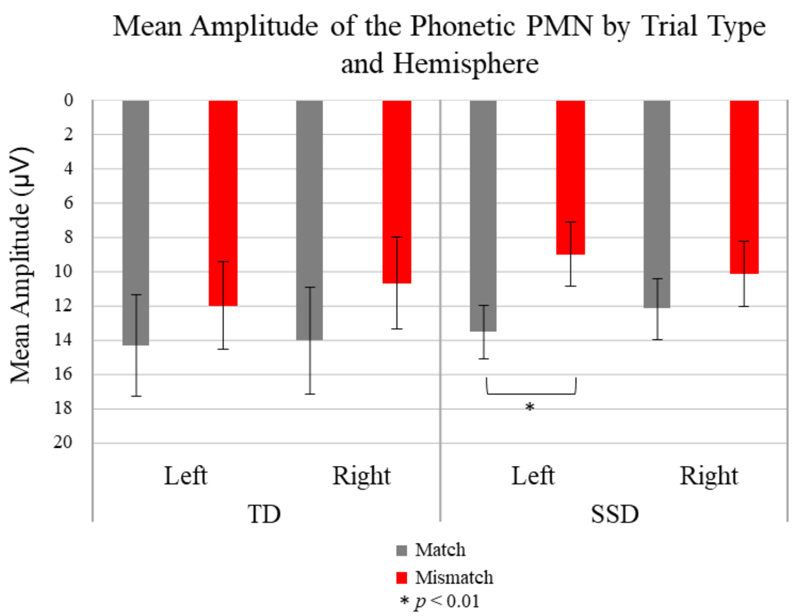

Figure 8. Bar graph displaying the mean amplitude of the PMN elicited by phonetic matches and mismatches for each group in each hemisphere of the anterior region of interest. Note that negative potentials are plotted upward, and error bars represent the mean plus and minus the standard error.

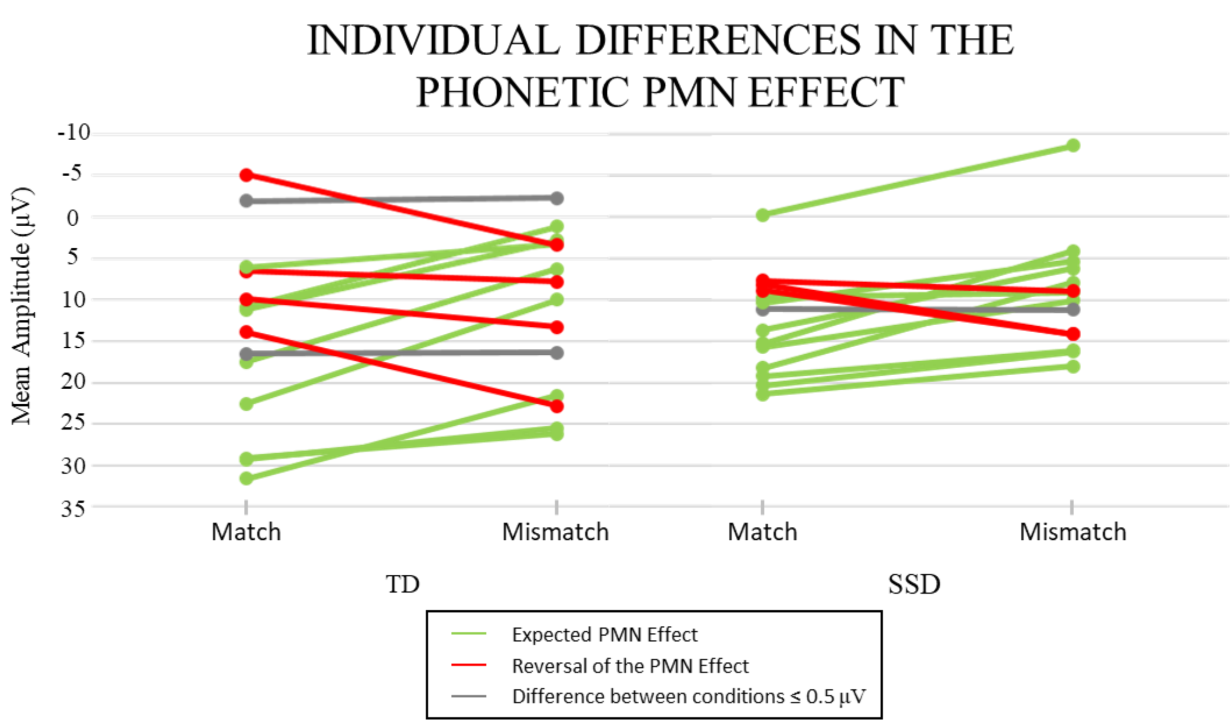

Figure 9. Individual PMN mean amplitude for phonetic matches and mismatches measured in the anterior ROI between 300-380ms. Negative potentials are plotted upward.

3.4.2. N400 Measures for the Anterior ROI

In the anterior ROI, there was a more negative mean amplitude N400 elicited for phonetic mismatches (e.g. “weaf”) compared to phonetic matches (e.g. “leaf”) in the 600-800ms time window, $F(1, 26) = 12.084$, $p = .002$, $\eta_p^2 = .317$, and the 800-1000ms time window, $F(1, 26) = 15.677$, $p = .001$, $\eta_p^2 = .376$. In addition, in the 600-800ms time window, there was a trial type by group interaction, $F(1, 26) = 7.549$, $p = .011$, $\eta_p^2 = .225$. When examined separately in this time window, the TD group demonstrated the larger N400 for phonetic mismatches compared to matches, $F(1, 13) = 15.578$, $p = .002$, $\eta_p^2 = .545$; however, the SSD group did not show this effect (trial type, $F(1, 13) = 0.351$, $p = .564$, interactions with trial type, ps > .270). Figure 10 displays the mean amplitude of the N400 for each group over the anterior ROI between 600-800ms.

3.4.3. N400 Measures for the Posterior ROI

Phonetic mismatches elicited a larger mean amplitude N400 compared to phonetic matches across all time windows of the posterior ROI (400-600ms, $F(1, 26) = 17.070$, $p < .001$, $\eta_p^2 = .396$, 600-800ms, $F(1, 26) = 8.143$, $p = .008$, $\eta_p^2 = .238$, 800-1000ms, $F(1, 26) = 8.733$, $p = .007$, $\eta_p^2 = .251$). This match/mismatch effect did not distinguish groups in any of the time windows (trial type by group interactions, ps > .108).

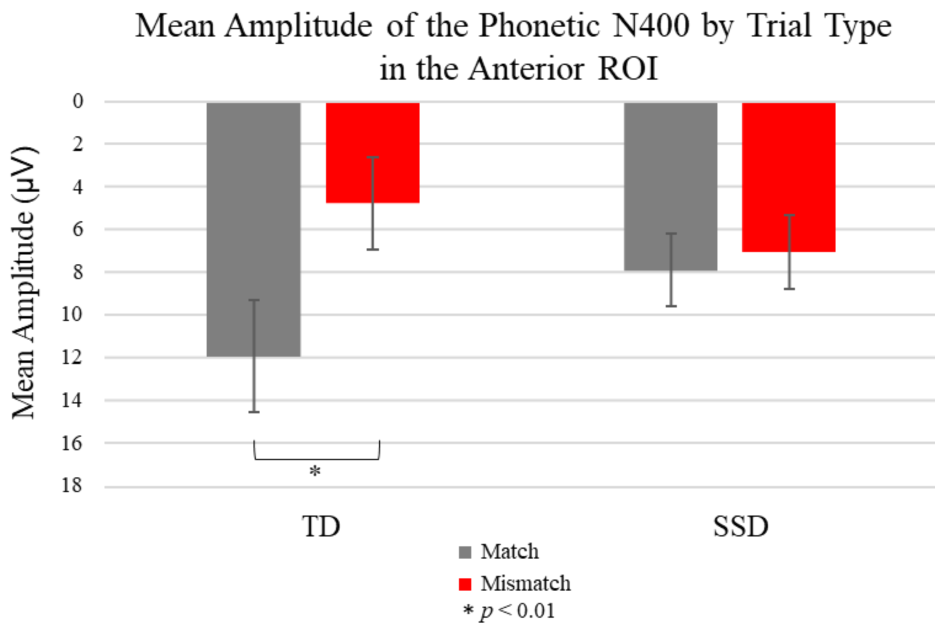

Figure 10. Bar graph displaying N400 mean amplitude elicited for phonetic matches and mismatches measured for each group between 600-800ms in the anterior ROI. Negative potentials are plotted upward, and error bars represent the mean plus and minus the standard error.

CHAPTER 4. DISCUSSION

The neural underpinnings of speech perception in 4-5-year-old children with TD and SSD were examined using a combined electrophysiological and behavioral approach. Processing of lexical and phonetic errors was compared using a match-mismatch task involving pictures followed by naturally spoken words. The pictures established lexical and phonological expectations about upcoming word labels which either matched the picture (phonetic and lexical matches), was an anomalous label (lexical mismatch), or contained an initial phoneme error (phonetic mismatch). On each trial, children were asked to judge whether the picture and the word matched.

As expected, children with SSD were less accurate in their overall judgment accuracy during the ERP task compared to TD peers. The match-mismatch task elicited the PMN and N400 ERP components known to be associated with phonetic and lexical processing, respectively. Lexical matches and mismatches elicited similar N400s for the TD and SSD groups in all of time windows of the anterior and posterior regions of interest. However, differences in the N400 were noted for the groups in the phonetic condition. In the anterior ROI, the TD group showed a larger N400 to the words with initial phoneme errors than correct pronunciations in both time windows whereas the SSD group only showed this effect in the later time window. The PMN was also measured in the phonetic condition over the anterior ROI. Although no differences between the TD and SSD groups were noted when groups were directly compared, when analyzed separately the SSD group demonstrated a larger amplitude PMN to phonetic mismatches compared to phonetic matches over the left hemisphere whereas the TD group did not show this effect. Overall results of the current study suggest subtle differences between children with SSD and TD in the neural processes underlying a speech perception task.

4.1. Relationship Between Speech Production and Speech Perception Abilities

The SSD group was less accurate in their production of the stimulus words and in their overall ERP task judgment accuracy compared to the TD group. These findings are consistent with the diagnostic characteristics of SSD as well as previous findings of speech perception deficits in children with SSD based on error detection tasks (Hearnshaw et al., 2018, 2019). For the phonetic condition, the relationship between speech production abilities and perception of initial phoneme errors was assessed across all participants. There was a positive correlation between standard scores on the GFTA/DEAP and phonetic judgment accuracy, but no significant correlation between production of the stimulus words and judgment accuracy. Hearnshaw and colleagues (2018) reported similar correlation results for measures of speech perception and speech production (both standardized assessments and stimulus word production) in young Australian-English speaking children. One possible reason for correlations between speech perception and standardized assessments of speech production, but not production of stimulus words, is that the standardized assessments evaluate a variety of phonemes in different word positions whereas the stimulus words in the current study and Hearnshaw et al (2018) focused on a few specific phonemes in the initial position of words. In addition, previous work has reported speech perception deficits for children with SSD when tasks include a variety of phonemes, not necessarily only the phonemes that they produce in error (Edwards et al., 2002; Hearnshaw et al., 2019). Correlations in the current study are consistent with the idea that, for some children with SSD, speech perception deficits may be generalized across phonemes rather than having a direct relationship to the phonemes that a child mispronounces (Edwards et al., 2002; Hearnshaw et al., 2018, 2019). In other words, although children with SSD demonstrate group-level deficits in speech perception compared to peers with TD, the relationship of that deficit to speech production abilities and specific phonemes is heterogenous and requires further study (Hearnshaw et al., 2018, 2019).

4.2. Neural Activity Underlying Lexical Processing is Similar for TD and SSD Groups

When presented with pictures followed by naturally spoken words, children with TD and SSD demonstrated similar increases in the amplitude of a broadly distributed N400 elicited by lexical mismatches compared to matches. This N400 match/mismatch effect for spoken word processing is thought to index increased effort required for lexical access and semantic integration when lexical expectations were violated (Federmeier et al., 2015; Kutas & Federmeier, 2011). The current findings indicate that for young children with SSD, who have language skills within normal limits, neural processes underlying lexical access of spoken words is comparable with that of typically developing peers.

For both TD and SSD groups, the N400 effect for violations in lexical expectations was distributed over anterior and posterior regions of interest. This broad distribution of the N400, is consistent with previous investigations of language processing in young, typically developing children (Atchley et al., 2006; Byrne et al., 1999; Coch & Gullick, 2012; Friederici, 2006; Henderson, Baseler, Clarke, Watson, & Snowling, 2011; Holcomb, Coffey, & Neville, 1992) and children with communication disorders such as stuttering and specific language impairment (Kreidler et al., 2017; Pijnacker et al., 2017). As children age, the distribution of the N400 becomes more focal and this topographic change is thought to reflect more efficient, adult-like processing of semantic information (Atchley et al., 2006; Byrne et al., 1999; Holcomb et al., 1992). For the children in the current study, the complexity of the ERP judgment task and use of picture stimuli may have also contributed to distribution of N400 activity over anterior sites. The task involved monitoring for both errors in pronunciation and meaning. Although the children did not need to identify the type of error to complete the task, the required dual monitoring may have increased cognitive load or demands on processing resources leading to recruitment of frontal sites (Friederici, 2006; Friedrich & Friederici, 2004). A more frontal N400 has also been noted for adults and children when integrating word meaning with visual information (Friedrich & Friederici, 2004; Kreidler et al., 2017; West & Holcomb, 2002).

4.3. Neural Activity Underlying Processing of Initial Phoneme Errors Distinguishes TD and SSD Groups

In the phonetic condition, words with initial phoneme errors elicited a larger amplitude PMN and N400 compared to words with correct pronunciations; however, the SSD and TD groups demonstrated different patterns of neural activity. Contrary to initial hypotheses, the SSD group showed a more reliable left lateralized PMN effect over anterior sites. However, when examining individual ERP waveforms, a proportion of participants in both the TD and SSD groups demonstrated the expected condition effect. In the same anterior region, the children with SSD demonstrated a delay in the N400 match/mismatch effect compared to the children with TD. These findings indicate subtle underlying differences in the neural processing of initial phoneme errors in 4-5-year-old children with SSD compared to their typically developing peers. These ERP differences in processing were not observed in the lexical condition, indicating unique group differences related to the processing of phonetic information as indexed by the PMN and anterior N400 ERP components.

4.3.1. Individual Variability and Development of the PMN

The SSD group demonstrated a larger PMN elicited by initial phoneme errors compared to correct pronunciations over left hemisphere anterior sites. Although the TD group did not show a consistent group-level PMN effect, examining the individual data revealed a similar number of participants in each group showing the expected patterns of mean amplitude across matches and mismatches. Specifically, of the 14 children in each group, eight children with TD and ten with SSD showed a more negative PMN mean amplitude elicited by initial phoneme errors than correct pronunciations. The lack of significant group differences over the left hemisphere paired with the presence of these individual PMN effects may indicate that this effect is still emerging for these young 4-5-year-old children. Studies of the PMN in children with developmental disorders, such as specific language impairment and dyslexia, have focused on children ages 8-12 years (Desroches et al., 2013; Malins et al., 2013). Additional research is needed to understand how the PMN develops, particularly in the preschool and early school-age years, and what phonological tasks or stimuli may elicit PMN effects in younger children. For example, the PMN elicited in the current study was observed only for the phonetic condition. This distinction between the lexical and phonetic conditions was unexpected as these conditions were designed to include the same initial phoneme contrasts. For example, a phonetic mismatch including the L/W phoneme contrast included a picture of leaf followed by the spoken non-word "weaf," and the lexical mismatch included a picture of wheel followed by the spoken word "leaf." On either type of mismatch trial involving initial /l/ and /w/, the initial phoneme of the spoken word does not meet the phonological expectation set by the picture prime and therefore should result in a larger PMN than the respective matches. In adults, a single phoneme violation of phonological expectations set by pictures, sentences, or phoneme elision tasks has been sufficient to elicit the PMN (Connolly & Phillips, 1994; Desroches et al., 2009; Newman & Connolly, 2009; Newman et al., 2003). Perhaps in young children additional phonetic information (e.g. mismatch in entire word onsets) or additional priming information (e.g. picture paired with sentence context) is needed to more consistently elicit the PMN effect.

4.3.2. Interaction Between Phonological Processing and Lexical Access in Children with SSD

Considering previous research using similar tasks to the current study, the combination of a PMN condition effect and delayed N400 in the SSD group is unexpected. In studies of children and adults, a larger and later N400 was seen for target words which violated lexical expectations but met initial phonological expectations (Desroches et al., 2009, 2013). For example, in those studies, a PMN effect was not elicited for a cohort condition (picture cone, spoken "comb") because the initial phoneme was consistent between the prime and target. However, for adults, the N400 effect elicited by the cohort mismatches compared to matches was larger and occurred over a later time window than effects for rhyme mismatches (picture cone, spoken "bone") and unrelated mismatches (picture cone, spoken "fox"; Desroches et al., 2009). In addition, both children with dyslexia and their peers with TD demonstrated a delay in the N400 elicited by cohort mismatches; however, for the children with dyslexia, the N400 cohort effect (mismatch – match) was larger than that of their peers with TD over a late time window. These differences were thought to indicate increased effort for lexical access after misdirection caused by the initial phonological information. In the current study, the children with SSD showed a delay in the N400 match/mismatch effect despite a significant PMN effect, which is thought to reflect the detection of the initial phonological mismatch. The children with SSD did not show this delay in the N400 effect in the lexical condition, indicating that for these children there is a unique effect of processing initial phoneme errors on lexical access. In other words, the presence of a PMN condition effect followed by a delay in the anterior N400, which was not present for lexical mismatches, suggests inefficiency in the initial phonological processing of phonetic errors and subsequent lexical access in children with SSD compared to TD.

These processing differences between the SSD and children with TD may reflect previously identified structural and functional differences in brain areas that are associated with generation of the PMN and N400 ERP components. Recall that older children with residual speech sound errors were noted to have increased gray matter in the bilateral STG and left SMG suggesting immaturities compared to peers with TD in these areas related to speech perception abilities (Preston et al., 2014). Furthermore, during a speech perception task involving picture-spoken word pairs, children with residual speech errors showed an over-reliance on pathways involved in articulatory-motor processing (e.g. STG, insula) and under-utilization of pathways involved in acoustic-to-lexical processing (e.g. left MTG, ITG) (Preston et al., 2012). There is also evidence that the left STG and left SMG are associated with the generation of the PMN component (Mody et al., 2008; Trébuchon et al., 2013). Therefore, differences in the PMN for children with SSD compared to peers with TD may result from underlying structural and functional differences in the brain areas generating this component.

Using EEG and magnetoencephalography (MEG), Mody and colleagues (2008) examined the PMN in children with reading difficulties ages 7-13 years. Like children with SSD, children with reading difficulties, such as dyslexia, are thought to have underlying impairments in phonological processing (Cabbage, Farquharson, Iuzzini-Seigel, Zuk, & Hogan, 2018; Lyon, Shaywitz, & Shaywitz, 2003). In this study, children classified as poor readers and good readers heard sentences with terminal target words that varied in semantic and phonological expectancy. The groups demonstrated similar response accuracy and reaction times when judging whether the presented sentences made sense. In the PMN time window, poor readers showed greater activation in the left STG compared to the good readers when terminal words were semantically unexpected and started with an initial phoneme differing in at least two phonetic features from the semantically expected target word (e.g. "The boy rolled the <u>ball</u> vs <u>hall</u>"). The poor readers were thought to show this increased left STG activation compared to good readers because of underlying deficits in speech perception and difficulty resolving violations of phonological expectations (Mody et al., 2008). In the current study, the more reliable left lateralized PMN effect in the SSD group may reflect similar heightened activation in the STG and difficulty in resolving initial phoneme errors that violate expectations set by the picture prime. This idea is consistent with the increased brain activity noted in the STG for older children with residual speech errors when completing a speech perception task similar to that used in the current study (Preston et al., 2012).

In the same anterior region of interest as the PMN, the SSD group demonstrated a delay in the subsequent N400 condition effect. A delay in the N400 effect indicates that phonetic errors reduced the efficiency of lexical access and integration for children with SSD. This interpretation is consistent with the findings that children with residual speech sound errors under-activated brain areas associated with acoustic-to-lexical processing during speech perception (Preston et al., 2012). Generation of the N400 is thought to involve a series of activations across temporal and frontal areas (Kutas & Federmeier, 2011; Swaab et al., 2012). These areas include the left medial and inferior temporal gyri, which have also been identified as regions that were under activated in children with residual speech sound errors (Preston et al., 2012; Trébuchon et al., 2013). It is possible that these underlying functional differences contributed to differences in the characteristics of the N400 effect for phonetic errors for children with SSD compared to TD in the current study. However, it is important to remember that the children with SSD did not show a similar delay in the N400 when processing lexical matches and mismatches. Therefore, the delay in the N400 effect elicited by phonetic matches and mismatches seems to be uniquely related to processing of the initial phoneme errors.

In summary, brain areas associated with the PMN (left STG and SMG), have also been identified as areas of structural and functional differences between children with residual speech errors and their typically developing peers (Mody et al., 2008; Preston et al., 2012, 2014; Trébuchon et al., 2013). In the current study, the left lateralized PMN in the SSD group may indicate inefficiency in pre-lexical phonological processing generated by these underlying structural and functional brain differences. Furthermore, in children with SSD the delay in the N400 following the PMN is consistent with both the inefficient processing of initial phonological information and under-activation of brain areas involved in acoustic to lexical processing (e.g. MTG, ITG), which have been associated with generation of the N400 (Trébuchon et al., 2013). This is some of the first evidence that neural processes underlying a speech perception task are less efficient for young children with SSD compared to their TD peers. Furthermore, this inefficiency is specifically related to processing of phonological information as it was not present when processing lexical information.

4.4. Limitations and Future Directions

The current study included three sound contrasts (L/W, R/W, S/T); however, the total number of trials in the study was limited in order to accommodate the attentional abilities of young children. As a result, there were not enough trials to investigate questions related to the influence of each phoneme contrast on the neural underpinnings of lexical and phonetic processing. Although the current study did not note a direct relationship between accuracy in producing the stimulus words and judgment accuracy for initial phoneme errors, ERPs are a more sensitive measure than task accuracy alone and future investigations may reveal differences in the neural activity elicited by certain phonemes or types of errors (e.g. substitutions vs.

distortions). Research related to the neural processing of specific phonemes and errors may also improve our understanding of why typical, developmental speech errors are naturally resolved in the speech of children with TD but persist in the speech of children with SSD beyond the expected ages. For example, with a later-developing phoneme such as /ɹ/, it may be possible to compare neural processing for a young TD group displaying a developmentally appropriate error (e.g. /ɹ/ → [w]), an older SSD group with the same non-developmental and typical error, and an age-matched TD group with accurate production.

Future studies may also expand on the findings of the current study by comparing neural activity related to different types of phonological priming (e.g., onset, rime) or stimuli (e.g. real words vs non-words). For example, the initial phoneme errors presented in the current study formed rhyming non-words with the picture prime (e.g. see leaf, hear "weaf"). Although we might expect modulation of the N400 for rhyming compared to non-rhyming stimuli (Coch, Grossi, Coffey-Corina, Holcomb, & Neville, 2002; Coch, Grossi, Skendzel, & Neville, 2005; Desroches et al., 2009, 2013; Malins et al., 2013), visual inspection of our phonetic mismatch condition (rhyming stimuli) and lexical mismatch condition (non-rhyming stimuli, e.g. see wheel, hear "leaf") revealed similar N400 mean amplitude over central-parietal sites. This lack of modulation, or rhyming effect, may be related to lexicality of the stimuli (rhyming non-words compared to non-rhyming real words), or to task instructions which did not involve active monitoring for rhyme. There is also some evidence that, compared to peers with TD, children with residual speech sound errors show differences in brain activity underlying speech perception of real words compared to non-words (Preston et al., 2012), and repetition of non-words (Tkach et al., 2011). Future studies may tease apart the effects of rhyming and lexicality on the PMN and N400 elicited in young children with SSD and TD using similar designs to studies in adults and older children (e.g. Desroches et al., 2013; Malins et al., 2013; Newman & Connolly, 2009).

The current study used natural speech to elicit cognitive ERP components known to underlie phonetic and lexical processing; however, it was not designed to assess earlier-occurring components which index sensory processing. Future studies may be specifically designed to assess these earlier components and provide insight into potential differences between children with SSD and TD in their auditory sensory processing. For example, there is some evidence of differences in the auditory brain stem responses of school-age children exhibiting SSD compared to their peers with TD (Gonçalves, Wertzner, Samelli, & Matas, 2011). Future studies may address how differences in early sensory processing may relate to the differences in phonological and lexical processing indexed by the PMN and N400.

4.5. Conclusions

Previous research suggests that as a group, children with SSD present with deficits in speech perception. These difficulties are thought to impact their ability to form well specified phonological representations for speech production and phonological awareness skills. Using a combined electrophysiological and behavioral approach, the current study provided some of the first evidence of inefficiencies in the neural processes underlying a speech perception task in young children with SSD. Specifically, when processing initial phoneme errors, children with SSD demonstrated a delay for lexical access and semantic integration, indexed by the N400, compared to their peers with TD. This delay was not present when the children with SSD were presented with errors in word meaning indicating that processing differences were specific to phonological information.

APPENDIX A. LIST OF STIMULI BY TRIAL TYPE AND PHONETIC CONTRAST

Table A-1. Picture and spoken word stimuli by trial type and phonetic contrast

Contrast	Phonetic Match		Phonetic Mismatch		Lexical Match		Lexical Mismatch	
	Picture	Spoken Word	Picture	Spoken Word	Picture	Spoken Word	Picture	Spoken Word
S/T	soup	soup	soup	toop	tooth	tooth	tooth	soup
S/T	sailboat	sailboat	sailboat	tailboat	table	table	table	sailboat
S/T	seahorse	seahorse	seahorse	teahorse	tv	tv	tv	seahorse
S/T	sun	sun	sun	tun	tub	tub	tub	sun
S/T	saw	saw	saw	taw	top	top	top	saw
L/W	leaf	leaf	leaf	weef	wheel	wheel	wheel	leaf
L/W	lollipop	lollipop	lollipop	wollipop	waterfall	waterfall	waterfall	lollipop
L/W	leg	leg	leg	weg	web	web	web	leg
L/W	ladder	ladder	ladder	wadder	wagon	wagon	wagon	ladder
L/W	lick	lick	lick	wick	witch	witch	witch	lick
R/W	rocket	rocket	rocket	wocket	wallet	wallet	wallet	rocket
R/W	ribbon	ribbon	ribbon	wibbon	window	window	window	ribbon
R/W	rain	rain	rain	wain	wave	wave	wave	rain
R/W	robber	robber	robber	wobber	water	water	water	robber
R/W	red	red	red	wed	wet	wet	wet	red

APPENDIX B. TRIAL ORDER FOR EXPERIMENTAL LISTS SET A AND B

Table B-1 displays the trial order for experimental lists Set A and B which were counter-balanced across participants. Trials were pseudorandomized within four blocks of 15 trials each, and each block was presented in the first and second half of the experiment. In list A, block order was 1, 2, 3, 4 in the first half and 2, 1, 4, 3 in the second half. List B had the halves reversed with 2, 1, 4, 3 in the first half, and 1, 2, 3, 4 in the second half. After each 15-trial block, the participant was provided with a break.

Table B-1. Picture and spoken word stimulus order for Set A and B

Set A			Set B		
Contrast	Trial Type	Picture/Spoken Word	Contrast	Trial Type	Picture/Spoken Word
Begin Experiment: Block 1			**Begin Experiment: Block 2**		
R/W	Phonetic Match	robber/robber	R/W	Lexical Match	wallet/wallet
S/T	Phonetic Mismatch	sailboat/tailboat	L/W	Phonetic Match	lollipop/lollipop
L/W	Lexical Match	waterfall/waterfall	L/W	Lexical Match	web/web
R/W	Lexical Match	window/window	S/T	Lexical Mismatch	table/sailboat
L/W	Phonetic Mismatch	ladder/wadder	S/T	Lexical Match	top/top
L/W	Phonetic Match	lick/lick	R/W	Lexical Mismatch	wave/rain
S/T	Lexical Mismatch	top/saw	S/T	Lexical Match	tooth/tooth
S/T	Phonetic Match	seahorse/seahorse	R/W	Phonetic Match	red/red
L/W	Lexical Mismatch	web/leg	S/T	Phonetic Mismatch	seahorse/teahorse
R/W	Phonetic Mismatch	rain/wain	R/W	Phonetic Mismatch	robber/wobber
L/W	Phonetic Match	leaf/leaf	S/T	Phonetic Match	sun/sun
R/W	Lexical Match	wet/wet	L/W	Lexical Mismatch	wagon/ladder
S/T	Lexical Mismatch	tooth/soup	L/W	Phonetic Mismatch	lick/wick
S/T	Lexical Match	tub/tub	R/W	Phonetic Match	ribbon/ribbon
R/W	Lexical Mismatch	wallet/rocket	L/W	Phonetic Mismatch	leaf/weaf
Block 2			**Block 1**		
R/W	Phonetic Match	red/red	R/W	Phonetic Match	robber/robber
S/T	Lexical Mismatch	table/sailboat	S/T	Phonetic Mismatch	sailboat/tailboat
L/W	Phonetic Mismatch	leaf/weaf	R/W	Phonetic Mismatch	rain/wain
S/T	Phonetic Match	sun/sun	S/T	Lexical Mismatch	tooth/soup
S/T	Lexical Match	tooth/tooth	R/W	Lexical Match	window/window
L/W	Lexical Mismatch	wagon/ladder	S/T	Phonetic Match	seahorse/seahorse
R/W	Phonetic Match	ribbon/ribbon	L/W	Phonetic Mismatch	ladder/wadder
R/W	Phonetic Mismatch	robber/wobber	L/W	Lexical Mismatch	web/leg
L/W	Lexical Match	web/web	S/T	Lexical Match	tub/tub

Table B-1. continued

S/T	Phonetic Mismatch	seahorse/teahorse	L/W	Phonetic Match	lick/lick
L/W	Phonetic Match	lollipop/lollipop	L/W	Phonetic Match	leaf/leaf
R/W	Lexical Mismatch	wave/rain	R/W	Lexical Mismatch	wallet/rocket
S/T	Lexical Match	top/top	L/W	Lexical Match	waterfall/waterfall
R/W	Lexical Match	wallet/wallet	S/T	Lexical Mismatch	top/saw
L/W	Phonetic Mismatch	lick/wick	R/W	Lexical Match	wet/wet
	Block 3			**Block 4**	
S/T	Lexical Match	table/table	L/W	Lexical Mismatch	waterfall/lollipop
R/W	Phonetic Mismatch	ribbon/wibbon	S/T	Lexical Match	tv/tv
S/T	Lexical Mismatch	tv/seahorse	R/W	Phonetic Mismatch	rocket/wocket
L/W	Lexical Match	wagon/wagon	S/T	Phonetic Match	sailboat/sailboat
R/W	Phonetic Mismatch	red/wed	R/W	Lexical Mismatch	window/ribbon
S/T	Phonetic Match	soup/soup	S/T	Lexical Mismatch	tub/sun
L/W	Phonetic Mismatch	lollipop/wollipop	R/W	Phonetic Match	rain/rain
R/W	Phonetic Match	rocket/rocket	L/W	Lexical Match	witch/witch
L/W	Lexical Mismatch	wheel/leaf	S/T	Phonetic Mismatch	soup/toup
R/W	Lexical Match	wave/wave	L/W	Phonetic Match	ladder/ladder
L/W	Phonetic Match	leg/leg	R/W	Lexical Mismatch	wet/red
S/T	Phonetic Mismatch	sun/tun	L/W	Phonetic Mismatch	leg/weg
R/W	Lexical Mismatch	water/robber	L/W	Lexical Match	wheel/wheel
S/T	Phonetic Match	saw/saw	S/T	Phonetic Mismatch	saw/taw
L/W	Lexical Mismatch	witch/lick	R/W	Lexical Match	water/water
	Block 4			**Block 3**	
L/W	Lexical Mismatch	waterfall/lollipop	R/W	Phonetic Match	rocket/rocket
R/W	Lexical Match	water/water	L/W	Phonetic Mismatch	lollipop/wollipop
R/W	Phonetic Mismatch	rocket/wocket	S/T	Phonetic Match	soup/soup
S/T	Phonetic Mismatch	soup/toup	R/W	Lexical Match	wave/wave
L/W	Lexical Match	witch/witch	L/W	Lexical Mismatch	wheel/leaf

Table B-1. continued

R/W	Lexical Mismatch	wet/red
S/T	Phonetic Match	sailboat/sailboat
L/W	Phonetic Mismatch	leg/weg
S/T	Phonetic Mismatch	saw/taw
L/W	Lexical Match	wheel/wheel
S/T	Lexical Mismatch	tub/sun
S/T	Lexical Match	tv/tv
R/W	Phonetic Match	rain/rain
L/W	Phonetic Match	ladder/ladder
R/W	Lexical Mismatch	window/ribbon
Begin second half: Block 2		
R/W	Lexical Match	wallet/wallet
L/W	Phonetic Match	lollipop/lollipop
L/W	Lexical Match	web/web
S/T	Lexical Mismatch	table/sailboat
S/T	Lexical Match	top/top
R/W	Lexical Mismatch	wave/rain
S/T	Lexical Match	tooth/tooth
R/W	Phonetic Match	red/red
S/T	Phonetic Mismatch	seahorse/teahorse
R/W	Phonetic Mismatch	robber/wobber
S/T	Phonetic Match	sun/sun
L/W	Lexical Mismatch	wagon/ladder
L/W	Phonetic Mismatch	lick/wick
R/W	Phonetic Match	ribbon/ribbon
L/W	Phonetic Mismatch	leaf/weaf
Block 1		
R/W	Phonetic Match	robber/robber

L/W	Lexical Mismatch	witch/lick
S/T	Phonetic Match	saw/saw
R/W	Phonetic Mismatch	red/wed
R/W	Lexical Mismatch	water/robber
S/T	Lexical Match	table/table
L/W	Lexical Match	wagon/wagon
S/T	Lexical Mismatch	tv/seahorse
L/W	Phonetic Match	leg/leg
S/T	Phonetic Mismatch	sun/tun
R/W	Phonetic Mismatch	ribbon/wibbon
Begin second half: Block 1		
R/W	Phonetic Match	robber/robber
S/T	Phonetic Mismatch	sailboat/tailboat
L/W	Lexical Match	waterfall/waterfall
R/W	Lexical Match	window/window
L/W	Phonetic Mismatch	ladder/wadder
L/W	Phonetic Match	lick/lick
S/T	Lexical Mismatch	top/saw
S/T	Phonetic Match	seahorse/seahorse
L/W	Lexical Mismatch	web/leg
R/W	Phonetic Mismatch	rain/wain
L/W	Phonetic Match	leaf/leaf
R/W	Lexical Match	wet/wet
S/T	Lexical Mismatch	tooth/soup
S/T	Lexical Match	tub/tub
R/W	Lexical Mismatch	wallet/rocket
Block 2		
R/W	Phonetic Match	red/red

Table B-1. continued

S/T	Phonetic Mismatch	sailboat/tailboat
R/W	Phonetic Mismatch	rain/wain
S/T	Lexical Mismatch	tooth/soup
R/W	Lexical Match	window/window
S/T	Phonetic Match	seahorse/seahorse
L/W	Phonetic Mismatch	ladder/wadder
L/W	Lexical Mismatch	web/leg
S/T	Lexical Match	tub/tub
L/W	Phonetic Match	lick/lick
L/W	Phonetic Match	leaf/leaf
R/W	Lexical Mismatch	wallet/rocket
L/W	Lexical Match	waterfall/waterfall
S/T	Lexical Mismatch	top/saw
R/W	Lexical Match	wet/wet
	Block 4	
L/W	Lexical Mismatch	waterfall/lollipop
S/T	Lexical Match	tv/tv
R/W	Phonetic Mismatch	rocket/wocket
S/T	Phonetic Match	sailboat/sailboat
R/W	Lexical Mismatch	window/ribbon
S/T	Lexical Mismatch	tub/sun
R/W	Phonetic Match	rain/rain
L/W	Lexical Match	witch/witch
S/T	Phonetic Mismatch	soup/toup
L/W	Phonetic Match	ladder/ladder
R/W	Lexical Mismatch	wet/red
L/W	Phonetic Mismatch	leg/weg
L/W	Lexical Match	wheel/wheel

S/T	Lexical Mismatch	table/sailboat
L/W	Phonetic Mismatch	leaf/weaf
S/T	Phonetic Match	sun/sun
S/T	Lexical Match	tooth/tooth
L/W	Lexical Mismatch	wagon/ladder
R/W	Phonetic Match	ribbon/ribbon
R/W	Phonetic Mismatch	robber/wobber
L/W	Lexical Match	web/web
S/T	Phonetic Mismatch	seahorse/teahorse
L/W	Phonetic Match	lollipop/lollipop
R/W	Lexical Mismatch	wave/rain
S/T	Lexical Match	top/top
R/W	Lexical Match	wallet/wallet
L/W	Phonetic Mismatch	lick/wick
	Block 3	
S/T	Lexical Match	table/table
R/W	Phonetic Mismatch	ribbon/wibbon
S/T	Lexical Mismatch	tv/seahorse
L/W	Lexical Match	wagon/wagon
R/W	Phonetic Mismatch	red/wed
S/T	Phonetic Match	soup/soup
L/W	Phonetic Mismatch	lollipop/wollipop
R/W	Phonetic Match	rocket/rocket
L/W	Lexical Mismatch	wheel/leaf
R/W	Lexical Match	wave/wave
L/W	Phonetic Match	leg/leg
S/T	Phonetic Mismatch	sun/tun
R/W	Lexical Mismatch	water/robber

Table B-1. continued

S/T	Phonetic Mismatch	saw/taw	S/T	Phonetic Match	saw/saw
R/W	Lexical Match	water/water	L/W	Lexical Mismatch	witch/lick
	Block 3			**Block 4**	
R/W	Phonetic Match	rocket/rocket	L/W	Lexical Mismatch	waterfall/lollipop
L/W	Phonetic Mismatch	lollipop/wollipop	R/W	Lexical Match	water/water
S/T	Phonetic Match	soup/soup	R/W	Phonetic Mismatch	rocket/wocket
R/W	Lexical Match	wave/wave	S/T	Phonetic Mismatch	soup/toup
L/W	Lexical Mismatch	wheel/leaf	L/W	Lexical Match	witch/witch
L/W	Lexical Mismatch	witch/lick	R/W	Lexical Mismatch	wet/red
S/T	Phonetic Match	saw/saw	S/T	Phonetic Match	sailboat/sailboat
R/W	Phonetic Mismatch	red/wed	L/W	Phonetic Mismatch	leg/weg
R/W	Lexical Mismatch	water/robber	S/T	Phonetic Mismatch	saw/taw
S/T	Lexical Match	table/table	L/W	Lexical Match	wheel/wheel
L/W	Lexical Match	wagon/wagon	S/T	Lexical Mismatch	tub/sun
S/T	Lexical Mismatch	tv/seahorse	S/T	Lexical Match	tv/tv
L/W	Phonetic Match	leg/leg	R/W	Phonetic Match	rain/rain
S/T	Phonetic Mismatch	sun/tun	L/W	Phonetic Match	ladder/ladder
R/W	Phonetic Mismatch	ribbon/wibbon	R/W	Lexical Mismatch	window/ribbon

APPENDIX C. ANALYSIS COMPARING ERPS ELICITED BY THE SAME SPOKEN WORDS USED FOR BOTH THE PHONETIC AND LEXICAL CONDITIONS

This analysis compared the TD and SSD groups on the mean amplitude of the N400 elicited by identical spoken word stimuli from the phonetic match (see leaf, hear “leaf”) and lexical mismatch (see wheel, hear “leaf”) conditions. These analyses utilized the time windows, ROIs, and statistical analyses described in the main text. Table C-1 displays the results from time windows in the anterior and posterior ROIs. To summarize, there was a larger negative mean amplitude N400 elicited by anomalous labels (lexical mismatch) compared to correct labels (phonetic match) across all time windows and regions of interest. Results were consistent with comparisons between the lexical match (see wheel, hear “wheel”) and lexical mismatch (see wheel, hear “leaf”) conditions which presented different spoken words but used the same picture prime. Because ERPs in this analysis were elicited by the same stimulus words, differences in the mean amplitude of the N400 can be definitively attributed to the context or lexical expectations established by the picture primes. Similar to the analysis of lexical match and mismatch conditions, these results suggest that children with SSD show neural processing for lexical violations consistent with their peers with TD.

Table C-1. Statistical analyses of the mean amplitude of the ERPs elicited by phonetic matches and lexical mismatches in the TD and SSD groups

	Statistical Analysis		F	df	H-F p	η_p^2
		N400 Anterior ROI				
600-800ms						
	Trial type		10.067	1, 26	.004*	.279
	Trial type by group interactions				*p*s > .310	
800-1000ms						
	Trial type		26.107	1, 26	< .001*	.279
	Trial type by group interactions				*p*s > .511	
		N400 Posterior ROI				
400-600ms						
	Trial type		17.051	1, 26	< .001*	.396
	Trial type by group interactions				*p*s > .210	
600-800ms						
	Trial type		27.490	1, 26	< .001*	.514
	Trial type by Group		4.799	1, 26	.038*	.156
	SSD analysis:	Trial type	6.349	1, 13	.026*	.328
	TD analysis:	Trial type	21.821	1, 13	< .001*	.627
800-1000ms						
	Trial type		7.351	1, 26	.012*	.220
	Trial type by group interactions				*p*s > .299	

Note. H-F p = Huynh-Feldt corrected p-values; * = p-values less than .05

APPENDIX D. ANALYSIS INCLUDING ONLY CORRECT ERP TRIALS

An additional group-level analysis was completed including only ERP trials for which a participant provided a correct response. These analyses utilized the time windows, ROIs, and statistical analyses described in the main text, but involved forming sub-groups of the TD and SSD groups. These sub-groups are referred to as TD_correct and SSD_correct. Ten children with TD and 11 with SSD demonstrated high judgment accuracy in both the lexical and phonetic conditions and generated enough artifact-free correct trials to form reliable ERPs. Children included in the sub-groups had at least 16 correct artifact-free match and mismatch trials in each condition. On average, the sub-groups had 19-23 trials in each condition. The number of correct artifact-free match and mismatch trials in each condition did not distinguish the sub-groups, $F(1, 20) < 3.000$, $p > .099$. Means and standard errors for the ERP judgment task are displayed in Table D-1 for each sub-group. Consistent with the TD and SSD groups, the TD_correct and SSD_correct sub-groups had similar age, $F(1, 20) = 2.624$, $p = .122$, and mother's level of education, $F(1, 20) = 2.255$, $p = .150$. As expected, the TD_correct sub-group performed with higher accuracy than the SSD_correct sub-group on the assessment of speech production abilities (GFTA-3 or DEAP), $F(1, 20) = 34.806$, $p < .001$. The sub-groups demonstrated similar performance on the assessments of language, $F(1, 20) < 0.668$, $p > .424$.

Results of the ERP analysis including only correct trials mirrored the analysis including all trials. Table D-2 reports results from the lexical condition. Overall, the mean amplitude of the N400 was larger for anomalous labels (lexical mismatches) compared to correct labels (lexical matches) across all time windows of the anterior and posterior ROIs. These findings indicate that the SSD_correct subgroup demonstrated underlying processing for lexical violations similar to their TD_correct peers.

Table D-3 reports results from the phonetic condition. Similar to the all trials analysis, a trial type (match/mismatch) by group interaction was explored in the PMN time window of the anterior ROI, and significant differences were not found when the groups were compared over the left and right hemispheres separately. Unlike the all trials analysis, the SSD group did not show a larger PMN for initial phoneme errors (phonetic mismatches) compared to correct pronunciations (phonetic matches) over the left or right hemisphere. In the 600-800ms time window of the anterior ROI, the TD_correct group had a larger N400 for phonetic mismatches compared to phonetic matches, but the SSD_correct sub-group did not. These group differences were not present in the 800-1000ms time window. Taken together, results in these time windows in the anterior ROI indicate that the SSD_correct sub-group was delayed in N400 effect elicited by initial phoneme errors compared to TD_correct peers. In the posterior ROI, the mean amplitude of the N400 was more negative for phonetic mismatches compared to phonetic matches across all time windows. Overall, findings from this analysis involving only correct trials are consistent with the all-trials analysis and indicate that, compared to their TD_correct peers, the SSD_correct sub-group shows a delay in processing initial phoneme errors over the anterior ROI.

Table D-1. Phonetic and lexical judgment accuracy of the TD_Correct and SSD_correct sub-groups

Group	Phonetic Judgment Percent Correct M (SE)	Lexical Judgment Percent Correct M (SE)
TD_Correct	93.6 (1.7)	98.2 (0.6)
SSD_Correct	89.0 (1.7)	93.5 (1.2)

Table D-2. Statistical analyses of the mean amplitude of the ERPs elicited by lexical matches and mismatches for the TD_correct and SSD_correct sub-groups

	Statistical Analysis	***F***	***df***	***H-F p***	η_p^2
	N400 Anterior ROI				
600-800ms					
	Trial type	11.284	1, 19	.003*	.373
	Trial type by Group interactions			*p*s > .485	
800-1000ms					
	Trial type	27.720	1, 19	< .001*	.593
	Trial type by Group interactions			*p*s > .779	
	N400 Posterior ROI				
400-600ms					
	Trial type	13.322	1, 19	.002*	.412
	Trial type by Group interactions			*p*s > .319	
600-800ms					
	Trial type	13.648	1, 19	.002*	.418
	Trial type by Group interactions			*p*s > .196	
800-1000ms					
	Trial type	4.601	1, 19	.045*	.195
	Trial type by Group interactions			*p*s > .360	

Note. H-F *p* = Huynh-Feldt corrected *p*-values; * = *p*-values less than .05

Table D-3. Statistical analyses of the mean amplitude of the ERPs elicited by phonetic matches and mismatches for the TD_correct and SSD_correct sub-groups

Statistical Analysis	***F***	***df***	***H-F p***	η_p^2
PMN				
300-380ms				
Trial type	.971	1, 19	.337	.049
Trial type x Group x Hemisphere	4.991	1, 19	.038*	.208
Left hemisphere analysis:				
Group	.485	1, 19	.494	.025
Group x Trial type	.089	1, 19	.978	< .001
Right hemisphere analysis:				
Group	.258	1, 19	.618	.013
Group x Trial type	1.221	1, 19	.283	.060
TD_correct analysis:				
Trial type	.952	1, 9	.355	.096
Trial type interactions			*p*s > .740	
SSD_correct analysis:				
Trial type x Hemisphere	13.542	1, 10	.004*	.575
Left hemisphere analysis:				
Trial type	1.712	1, 10	.220	.146
Right hemisphere analysis:				
Trial type	0.217	1, 10	.651	.021
N400 Anterior ROI				
600-800ms				
Trial type	7.513	1, 19	.013*	.283
Trial type by Group	9.555	1, 19	.006*	.335
TD_correct analysis:				
Trial type	13.477	1, 9	.005*	.600
SSD_correct analysis:				
Trial type	0.879	1, 10	.784	.008
Trial type interactions			*p*s > .221	
800-1000ms				
Trial type	9.741	1, 19	.006*	.339
Trial type by Group interactions			*p*s > .124	
N400 Posterior ROI				
400-600ms				
Trial type	10.727	1, 19	.004*	.361
Trial type by Group interactions			*p*s > .104	
600-800ms				
Trial type	6.016	1, 19	.024*	.240
Trial type by Group interactions			*p*s > .073	
800-1000ms				
Trial type	10.283	1, 19	.005*	.351
Trial type by Group interactions			*p*s > .272	

Note. H-F *p* = Huynh-Feldt corrected *p*-values; * = *p*-values less than .05

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