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Research Article

Neural Indices of Semantic Processing in Early Childhood Distinguish Eventual Stuttering Persistence and Recovery

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Purpose: Maturation of neural processes for language may lag in some children who stutter (CWS), and event-related potentials (ERPs) distinguish CWS who have recovered from those who have persisted. The current study explores whether ERPs indexing semantic processing may distinguish children who will eventually persist in stuttering (CWS-ePersisted) from those who will recover from stuttering (CWS-eRecovered).

Method: Fifty-six 5-year-old children with normal receptive language listened to naturally spoken sentences in a story context. ERP components elicited for semantic processing (N400, late positive component [LPC]) were compared for CWS-ePersisted, CWS-eRecovered, and children who do not stutter (CWNS).

Results: The N400 elicited by semantic violations had a more focal scalp distribution (left lateralized and less anterior) in the CWS-eRecovered compared with CWS-ePersisted. Although the LPC elicited in CWS-eRecovered and CWNS did not differ, the LPC elicited in the CWS-ePersisted was smaller in amplitude compared with that in CWNS.

Conclusions: ERPs elicited in 5-year-old CWS-eRecovered compared with CWS-ePersisted suggest that future recovery from stuttering may be associated with earlier maturation of semantic processes in the preschool years. Subtle differences in ERP indices offer a window into neural maturation processes for language and may help distinguish the course of stuttering development.

Developmental stuttering is characterized by the involuntary production of speech disfluencies including sound, syllable, part-word repetitions, and/or dysrhythmic phonations (Yairi & Seery, 2015). A consensus in the research literature has emerged to view stuttering as a multifactorial, neurodevelopmental disorder whose etiology involves dynamic interactions between numerous etiological factors, such as speech motor control, language, and temperament (for reviews, see Bloodstein & Bernstein Ratner, 2008; Conture & Curlee, 2007; Ludlow & Loucks, 2003; Packman, 2012; Smith & Weber, 2017; Van Riper, 1982). Childhood stuttering has also been associated with incongruent development between these multiple factors (Anderson, Pellowski, & Conture, 2005; Choo, Burnham, Hicks, & Chang, 2016; Coulter, Anderson, & Conture, 2009). Up to 8% of young children experience "stuttering-like" disfluencies (SLDs), with as many as 80% of these children eventually recovering from stuttering before adolescence, regardless of therapeutic history (Yairi & Ambrose, 2013). However, very little is known regarding how the development of etiological factors contributes to persistence or recovery in stuttering.

The onset of stuttering typically occurs around 33 months, consistent with a period of rapid speech motor and language development that influences the emergence and chronicity of the disorder (for reviews, see Smith & Weber, 2017; Yairi & Ambrose, 2005). The speech motor systems of children who stutter (CWS) are compromised by deficiencies in the structural and functional connectivity of neural networks underlying speech-language processes (Chang et al., in press; Chang, Erickson, Ambrose, Hasegawa-Johnson, & Ludlow, 2008; Chang & Zhu, 2013; Chang, Zhu, Choo, & Angstadt, 2015; Chow & Chang, 2017), likely resulting in disruptions to motor command signaling to speech muscles (Smith & Weber, 2017). The speech motor control processes of CWS appear to be more prone to destabilize with increasing linguistic demands compared with their fluent peers, suggesting that language has an influence on the appearance of stuttering (MacPherson &

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Smith, 2013; Smith, Sadagopan, Walsh, & Weber-Fox, 2010; Usler, Smith, & Weber, 2017; Walsh, Mettel, & Smith, 2015).

A rich literature supports the role of linguistic processes in stuttering (for reviews, see Bernstein Ratner, 1997; Bloodstein & Bernstein Ratner, 2008; Conture, Zackheim, Anderson, & Pellowski, 2004). SLDs are also more likely to occur at the beginning of sentences and phrases containing complex syntactic structure and at predictable linguistic boundaries (e.g., Bernstein Ratner, 1997; Conture et al., 2004). Although most CWS do not exhibit overt language impairment, there may be subclinical differences between CWS and their typically fluent peers (for a review, see Ntourou, Conture, & Lipsey, 2011). Although persons who stutter perform similarly to their fluent peers on behavioral language assessments, differences have been observed in the neural processes underlying language processing compared with their fluent peers (Cuadrado & Weber-Fox, 2003; Ingham, 2001; Sato et al., 2011; Weber-Fox & Hampton, 2008; Weber-Fox, Hampton Wray, & Arnold, 2013; Weber-Fox, Spencer, Spruill, & Smith, 2004; Weber-Fox, Spruill, Spencer, & Smith, 2008).

The current study focuses on one aspect of language, lexical access. Ease of lexical access is fundamentally important for speech production, as this is one of the first steps in generating a spoken message (e.g., Hagoort & Levelt, 2009; Hickock, 2012; Indefrey & Levelt, 2000; Levelt, Roelofs, & Meyer, 1999). Lexical access and selection for speech production occur very quickly, in less than 200 ms (Hagoort & Levelt, 2009). Delayed, inefficient, or inaccurate lexical access during speech has been shown by Hall and colleagues to have detrimental effects on fluency (Hall, 1996, 1999; Hall & Burgess, 2000; Hall, Yamashita, & Aram, 1993). Words that are less familiar and/or of lower frequency are generally more disfluent than higher-familiarity/frequency words (Hubbard & Prins, 1994; for a review, see Bernstein Ratner, 1997). CWS also exhibited lower performance on measures of receptive and expressive language—specifically, receptive vocabulary—compared with their fluent peers (Anderson & Conture, 2000). In addition, the benefits of semantic priming observed in fluent peers (i.e., faster response times to stimuli after semantically related primes) were not observed in CWS. Instead, CWS exhibited slower response times after semantic priming (Pellowski & Conture, 2005). However, the role that the neural mechanisms underlying lexico-semantic processing play in the chronicity of stuttering remains less clear.

Semantic Processing in Stuttering

The neural processes underlying semantics, specifically the ease and efficiency of lexical access and/or integration, can be evaluated without the demands of overt speech production using event-related potentials (ERPs). ERPs are a noninvasive measure of populations of neurons firing in synchrony (Luck, 2014; Nunez, 1995). Electrophysiological activity is time-locked to specific stimuli and averaged across many trials to provide measureable time-locked components with high temporal resolution. ERPs are ideal for use with children as they are able to quietly sit and listen to linguistic stimuli while their neural activity is recorded. These recorded potentials provide information about underlying neural processes for language.

Ease of lexical access and/or integration is reflected by the N400, an ERP component with negative polarity occurring between 200 and 600 ms after stimulus onset in adults (Kutas & Federmeier, 2011; Kutas & Hillyard, 1980). The N400 can be elicited by a variety of stimuli, including spoken and signed words, drawings, photographs, and objects (Kutas & Federmeier, 2011). Often, this ERP signature is elicited by an unexpected semantic word or semantic violation in sentence level stimuli, and larger N400 amplitudes are elicited by words with less semantic expectancy in a given context (Kutas & Federmeier, 2011; Kutas & Hillyard, 1980). During the processing of visual stimuli, an N400 effect elicited over anterior electrode sites may reflect semantic processing for the visual comprehension of static and/or dynamic continuous images such as video or animation. Visual stimuli incongruent with previous contexts elicit larger anterior N400 activity compared with congruent stimuli in typical adults (Coch, Maron, Wolf, & Holcomb, 2002; Ganis, Kutas, & Sereno, 1996; McPherson & Holcomb, 1999; Sitnikova, Holcomb, & Kuperberg, 2008; Sitnikova, Kuperberg, & Holcomb, 2003; West & Holcomb, 2002). Across development, both N400 amplitudes and latencies decrease, and N400 distributions, generally largest over posterior electrode locations for auditory stimuli, become more focal (i.e., more posterior and less anterior) with age and increasing linguistic proficiency. Thus, smaller N400 amplitudes, earlier N400 peak latencies, and more focal N400 scalp distributions reflect more mature neural processes (Hahne, Eckstein, & Friederici, 2004; Hampton Wray & Weber-Fox, 2013; Holcomb, Coffey, & Neville, 1992; see Friederici, 2006, for a review).

The N400 is often followed by the late positive component (LPC), a late positivity occurring between 500 and 900 ms after stimulus onset in adults. The LPC is thought to index sentence level reanalysis and may be related to effortful integration of verbal meaning (Van Petten & Luka, 2012). Although developmental changes in the LPC have not been studied comprehensively to date, a study by Juottonen, Revonsuo, and Lang (1996) on the processing of semantically incongruous target words within sentences found only an N400 in school-age children; however, an N400–LPC complex was found in adults, revealing that the LPC for semantic processing emerges later in development. On the basis of changes across development in other linguistically based components reflecting sentence level analyses (e.g., P600), it is posited that the amplitude of the LPC increases and the latency of the LPC decreases with age and increased language proficiency (e.g., Hahne et al., 2004; Hampton Wray & Weber-Fox, 2013; Pakulak & Neville, 2010). Changes in morphology of the LPC have been found to be independent of changes in the N400, suggesting that the two components likely index different aspects of linguistic processing (Van Petten & Luka, 2012).

Previous studies using ERPs to evaluate semantic processing in adults who stutter have revealed atypical lexical access, marked by a less efficient biphasic neural pattern for semantic processing in adults who stutter compared with fluent peers, who exhibited the expected monophasic N400 component (Weber-Fox & Hampton, 2008). To better understand the role of neural processes for language closer to the onset of stuttering, neural processes underlying language were evaluated in 4- and 5-year-old CWS and typically fluent peers (Weber-Fox et al., 2013). Despite normal receptive and expressive language abilities, preschool-age CWS exhibited neural patterns for semantic processing that subtly differed from their typically fluent peers. These differences were marked by slightly longer peak latencies for N400s elicited by both semantic canonical and violation conditions in the CWS, suggesting delayed and less efficient lexical access and/or integration in preschool-age CWS compared with fluent peers (Weber-Fox et al., 2013).

Persistence Versus Recovery in Developmental Stuttering

Risk factors have been identified to help better understand stuttering persistence versus recovery, including family history of stuttering, gender, age of onset, and time since onset (Yairi & Ambrose, 1999; Yairi, Ambrose, Paden, & Throneburg, 1996). Speech motor coordination indices, clinical measures of nonword repetition abilities, and articulation proficiency also have a predictive value for stuttering outcomes (Spencer & Weber-Fox, 2014; Walsh et al., 2015). The chronicity of stuttering is also related to developmental differences in neural connectivity necessary for fluent speech production (Chang et al., 2008, 2015, in press; Chow & Chang, 2017).

Previous studies evaluating linguistic factors as a predictor of stuttering persistence versus recovery have yielded inconsistent results. Children who persisted in stuttering over 12 months exhibited significantly lower language comprehension and verbal expression scores, although within the normal range, on portions of the Preschool Language Scale (Zimmerman, Steiner, & Pond, 1979) compared with fluent peers and children who recovered; Preschool Language Scale scores correctly predicted stuttering chronicity in 10 of 12 CWS (Yairi et al., 1996). A separate study identified greater variability in CWS who persisted in stuttering on indices of semantic development, marked by limited change or declining performance over a 12-month period (Watkins & Yairi, 1997). In contrast, a larger study evaluating language abilities in children who persisted and recovered from stuttering over a 4-year period revealed similar language abilities between children who persisted and those who recovered. Specifically, semantic development did not differ between CWS who persisted and recovered, with both groups performing at or above developmental expectations (Watkins, Yairi, & Ambrose, 1999). A recent longitudinal, language sample analysis of CWS between the ages of 4 and 6 years showed that increased growth rate in syntactic ability, but not vocabulary diversity, was predictive of eventual recovery from stuttering (Leech, Ratner, Brown, & Weber, in press).

Given these mixed findings, the use of ERPs as a highly sensitive measure of neural processes underlying language is critical for improving our understanding of language factors involved in persistence or recovery. Previous ERP studies from our laboratory have identified differences in phonological and syntactic processing between school-age children who have recovered versus persisted in stuttering (Mohan & Weber, 2015; Usler & Weber-Fox, 2015). The current study is a retrospective analysis of neural processes underlying semantics, represented by the N400 and LPC, in preschool-age children. Given recent findings of developmental differences in the N400 between 4- and 5-year-old typically developing children (Hampton Wray, 2015), only 5-year-olds were analyzed in the current study to determine whether semantic processing is associated with future persistence or recovery from childhood stuttering. Because the LPC reflects neural processes similar to that of the P600, a component whose elicitation (or lack thereof) has been associated with stuttering chronicity (Usler & Weber-Fox, 2015), LPC elicitation was also included in the analyses. As the children in the current study have been part of a 5-year longitudinal project, we now know which children persisted and which children eventually recovered from stuttering. We hypothesized that neural correlates of semantic processing (indexed by N400/LPC morphology, latency, and distribution) would distinguish 5-year-old children who eventually recovered and persisted in stuttering. More specifically, we expect that children who eventually persisted in stuttering (CWS-ePersisted), on average, would exhibit ERP signatures of immaturity in semantic processing compared with children who eventually recovered (CWS-eRecovered) and children who do not stutter (CWNS), such as (a) a larger N400 mean amplitude for the violation condition, (b) a later N400 peak latency, and (c) a more broadly distributed N400. Given that LPC amplitude likely increases with maturity in lexico-semantic processing, we also hypothesized that the typically developing CWNS would exhibit a more robust LPC effect compared with the other two groups with a history of stuttering.

Method

Participants included 56 children (5 years old) who were a part of the larger longitudinal Purdue Stuttering Project. Participants were tested at two sites, Purdue University (79%) and the University of Iowa (21% of the participants in the current study). Many of the children who participated in the current study were also included in a 2013 study (Weber-Fox et al., 2013). The children were followed over the course of the longitudinal study, and their recovery status was tracked. Children were divided into three groups as follows: children who had no history of stuttering (CWNS; n = 24 [15 boys, nine girls]), CWS-eRecovered (n = 19 [14 boys, five girls]), and CWS-ePersisted (n = 13 [nine boys, four girls]). All children participated in behavioral/clinical and electroencephalographic (EEG) testing sessions, which occurred on separate days within a 7-day time frame. All children also completed a series of kinematic and electromyographic studies. Results from those studies are presented elsewhere (e.g., MacPherson & Smith, 2013; Walsh et al., 2015).

According to parental report, participants had no neurological deficits and showed normal or corrected-to-normal vision. All children passed a hearing screening in both ears administered at 20 dB for 1000, 2000, and 4000 Hz. All children completed an abbreviated version of the Edinburgh Handedness Inventory (Oldfield, 1971). The following children were left-handed: five CWNS (21%), two CWS-eRecovered (11%), and one CWS-ePersisted (8%). No association was found between group and handedness according to a chi-square test of independence, $\chi^2(2, N = 56) = 1.52$, $p = .47$. This study did not control for therapeutic history to recruit the largest number of possible participants. In total, nine CWS-ePersisted and eight CWS-eRecovered participated in therapy for stuttering, indicating that group differences would likely not be attributable to therapeutic effects.

All participants completed a battery of behavioral assessments, including the Columbia Mental Maturity Scale (Burgemeister, Blum, & Lorge, 1972) to assess nonverbal intelligence and the Test for Auditory Comprehension of Language–Third Edition (TACL-3; Carrow-Woolfolk, 1999) to evaluate receptive language skills, including vocabulary. All participants showed nonverbal intelligence and receptive language performance within the normal range. As can be seen in Table 1, groups were comparable in age, nonverbal intelligence, and receptive language abilities. However, there were differences between groups on maternal education, a key factor used in determining a child's socioeconomic status (SES). The highest level of maternal education was determined using a 7-point scale (Hollingshead, 1975), with 4 points for high school education, 5 points for completion of partial college, 6 points for completion of a 4-year college degree, and 7 points for completion of a graduate degree. A nonparametric independent-samples median test revealed significant differences between the three groups in maternal education ($p = .01$), while further analyses revealed that CWNS exhibited a higher maternal education compared with CWS-ePersisted, whereas there were no differences between CWS-eRecovered and CWS-ePersisted or between CWNS and CWS-eRecovered. Median ratings and ranges for each group are provided in Table 1.

To be diagnosed and placed in the CWS group upon entry into the study, participants were required to meet the criteria developed by Yairi and Ambrose (1999). Briefly, a child must have been considered to exhibit stuttering by his or her parent and at least one certified speech-language pathologist, show a stuttering severity rating of 2 or higher on an 8-point (0–7) scale by the parent and the speech pathologist, and exhibit at least three SLDs per 100 syllables of spontaneous speech. For one CWS who eventually recovered, parents reported that the language samples collected during the parent–child and clinician–child interactions were not representative of the child's disfluencies at home and in other contexts. In this case, the project speech-language pathologist assessed the child's fluency during additional interactions during the visit to the laboratory and judged this child to be stuttering based on the observed frequency of SLDs during these additional interactions. A child was considered to have recovered from stuttering when these criteria were no longer satisfied for at least 2 consecutive years.

Sentence Stimuli

Participants watched five cartoon videos of Claymation penguin characters via Presentation® software (Version 9.70, Neurobehavioral Systems, Inc., Berkeley, CA) with accompanying naturally spoken sentences. These stimuli were created in collaboration with the Brain Development Lab at the University of Oregon (Helen Neville, Director). Each story lasted approximately 5–7 min, for a total EEG recording time of approximately 30–40 min including breaks. Each story contained 10 canonical and 10 violation sentences for five different linguistic conditions (semantic, phrase structure, regular verb agreement, irregular verb agreement, and jabberwocky), for a total of 500 sentences across the five stories. The focus of this study was the semantic condition, including the semantically canonical sentences (*The kids are in their beds under their blankets.*) and sentences containing semantic

Table 1. Group mean (*SE*) and ranges for age, maternal education, nonverbal intelligence, and receptive language scores.

Characteristics	CWNS	CWS-eRecovered	CWS-ePersisted	Group statistics
Age	65.29 (0.87)	63.68 (0.82)	65.00 (1.08)	$F(2, 53) < 1$
Range	59–71	59–70	60–70	
Maternal ed	6.5	6	5	$p = .01^*$
Range	3–7	4–7	4–7	
CMMS	114.67 (1.69)	109.79 (2.20)	109.92 (2.24)	$F(2, 53) = 2.11, p = .13$
Range	102–127	95–132	94–122	
TACL-3	121.38 (2.75)	114.84 (3.00)	113.69 (3.59)	$F(2, 53) = 1.95, p = .15$
Range	91–143	91–139	87–136	

Note. Ranges are listed below means when applicable. Ages are given in months. CMMS = Columbia Mental Maturity Scale; CWNS = children who do not stutter; CWS-ePersisted = children who eventually persist; CWS-eRecovered = children who eventually recover; TACL-3 = Test for Auditory Comprehension of Language–Third Edition.

*$p < .05$.

violations (*The kids are in their eyes under their blankets.*).[1] Each child heard 50 canonical and 50 semantic violation sentences (see Table 2). Two scenarios were developed for each story so that a sentence that served as a violation condition in one scenario was counterbalanced with a canonical sentence in a second scenario. Furthermore, each critical word that served as a canonical word in one scenario served as a violation word in a different story so that all critical words were also counterbalanced across stories and participants. Scenario presentation was counterbalanced between and within groups.

Videos were presented on a 47.5-cm monitor positioned approximately 172 cm from the child. Sentences were presented via midline speaker located directly above the monitor on which videos were played. To minimize eye movement, the cartoon subtended a visual angle of approximately 4.9° horizontally and 3.8° vertically. The sound levels of the auditory stimuli (70–75 dB SPL) were calibrated using a B&K (Brüel & Kjær) sound level meter. Given that the cartoon videos provided dynamic visual cues alongside the sentence stimuli, the auditory semantic violations presented violations in meaning and violations of audiovisual congruency. This type of audiovisual semantic violation may engage two separate neural systems underlying the processing of semantics—an anterior N400 elicited by visual information and a central–parietal N400 elicited by auditory information (for a review, see Sitnikova et al., 2008).

Table 2. Examples of sentence stimuli for each condition.

Sentence type	Example sentences
Semantic canonical	Grandpa needs to clean the room up. He ate all his dinner quickly. They play a game in the snow.
Semantic violation	Grandpa needs to clean the *smile* up. He ate all his *door* quickly. They play a *hand* in the snow.

Note. Example sentences reprinted from Weber-Fox et al. (2013), Copyright © 2013, with permission from Elsevier.

Procedures

Participants were seated in a sound-attenuating booth, and a researcher sat with the child throughout the experiment to encourage the child to remain still and attend to the stories. Each child received the following instructions:

> While you sit in this chair, you will watch and listen to five stories about a penguin and his family and friends. It is important to keep your arms, legs, and head as still as you can while you are watching the stories. At the end of each story, you will have a break where you can move and stretch if you need to. You will also get to pick out a sticker and place it on your activity sheet at the end of each story. When you have five stickers on your sheet, you will be finished and will get to pick out a toy!

These procedures were created and previously used by our laboratory (Weber-Fox et al., 2013, pp. 210).[2]

EEG Recording

Continuous EEG signals were recorded using Neuroscan 4.2 data acquisition software via 32 Ag -AgCl electrodes secured in an elastic cap (Quik-cap, Compumedics Neuroscan, Inc., Charlotte, NC). Twenty-eight electrodes were placed over homologous locations of the two hemispheres according to the criteria of the international 10–10 system (American Electroencephalographic Society, 1994). Electrode locations were as follows: lateral sites F7/8, FT7/8, T7/8, TP7/8, and P7/8; medial–lateral sites F3/4, FC3/4, C3/4, CP3/4, P3/4, and O1/2; and midline sites Fz, FCz, Cz, CPz, Pz, and Oz. Continuous EEG data were recorded within a bandpass of 0.1–100 Hz and digitized online at a rate of 512 Hz (Neuroscan 4.2). EEG data were referenced online to linked electrodes positioned over the left and right mastoids. Additional electrodes were placed on the right and left outer canthi to capture horizontal movement (HEOG) and on the left inferior and superior orbital ridges to capture vertical eye movement (VEOG). Electrode impedances were adjusted to 5 kΩ or less for all sites, with the exception of VEOG and HEOG, which were adjusted to 10 kΩ or less.

ERP Analyses

All data analyses were completed using EEGLAB (Delorme & Makeig, 2004) and ERPLAB (Lopez-Calderon & Luck, 2014) in MATLAB (MathWorks). Offline, for ease of analysis, EEG data were down-sampled to 256 Hz and low-pass filtered at 30 Hz. Independent component analysis was performed and assessed by two independent raters to detect eye movement artifact components, which were subsequently removed from the data. EEG data were time-locked to the onset of target words (underlined in Table 2) and epoched from 200 ms before to 2000 ms after the onset of each target word. The 200-ms period before the onset of the word for each epoch served as the baseline period, and each epoch was baseline corrected before averaging. Artifact rejection was completed using an automatic detection algorithm for data changing 100 μV or more within a 200-ms window, which moved through the entire data set at 50-ms increments. Artifact-free trials were averaged by condition for each participant. Separate grand averages for semantically canonical and violation conditions were formed for each group: CWNS, CWS-eRecovered, and CWS-ePersisted. The mean number and range of accepted trials are detailed in Table 3 and did not differ between groups: canonical accepted, $F(2, 53) < 1$; violation accepted, $F(2, 53) = 2.82$, $p = .07$. ERPs for the CWS-eRecovered group were products of the average of approximately 38 trials, compared with the 40 averaged trials for CWNS and CWS-ePersisted.

[1]Example sentences reprinted from Weber-Fox et al. (2013), Copyright © 2013, with permission from Elsevier.
[2]Instructions reprinted from Weber-Fox et al. (2013), Copyright © 2013, with permission from Elsevier.

Table 3. Means and standard errors for the number of trials accepted for each condition and group with associated ranges for each group.

Sentence type	CWNS	CWS-eRecovered	CWS-ePersisted
Canonical condition	39.67 (0.69)	39.53 (0.56)	39.38 (0.90)
Range	31–44	31–43	33–44
Violation condition	40.13 (0.57)	38.37 (0.79)	40.54 (0.58)
Range	36–43	30–42	36–43

Note. CWNS = children who do not stutter; CWS-ePersisted = children who eventually persist; CWS-eRecovered = children who eventually recover.

The mean amplitudes of the N400 and the LPC, elicited by canonical words and violations of semantic expectation, were measured for each participant. Mean amplitudes were calculated as the amplitude (in microvolts) relative to baseline within the designated temporal window (Luck, 2014). The peak latencies of the N400 elicited by semantic violations were measured as the time (in milliseconds) of the most negative point within the specified temporal window (Luck, 2014). Peak latency measures for the canonical condition were not included in the current study because N400 components with reliable peaks were not consistently elicited for expected, semantically appropriate words. Because of the lack of defined, reliable peaks over lateral sites, measurement of N400 peak latency was restricted to medial–lateral and midline sites. The peak latency for the LPC was also not measured because this component was broad, without consistent, reliable peaks. Temporal windows for analyses were selected based on existing literature on semantic processing in young children (Hahne et al., 2004; Hampton Wray & Weber-Fox, 2013; Holcomb et al., 1992; Weber-Fox et al., 2013) and visual inspection of the current data. Mean amplitudes and peak latencies of the N400 were measured between 300 and 800 ms, and mean amplitudes of the LPC were measured between 1100 and 1700 ms. In young children, later time windows compared with those evaluated in adults are necessary, as neural processes for language are generally slower in young children (Hahne et al., 2004; Hampton Wray & Weber-Fox, 2013; Holcomb et al., 1992; Weber-Fox et al., 2013).

Statistical analyses of the ERPs were performed to evaluate overall differences in mean amplitude, peak latency, and distribution of components between groups. Repeated-measures omnibus ANOVAs were performed including the between-group factor of group (CWNS, CWS-eRecovered, and CWS-ePersisted) and within-group factors of condition (control, violation), hemisphere (left, right), anterior/posterior distribution (frontal, frontal–temporal, central, central–parietal, parietal, occipital), and laterality (lateral, medial–lateral). If a significant interaction with group was revealed, further analysis using a step-down ANOVA was completed to provide greater specificity regarding the nature of the interaction between groups. On the basis of previous evidence that the dynamic audiovisual stimuli we presented may elicit both anterior and posterior N400s (Sitnikova et al., 2008) and to test a priori hypotheses of differences in distribution of the N400 between groups, additional, separate, repeated measures ANOVAs were performed for two regions of interest (ROIs): anterior (F3, Fz, F4, FC3, FCz, FC4) and posterior (C3, Cz, C4, CP3, CPz, CP4, P3, Pz, P4) electrode sites (see Figure 1). Similar anterior–posterior electrode distributions have been analyzed in previous ERP investigations of N400/LPC elicitation (e.g., Sitnikova et al., 2003). Significance values were set at $p < .05$. For all repeated measures with greater than 1 *df* in the numerator, the Huynh–Feldt adjusted *p* values are reported (Hays, 1994). Effect sizes, indexed by partial eta-squared (η_p^2), are reported for all significant effects.

Results

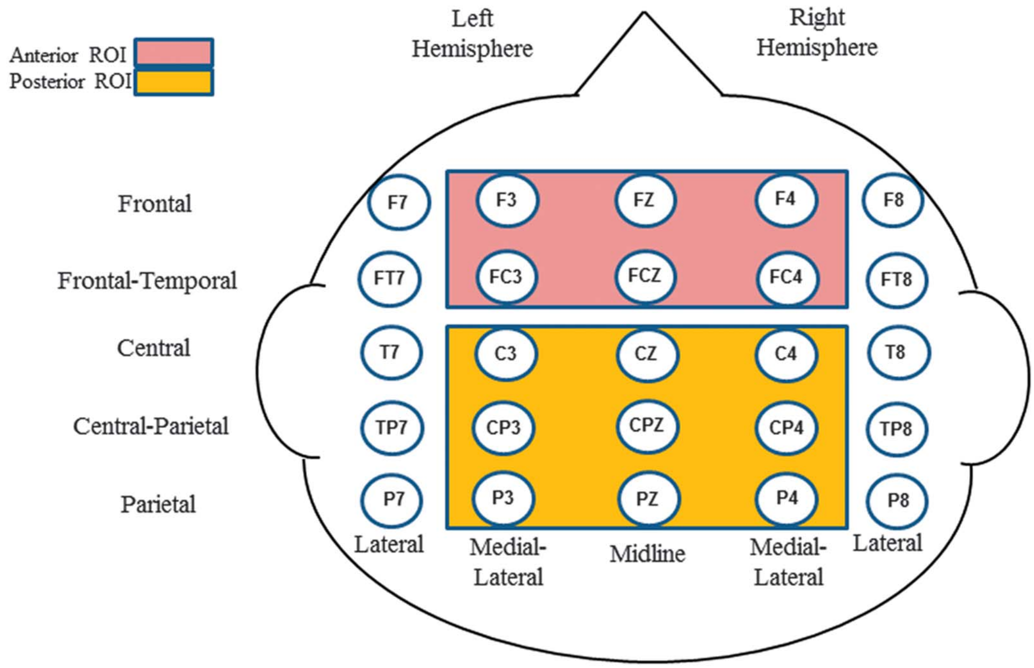
Grand-averaged ERP waveforms elicited by the semantic canonical and violation conditions for the CWNS, CWS-eRecovered, and CWS-ePersisted are illustrated in Figures 2, 3, and 4, respectively. Group statistics for elicited ERP mean amplitudes are provided for the N400 (see Table 4) and LPC (see Table 5).

N400 Analyses

N400 (300–800 ms): Omnibus Analyses

Across all three groups, a larger negativity (N400 effect) was elicited by semantic violations compared with canonical sentences, $F(1, 53) = 11.03$, $p = .002$, $\eta_p^2 = .17$. N400 mean amplitudes did not differ between CWNS, CWS-ePersisted, and CWS-eRecovered, $F(2, 53) = 0.77$, $p = .47$; however, a Group × Condition × Hemisphere × Laterality interaction was observed, $F(2, 53) = 3.68$, $p = .03$, $\eta_p^2 = .12$. Step-down ANOVAs of group comparisons revealed significant interactions between group, hemisphere, and laterality ($ps \leq .04$). Larger N400 amplitudes elicited by the violation compared with the canonical condition were most prominent over left lateral electrodes for CWS-eRecovered, with decreasing amplitudes moving from left to right across the scalp (see Figure 5). No apparent N400 effect was elicited for the CWS-eRecovered over the right hemisphere. An opposite hemispheric N400 topography was observed for CWS-ePersisted—an N400 was observed across the scalp, but smallest in amplitude over left lateral sites. CWNS, on the other hand, exhibited broad N400s across both the left and right hemispheres. No group differences were observed in regard to N400 peak latency to semantic violations; there was no significant group effect, $F(2, 53) = 0.56$, $p = .58$, and there were no significant interactions with group.

Figure 1. Electrode configuration with regions of interest (ROIs).



N400 (300–800 ms): Anterior ROI Analyses

In the anterior ROI for each group, larger N400 mean amplitudes were elicited by the semantic violation than the canonical sentences, $F(1, 53) = 8.85$, $p = .004$, $\eta_p^2 = .14$. A significant interaction of group and condition revealed differences between groups, $F(2, 53) = 3.43$, $p = .04$, $\eta_p^2 = .12$. Step-down ANOVAs of pairwise comparisons between groups revealed that CWS-eRecovered exhibited

Figure 2. Grand-averaged event-related potentials of all participants who do not stutter (CWNS) elicited by the semantic canonical (black) and violation (red) conditions, showing N400 and LPC waveforms. Grand averages were low-pass filtered at 12 Hz for display purposes only. Negative is plotted upward. Scalp topographic maps illustrate neural activity distribution (in microvolts) during elicitation of the N400 and late positive component (LPC).

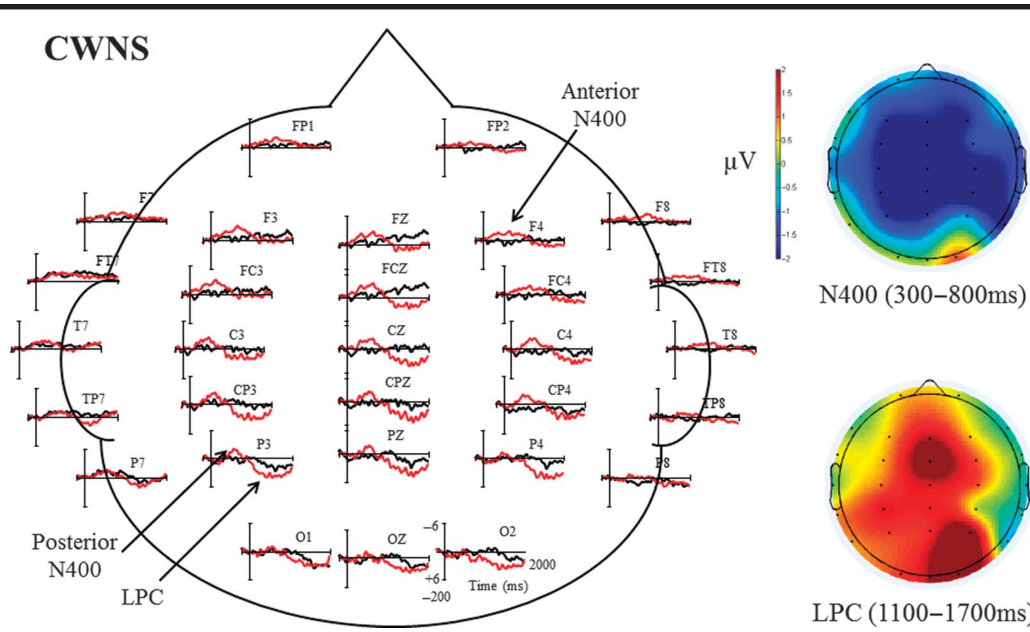
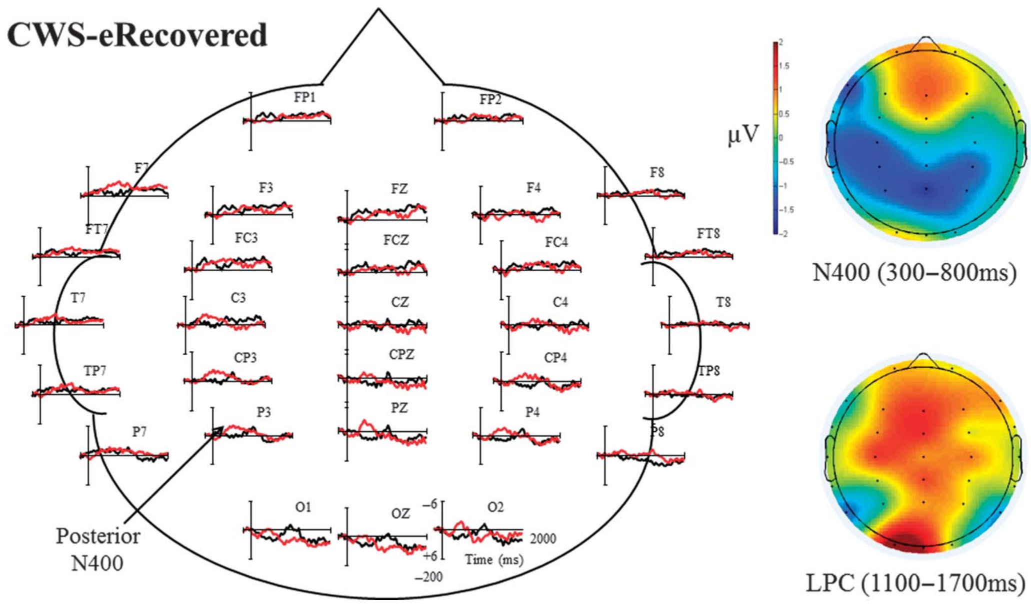


Figure 3. Grand-averaged event-related potentials of all participants who will recover from stuttering (CWS-eRecovered) elicited by the semantic canonical (black) and violation (red) conditions, showing N400 waveforms. Negative is plotted upward. Scalp topographic maps illustrate neural activity distribution (in microvolts) during elicitation of the N400 and late positive component (LPC).



smaller N400 mean amplitudes for the violation compared with CWS-ePersisted for the anterior ROI, $F(1, 30) = 6.77$, $p = .01$, $\eta_p^2 = .18$. Comparisons of the N400 effect—ERP difference waveforms of semantic violation minus semantic canonical responses—for CWS-eRecovered and CWS-ePersisted are illustrated in Figure 6. A Group × Condition interaction was not significant between CWNS and CWS-ePersisted, $F(1, 35) = 0.54$, $p = .47$, but neared significance between CWNS and CWS-eRecovered, $F(1, 41) = 4.10$, $p = .05$. The peak latency of the N400 elicited by semantic violations in the anterior ROI did not differ between groups, $F(2, 53) = 0.14$, $p = .87$. Over anterior electrode sites, N400

Figure 4. Grand-averaged event-related potentials of all participants who will persist in stuttering (CWS-ePersisted) elicited by the semantic canonical (black) and violation (red) conditions, showing N400 waveforms. Negative is plotted upward. Scalp topographic maps illustrate neural activity distribution (in microvolts) during elicitation of the N400 and late positive component (LPC).

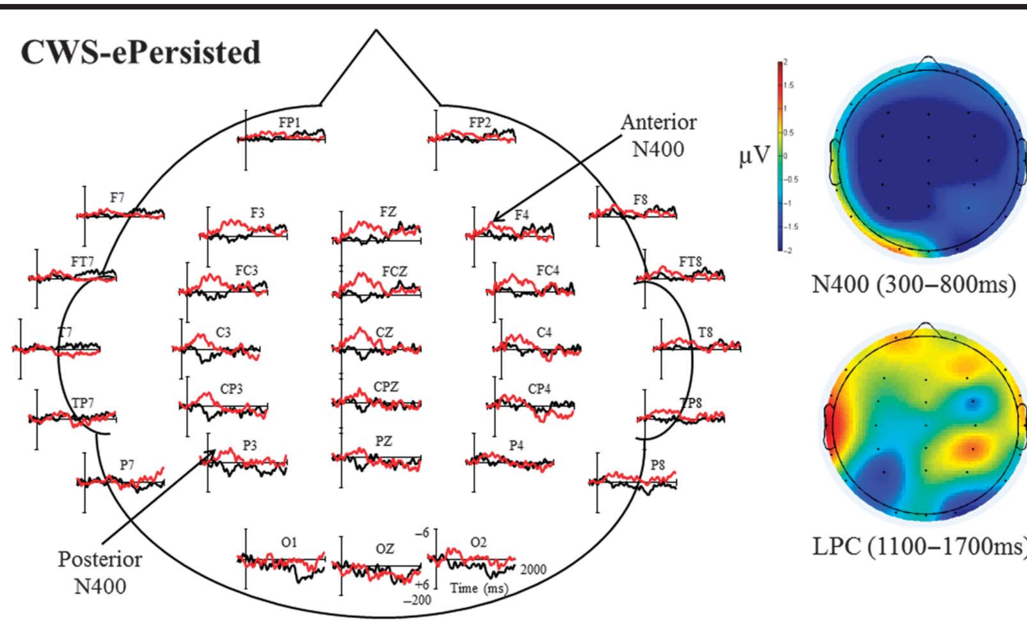


Table 4. ANOVA results for N400 mean amplitude effects.

Statistical analyses	*F*	*df*	*p*	η_p^2
Omnibus analyses				
N400 mean amplitude (300–800 ms)				
All groups				
Condition	11.03	1, 53	.002*	.17
Group × Condition	0.77	2, 53	.47	.03
Group × Condition × Laterality	2.42	2, 53	.10	.08
Group × Condition × Hemisphere × Laterality	3.68	2, 53	.03*	.12
Step-down ANOVA group comparisons				
CWNS and CWS-ePersisted				
Condition	9.81	1, 35	.003*	.22
Group × Condition	0.05	1, 35	.82	.001
Group × Condition × Laterality	1.04	1, 35	.32	.03
Group × Condition × Hemisphere × Laterality	1.31	1, 35	.26	.04
CWNS and CWS-eRecovered				
Condition	5.31	1, 41	.03*	.12
Group × Condition	0.92	1, 41	.34	.02
Group × Condition × Laterality	2.03	1, 41	.16	.05
Group × Condition × Hemisphere × Laterality	3.38	1, 41	.07	.08
CWS-eRecovered and CWS-ePersisted				
Condition	8.50	1, 30	.01*	.22
Group × Condition	1.91	1, 30	.18	.06
Group × Condition × Laterality	4.46	1, 30	.04*	.13
Group × Condition × Hemisphere × Laterality	6.45	1, 30	.02*	.18
Anterior ROI analyses				
N400 mean amplitude (300–800 ms)				
All groups				
Condition	8.85	1, 53	.004*	.14
Group × Condition	3.43	2, 53	.04*	.12
Step-down ANOVA group comparisons				
CWNS and CWS-ePersisted				
Condition	12.82	1, 35	.001*	.27
Group × Condition	0.54	1, 35	.47	.02
CWNS and CWS-eRecovered				
Condition	2.10	1, 41	.16	.05
Group × Condition	4.10	1, 41	.05	.09
CWS-eRecovered and CWS-ePersisted				
Condition	4.37	1, 30	.045*	.13
Group × Condition	6.77	1, 30	.01*	.18
Posterior ROI analyses				
N400 mean amplitude (300–800 ms)				
All groups				
Condition	11.47	1, 53	.001*	.18
Group × Condition	0.53	2, 53	.59	.02

Note. ANOVA = analysis of variance; CWNS = children who do not stutter; CWS-ePersisted = children who eventually persist; CWS-eRecovered = children who eventually recover; ROI = region of interest.

*$p < .05$.

amplitude, but not latency, distinguished those who will eventually recover from stuttering from those who will eventually persist in stuttering. In addition, N400 elicitation did not differ between those who will persist in stuttering and fluent controls. As illustrated in Figure 7, a reduced N400 effect distinguished the recovered group from the other two groups across the anterior ROI. Despite these group differences, a significant overlap in ERP elicitation was found across the groups. As Figure 8 reveals, there was

Table 5. ANOVA results for LPC mean amplitude effects.

Statistical analyses	*F*	*df*	*p*	η_p^2
LPC mean amplitude (1100–1700 ms)				
All groups				
Condition	0.85	1, 53	.36	.02
Group × Condition	0.13	2, 53	.88	.01
Group × Condition × Laterality	3.56	2, 53	.04*	.12
Step-down ANOVA group comparisons				
CWNS and CWS-ePersisted				
Condition	0.47	1, 35	.50	.01
Group × Condition	0.17	1, 35	.68	.01
Group × Condition × Laterality	6.74	1, 35	.01*	.16
CWNS and CWS-eRecovered				
Condition	1.22	1, 41	.28	.03
Group × Condition	0.12	1, 41	.73	.003
Group × Condition × Laterality	0.40	1, 41	.53	.01
CWS-eRecovered and CWS-ePersisted				
Condition	0.28	1, 30	.60	.01
Group × Condition	0.04	1, 30	.85	.001
Group × Condition × Laterality	3.67	1, 30	.07	.11

Note. ANOVA = analysis of variance; CWNS = children who do not stutter; CWS-ePersisted = children who eventually persist; CWS-eRecovered = children who eventually recover; LPC = late positive component.

*$p < .05$.

considerable individual variability in the N400 effect across the anterior ROI.

N400 (300–800 ms): Posterior ROI Analysis

Similar to the anterior ROI, a significant N400 effect was observed for the posterior ROI across groups,

Figure 5. N400 mean amplitudes (and standard errors) elicited by the violation condition across hemispheric lateral and medial–lateral electrode sites in the left and right hemispheres. Larger N400 amplitudes were most prominent over left lateral electrodes for participants who will eventually recover from stuttering (CWS-eRecovered), with decreasing amplitudes moving from left to right across the scalp. Negative is plotted upward. CWNS = children who do not stutter; CWS-ePersisted = children who eventually persist; CWS-eRecovered = children who eventually recover.

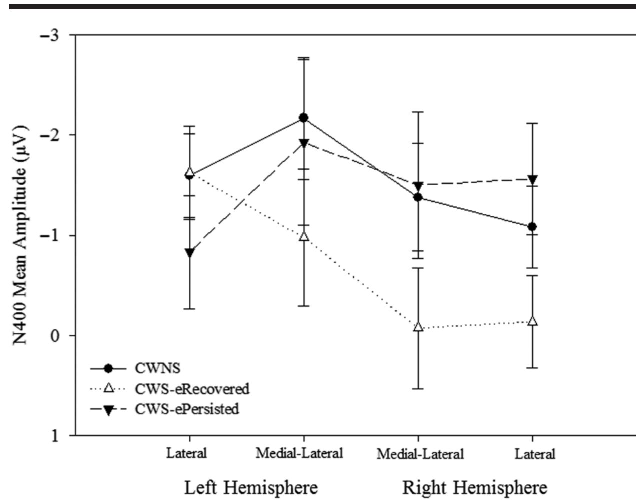
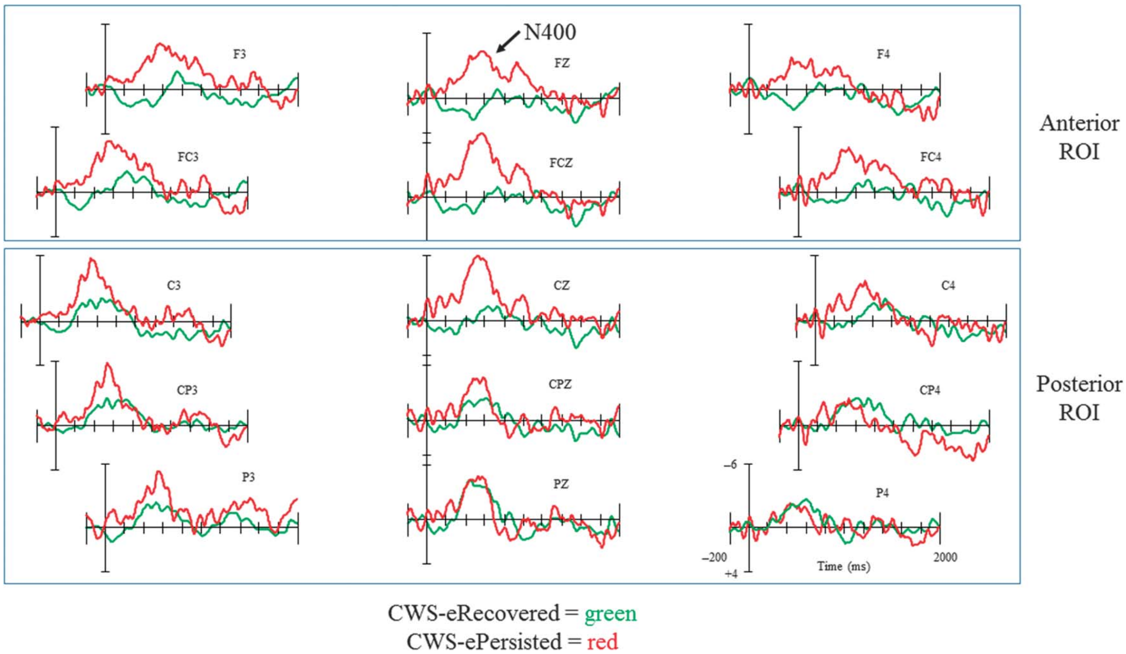
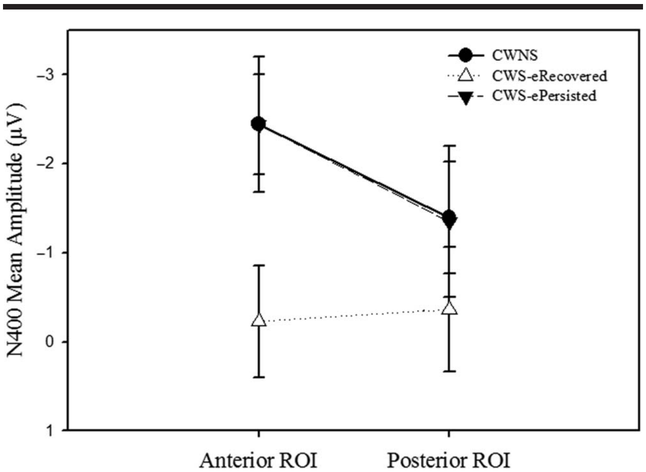


Figure 6. Comparisons of event-related potential difference waveforms in anterior and posterior regions of interest between participants who will recover (CWS-eRecovered; green) and participants who will persist (CWS-ePersisted; red). Group differences in N400 effects are evident across anterior electrode sites. Negative is plotted upward. ROI = region of interest.



$F(1, 53) = 11.47$, $p = .001$, $\eta_p^2 = .18$. However, unlike the results for the anterior ROI, the Group × Condition interaction was not significant for N400 mean amplitude, $F(2, 53) = 0.53$, $p = .59$. The N400 effect in the posterior ROI did not distinguish CWS-eRecovered from CWNS and/or CWS-ePersisted (see Figure 7). In addition, no group differences in N400 peak latency elicited by semantic violations were observed for the posterior ROI, $F(2, 53) = 0.80$, $p = .46$.

Figure 7. N400 mean amplitude group means (and standard errors) for the violation condition over anterior (F3, Fz, F4, FC3, FCz, FC4) and posterior (C3, Cz, C4, CP3, CPz, CP4, P3, Pz, P4) electrode sites. Negative is plotted upward. CWNS = children who do not stutter; CWS-ePersisted = children who eventually persist; CWS-eRecovered = children who eventually recover; ROI = region of interest.



LPC Analyses

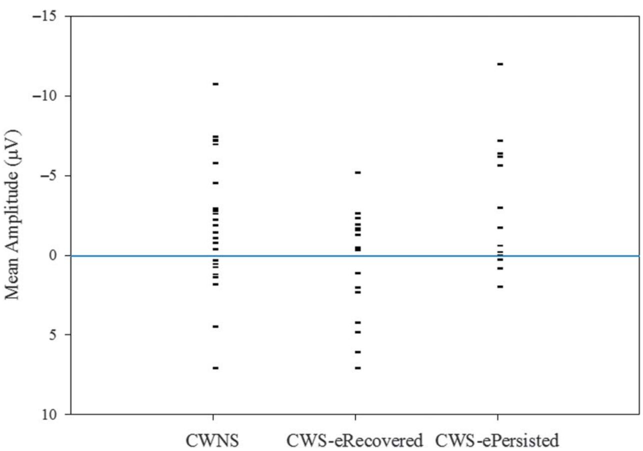
LPC Mean Amplitude (1100–1700 ms): Omnibus Analyses

An overall LPC mean amplitude condition effect was not significant, $F(1, 53) = 0.85$, $p = .36$. However, LPC mean amplitude for the CWNS, CWS-ePersisted, and CWS-eRecovered groups differed by condition and laterality, $F(2, 53) = 3.56$, $p = .04$, $\eta_p^2 = .12$. To better understand the nature of this interaction, step-down ANOVAs with the same structure as described above were used to compare the LPC mean amplitude in pairwise group comparisons. As shown in Figure 9, a Group × Condition × Laterality interaction was significant between CWNS and CWS-ePersisted, $F(1, 35) = 6.74$, $p = .01$, $\eta_p^2 = .16$, but neither between CWNS and CWS-eRecovered nor between CWS-eRecovered and CWS-ePersisted. Overall, CWNS exhibited the largest LPC mean amplitude over medial–lateral sites, whereas the LPC was not apparent in the CWS-ePersisted. The LPC mean amplitude was intermediary in amplitude for CWS-eRecovered, who did not differ from the other two groups.

Associations Between ERP Effects, TACL-3, and SES

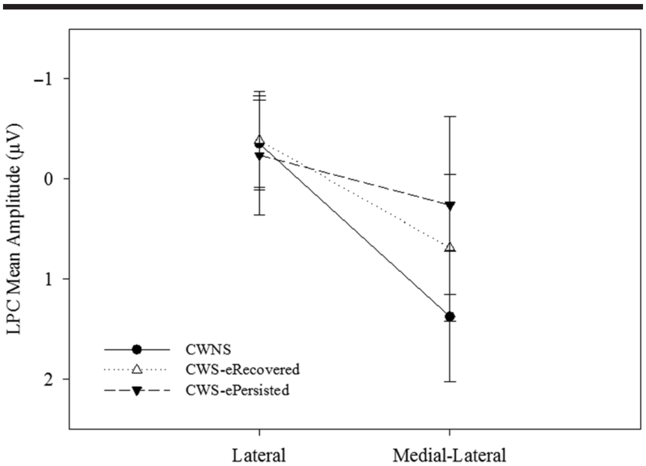
All three groups displayed similar nonverbal intelligence and language proficiencies as measured by behavioral

Figure 8. Scatter plot showing the distribution of mean amplitudes of the N400 effect (300–800 ms) over the anterior region of interest (averaged across anterior electrodes: F3, Fz, F4, FC3, FCz, FC4). The N400 effect represents the difference between the violation and canonical conditions (violation minus canonical). This distribution reveals individual differences within groups of those who will persist (CWS-ePersisted), those who will recover (CWS-eRecovered), and participants who do not stutter (CWNS). Each datum represents a single child. Negative is plotted upward.



tests. Given that group differences in SES were observed between the CWS-ePersisted and CWNS, SES was included as a covariate in our omnibus statistical analyses of the N400 and LPC. However, no significant effects of SES were observed. Pearson correlations were also performed to determine possible associations between elicited ERP effects and assessment scores for semantic ability. No significant correlations were observed between individual TACL-3 scores and amplitudes of the N400 and LPC elicited by semantic violations at the Pz electrode site (which exhibited stereotypical N400 and LPC effects). This lack of apparent association between TACL-3 scores and ERP morphology is not surprising. Individuals with neurodevelopmental disorders often exhibit different developmental time courses across skills, along with differences in the brain networks and neural processes underlying a given skill, despite performance on standardized tests that is within normal limits (Karmiloff-Smith, 2009). Thus, normal behavioral performance on the TACL-3 does not necessarily correspond to semantic processing comparable with typically developing peers.

Figure 9. Late positive component (LPC) mean amplitudes (and standard errors) elicited by the violation condition across lateral and medial–lateral electrode sites. Negative is plotted upward. CWNS = children who do not stutter; CWS-ePersisted = children who eventually persist; CWS-eRecovered = children who eventually recover.



Discussion

We investigated neural indices of semantic processing in 5-year-old CWS based on eventual recovery (CWS-eRecovered) or persistence (CWS-ePersisted) status as compared with fluent peers (CWNS). Neural processes for language differentiated children based on eventual stuttering status (persistence or recovery).

N400 Amplitude Distinguishes CWS Who Will Eventually Recover From Those Who Will Persist

We hypothesized that differences in N400/LPC morphology, latency, and distribution might distinguish 5-year-old children who will eventually recover from those who will persist in stuttering. Our results differed from our hypotheses in a number of aspects. First, CWS-ePersisted, on average, exhibited N400s elicited by semantic violations that were similar in overall amplitude to the CWNS. We had originally hypothesized that children whose stuttering will persist would exhibit ERP signatures indicating immaturity in semantic processing compared with CWNS because previous ERP studies of slightly older children who were stuttering indicated lags in neural development for syntactic and phonological processing (Mohan & Weber, 2015; Usler & Weber-Fox, 2015). However, this hypothesis was not confirmed. Second, the current study found no differences in N400 peak latency across the three groups, which were confirmed by overlapping timing of the peaks in the difference waves (see Figure 6). A previous study that included a broader age range of children, 4 and 5 years, observed N400 peak latency differences between CWS and CWNS (Weber-Fox et al., 2013). The more refined groupings of the current study indicate that speed of lexical processing is similar between CWS-ePersisted, CWS-eRecovered, and CWNS at the age of 5 years.

Interestingly, differences in the hemispheric laterality of N400 amplitudes distinguished our two groups who stutter. A right-lateralized N400 effect was observed in CWS-ePersisted, whereas N400 amplitudes were larger over left lateral electrodes for CWS-eRecovered—N400 mean amplitudes elicited by the violation condition were most prominent over the left hemisphere. This hemispheric difference is aligned with evidence from neuroimaging research that suggests that childhood stuttering is associated with attenuated left-hemisphere frontal and temporal anatomy and physiology (Chang et al., 2008, 2015). Increased right-hemisphere activation, perhaps compensatory in nature, has been associated with adult stuttering (Kell et al., 2009; Neef et al., 2011; Preibisch et al., 2003). Together with previous findings, the current findings suggest different patterns of neural activation for semantic processing over the left and right hemispheres in young children who will eventually persist in versus recover from stuttering and may reflect different patterns of neural connectivity during childhood in these two groups.

ROI analyses also revealed group differences in N400 amplitude between CWS who would eventually persist in or recover from stuttering over anterior electrode sites. CWS-ePersisted exhibited an anterior N400 effect, which has been associated with the detection of semantic violations in regard to the contextual framework of the visual stimuli. In the current study, additional contextual cues in the form of visual information were provided in the accompanying cartoon videos. This contextual information could have led to stronger expectations of the subsequent word(s). When this expectation was violated, the CWS-ePersisted exhibited a more anterior neural response compared with the CWS-eRecovered. This anterior N400 effect is evoked during difficulty integrating context between continuously presented visual images (Sitnikova et al., 2008). Thus, it is speculated that CWS-ePersisted relied on the dynamic visuals of the cartoon in aiding their processing of the auditory semantic violations. Visual inspection of ERP waveforms from a previous study of language processing in young CWS (Weber-Fox et al., 2013) revealed that N400 amplitude differences may have also been present in earlier data; however, with the CWS-ePersisted and CWS-eRecovered combined into one group, differences did not reach statistical significance.

When greater reliance is placed on surrounding context for the integration or understanding of a given word, an unexpected or semantically incongruous word requires recruitment of additional neural resources to process the word, resulting in larger amplitude, more broadly distributed N400 components. With age and proficiency, more skilled language users exhibit decreased reliance on sentence context to integrate semantic information; there is a marked decrease on the contextual reliance with age and increased language abilities, reflected by smaller N400 mean amplitudes with maturation. Smaller N400 mean amplitudes elicited by semantic violations over anterior sites suggest more mature neural functions mediating semantic processing in CWS-eRecovered compared with their persisting peers. This interpretation is supported by previous research on the N400 elicitation in children (Hahne et al., 2004; Hampton Wray & Weber-Fox, 2013; Holcomb et al., 1992). A cross-sectional study of children and adults aged 5–26 years revealed that mean amplitudes of the N400 decreased with age and distribution of the N400 became more focal with age, marked by a more posterior distribution (Holcomb et al., 1992). These results were interpreted as younger children relying more heavily on sentence context as a processing strategy compared with older children and adults, which mirrors results in behavioral studies (Bates et al., 1984; Bever, 1970; Hirsh-Pasek & Golinkoff, 1996; Lindner, 2003; Strohner & Nelson, 1974; Thal & Flores, 2001).

The current findings extend previous results from a study of neural processes underlying language in 4- to 5-year-old CWS (Weber-Fox et al., 2013). Weber-Fox and colleagues (2013) did not observe differences in N400 mean amplitude between groups of CWS and CWNS. In addition to including 4-year-olds in their analyses, that study combined CWS who would eventually persist and those who would recover into one group because the status of persistence or recovery was not yet known. When separating CWS based on eventual diagnosis, we observed differences in N400 mean amplitude specific to eventual recovery status. The ERP correlates of semantic ability per se may not distinguish between CWS and CWNS at the age of 5 years. This finding was frankly surprising and contrary to our hypothesis. However, this finding of typical semantic development for CWS is consistent with previous ERP studies of slightly older children (e.g., Usler & Weber-Fox, 2015), a longitudinal analysis of language samples (e.g., Leech et al., in press), and previous mappings of language development associated with stuttering persistence and recovery (Watkins & Yairi, 1997). Alternately, it appears that the relatively advanced semantic abilities of a subset of CWS may either bootstrap eventual recovery or serve as a buffer against eventual persistence. The current findings highlight the benefits of and need for more studies of young CWS that can focus on specific developmental windows and include children for whom eventual recovery status is known.

LPC Amplitude Distinguishes CWNS From CWS-eRecovered and CWS-ePersisted

Differences between the CWNS, CWS-eRecovered, and CWS-ePersisted were also found in the amplitude of the LPC elicited by semantic violations. Previous studies have suggested that elicitation of the LPC may reflect a multitude of positive deflections differing in spatial distribution related to postlexical sentence-level evaluative reanalysis (for a review, see Van Petten & Luka, 2012), including an attempt to revise sentence parsing (Friederici, Hahne, & Mecklinger, 1996), conflict monitoring processes (Kutas, DeLong, & Smith, 2011), and the disconfirmation of lexical predictions (Thornhill & Van Petten, 2012). Previous studies of semantic processing using video stimuli also found an increased posterior LPC effect after an increased anterior N400 to contextually inappropriate objects compared with appropriate objects (Sitnikova et al., 2003). Given that our paradigm included auditory sentences with semantic violations in the context of complex visual scenes, the LPC likely reflected a reanalysis after detection of the auditory semantic error during an otherwise congruent dynamic scene (Sitnikova et al., 2003).

LPC mean amplitude was largest for CWNS and smallest for CWS-ePersisted over medial–lateral sites, whereas the recovered group exhibited an intermediary LPC compared with the other two groups. We speculate that CWNS exhibit more mature neural mechanisms for postlexical processing compared with CWS-eRecovered and CWS-ePersisted and, as a result, bear an increased cognitive cost by the reprocessing of the detected semantic violation (Van Petten & Luka, 2012). In the current study, subjects were matched for age and receptive language but differed in SES. Although this difference may at least in part contribute to the differences in mean amplitudes for the LPC observed between groups, SES did not distinguish our groups who will eventually recover from or persist in stuttering. Furthermore, the LPC appears to have not yet emerged for those with persistent stuttering, suggesting possible maturational delay for some aspects of semantic processing. Juottonen et al. (1996) suggest that the N400 and LPC differ in the implicit versus explicit nature of processing and the ability to integrate verbal information into semantic memory. LPC amplitude differences may represent the explicit recognition of complex semantic information in memory, with the lack of an LPC in children indicating an inability to do this. Although information regarding the development of the LPC is limited, the LPC is likely related to the P600, a component that reflects reanalysis or reprocessing of information after a violation of a rule-based expectancy (Yamada & Neville, 2007). Previous studies have revealed differences in P600 mean amplitudes as a function of age (Hahne et al., 2004), language proficiency (Hampton Wray & Weber-Fox, 2013; Pakulak & Neville, 2010), and SES (Pakulak & Neville, 2010). Together with previous findings, the reduced or absent LPC in both CWS groups may reflect less mature, later processes for semantics compared with typically fluent peers.

Theoretical Implications

Our findings support the view that developmental stuttering is a heterogeneous and multifactorial disorder involving atypical or immature neural correlates for language processing (Smith & Weber, 2017). N400/LPC elicitation differed between CWS who will eventually recover from or persist in stuttering and their fluent peers, but considerable individual differences were observed between participants. Thus, semantic processing, as indexed by N400/LPC elicitation, is likely only a single factor associated with the disorder. Of greater etiological significance may be the effect of dyssynchronous development between various aspects of language (Anderson & Conture, 2000; Hall & Burgess, 2000). Atypical lexical development and possible dyssynchrony between lexical and syntactic abilities have been associated with increased speech disfluency (Hall, 1996, 1999; Hall et al., 1993).

Atypical processing of lexico-semantics and related effects of other aspects of language likely contribute to decreasing overall cognitive control of an unstable speech motor system during speech production. A convergence of evidence supports the notion that the speech motor systems of individuals who stutter are particularly susceptible to the interference of other cognitive processes, with stuttering resulting when higher-level cognitive loads supersede the processing capacity necessary for fluent speech (Adams, 1990). A series of behavioral studies by Bosshardt and colleagues have found evidence that increasing cognitive demands and atypical lexico-semantic abilities contribute to the breakdown of speech production in adults who stutter (Bosshardt, 1993, 1999, 2002; Bosshardt, Ballmer, & de Nil, 2002; Bosshardt & Fransen, 1996). Bosshardt and Fransen (1996) noted that adults who stutter exhibited a decreased speed of semantic encoding, but not speed of lexical access, compared with fluent controls. It is likely that the efficiency of neural processes underlying semantic processing may play a role in the persistence in or recovery from stuttering in a dynamic association with other higher-level linguistic, cognitive, and psychosocial factors that produce cognitive loads on the speech motor system.

Kinematic studies have revealed that neuromotor patterning of oral muscles of school-age children with persistent stuttering remains relatively unstable compared with those who have recovered and typically fluent children, suggesting that recovery from stuttering is related to catching up to their fluent peers in speech motor development (Usler et al., 2017). The greater speech motor plasticity that characterizes some children with persistent stuttering may indicate a period of dynamic speech development associated with language acquisition (Goffman, 2010). In contrast, the speech motor abilities of children who recovered from stuttering have stabilized to the level of typically fluent children. Similar to speech motor development, the CWS-eRecovered in our current study may undergo a relatively accelerated maturation of linguistic processes, which is reflected in the comparably advanced morphology of N400 elicitation compared with CWS-ePersisted and even CWNS. This precocious development in language processing at the age of 5 years may serve as one catalyst toward the pathway for recovery from stuttering. Our findings are consistent with those of recent neuroimaging studies reporting atypical gray matter development in Broca's area in people who stutter (Beal et al., 2015), maturational differences between CWS and CWNS in white matter connectivity in the inferior frontal gyrus (Chang et al., 2015), and different developmental trajectories in the growth of white matter tracts between children who persisted in versus recovered from stuttering (Chow & Chang, 2017). In that study, Chow and Chang revealed relatively slower growth in fractional anisotropy of white matter pathways, including the arcuate fasciculus, that connect frontotemporal and motor brain regions to be characteristic of persistent stuttering.

Findings from our laboratory highlight the fact that neural indicators of stuttering status are not static but instead are dynamic, reflecting developmental changes related to more recently acquired linguistic proficiencies. A previous study of slightly older CWS (6–7 years old) divided children based on persistence and recovery status at the time of the study. In these older, school-age children, no differences were observed in neural indices for lexical access between children who were persisting in stuttering, children who had recovered from stuttering, and fluent controls (Usler & Weber-Fox, 2015). This suggests that the earlier maturation of semantic processing observed in the current study in 5-year-old CWS-eRecovered may not continue, with both CWS who persist and CWNS exhibiting comparable neural indices of semantic processing by 6–7 years old. However, Usler and Weber-Fox (2015) found that the CWS who were persisting in stuttering exhibited differences in syntactic processes compared with both CWNS and children who had recovered from stuttering. Together, the current and previous (Usler & Weber-Fox, 2015) findings may also provide insight as to the inconsistencies in previous studies of language abilities in CWS. Future longitudinal studies of language processing in these children with known outcomes of recovery or persistence, or studies of older CWS who persist versus recover, are needed to refine our understanding of the developmental trajectories of the neural indices mediating different language functions when language growth is steep and dynamic. It is important to note that all the children in the current study exhibited receptive language abilities within normal limits and the groups did not differ from one another in performance on standardized receptive language tasks. The current results indicating differences in neural function between groups reflect the highly sensitive nature of measures of neural processing, such as ERPs. Future studies should continue to investigate the neural bases of lexico-semantic processes in CWS longitudinally, particularly with larger sample sizes than the current study, which would allow for the possible influence of gender differences on semantic development. Further elucidating the role of semantic processes in shaping the neurodevelopmental pathways toward either recovery or persistence will also have considerable clinical implications.

Conclusion

The findings from the current study indicate that 5-year-old CWS at the time of testing who would eventually recover from stuttering exhibited more mature neural processes for lexical access and integration compared with their peers who would persist in stuttering. Still, those who would eventually recover appeared to lag behind their fluent counterparts in regard to neural indices of postlexical processing, despite comparable performance on a receptive language assessment. These findings are the first to show that neural maturation for language processing may distinguish eventual persistence in and recovery from stuttering in young children. Furthermore, these findings illustrate that recovery from stuttering may be associated with relative strengths, in this case, with more mature neural processes for lexical access mediating semantic processing.

Acknowledgments

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