Phonologic Processing in Adults Who Stutter: Electrophysiological and Behavioral Evidence

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Event-related brain potentials (ERPs), judgment accuracy, and reaction times (RTs) were obtained for 11 adults who stutter and 11 normally fluent speakers as they performed a rhyme judgment task of visually presented word pairs. Half of the word pairs (i.e., prime and target) were phonologically and orthographically congruent across words. That is, the words looked orthographically similar and rhymed (e.g., *thrown, own*) or did not look similar and did not rhyme (e.g., *cake, own*). The phonologic and orthographic information across the remaining pairs was incongruent. That is, the words looked similar but did not rhyme (e.g., *gown, own*) or did not look similar but rhymed (e.g., *cone, own*). Adults who stutter and those who are normally fluent exhibited similar phonologic processing as indexed by ERPs, response accuracy, and RTs. However, longer RTs for adults who stutter indicated their greater sensitivity to the increased cognitive loads imposed by phonologic/orthographic incongruency. Also, unlike the normally fluent speakers, the adults who stutter exhibited a right hemisphere asymmetry in the rhyme judgment task, as indexed by the peak amplitude of the rhyming effect (difference wave) component. Overall, these findings do not support theories of the etiology of stuttering that posit a core phonologic-processing deficit. Rather we provide evidence that adults who stutter are more vulnerable to increased cognitive loads and display greater right hemisphere involvement in late cognitive processes.

KEY WORDS: stuttering, brain, phonology, language functions

It has been hypothesized that stuttering cannot be attributed to a single cause but is the result of nonlinear interactions between a vulnerable speech motor system and a variety of factors that interact with the functioning of this system (Smith, 1990; Smith & Kelly, 1997). Some of these factors may include genetic predispositions, effects of emotional and autonomic arousal, and linguistic and other cognitive processing demands (Smith & Kelly, 1997). It is clear from a large body of literature that the interactions between these variables in the development of stuttering will need to be uncovered for a more complete understanding of the disorder (e.g., Ambrose, Yairi, & Cox, 1993; Bosshardt, Ballmer, & de Nil, 2002; Paden, Ambrose, & Yairi, 2002; Ratner, 1997; Smith & Kleinow, 2000; Weber & Smith, 1990; Weber-Fox, 2001; Wolk, Edwards, & Conture, 1993; Yaruss, 1999; Zelaznik, Smith, Franz, & Ho, 1997).

The current study focuses on one potential factor that has received a great deal of attention in the literature on stuttering in the last decade, namely phonologic encoding (see Nippold, 2001, 2002, for review). Greater delays in phonologic development were found for young

children who exhibited persistent stuttering compared to those who recovered from stuttering (Paden, Yairi, & Ambrose, 1999). Also, among children who stutter, phonologic disorders have been reported to occur at a higher rate (e.g., as high as 30–40%) compared to the incidence in the general population (2–6%; Beitchman, Nair, Clegg, & Patel, 1986; Conture, Louko, & Edwards, 1993; Louko, 1995; Melnick & Conture, 2000; Ratner, 1995; Wolk, 1998). However, the rates of co-occurrence of stuttering and phonologic disorders vary considerably across studies that also differ in aspects of methodology, including diverse criteria for identifying phonologic disorders (Nippold, 2001, 2002). Nevertheless, as Nippold (2002) summarized, there continues to be a general conclusion that phonologic disorders and/or subclinical differences in phonologic processing co-occur with fluency disorders and further that this co-occurrence may have implications for the treatment of children who exhibit both disorders.

One recent theory that relates phonologic processing and stuttering is the covert repair hypothesis that is based on Levelt's (1998) well-known model of language production (Kolk & Postma, 1997; Postma & Kolk, 1993). The covert repair hypothesis posits that phonologic encoding is slower in individuals who stutter compared to normally fluent speakers. Slowed phonologic-encoding processes are thought to result in more errors in segment selections for phonetic plans (Kolk & Postma, 1997). Under this hypothesis, the speech flow of persons who stutter is interrupted when an error in phonetic planning is detected via the internal monitoring loop utilized in subvocalization just prior to overt speech (Levelt, 1998). Thus, within this framework, stuttering events are the consequences of covert repair reactions to errors in speech plans (Kolk & Postma, 1997). Yaruss and Conture (1996) tested predictions of the covert repair hypothesis in a group of boys (age 4–6 years) who stuttered. These children were grouped according to whether they exhibited normal or disordered phonologic abilities. Predictions of the covert repair hypothesis regarding the co-occurrence of disfluencies and speech errors were supported for the children's nonsystematic (slip of the tongue) errors but not the systematic (rule-based) phonologic errors (Yaruss & Conture, 1996). Also, predictions that faster speaking rates or shorter response latencies would be associated with more speech errors or speech disfluencies were not supported (Yaruss & Conture, 1996). Consistent with the covert repair hypothesis is the general finding that slower speaking rates promote fluency in individuals who stutter. Also, repetitive reading of a passage, which is thought to reduce phonetic planning demands, results in the adaptation phenomenon of increased fluency over successive readings (Kolk & Postma, 1997). The implication of this hypothesis is that the neural processes underlying phonologic processing in persons who stutter operate more slowly compared to their normally fluent peers. As described below, the present study was designed to examine this hypothesis directly by utilizing both measures of rhyme judgment behavior and event-related brain potentials (ERPs). Under the covert repair hypothesis, we would predict that adults who stutter would show slower reaction times (RTs), longer latencies of ERP components, and perhaps atypical structure of the ERPs elicited in a rhyme judgment task.

ERPs are averaged electrical responses originating from synchronized activity of populations of neurons that are recorded over locations on the scalp. Components in the ERP waveforms are characterized by their latencies, amplitudes, scalp distributions, and polarity (Nunez, 1995). Previously, ERPs elicited in rhyming paradigms have been used to study phonologic processing in normal adult speakers and typically developing children (Coch, Grossi, Coffey-Corina, Holcomb, & Neville, 2002; Grossi, Coch, Coffey-Corina, Holcomb, & Neville, 2001; Kramer & Donchin, 1987; Polich, McCarthy, Wang, & Donchin, 1983; Rugg, 1984; Rugg & Barrett, 1987; Weber-Fox, Spencer, Cuadrado, & Smith, 2003). In each of these studies, the stimuli consisted of a briefly presented prime word, followed after a short delay by a target word that required a rapid rhyme judgment. A reliable ERP index of rhyme is an increase in amplitude of a negative component occurring around 350–450 ms poststimulus that is larger for a nonrhyming target than for a rhyming target. This effect is specific to a rhyme judgment task and does not occur when the same stimuli are used in a visual matching task (Polich et al., 1983). Results from articulatory suppression paradigms (e.g., repeating a word such as "the, the, the…" while performing visual rhyme judgment tasks) indicate that rhyme judgments require the transformation of orthographic information into phonologic representations and are thought to activate the "articulatory loop" or "inner voice" (Arthur, Hitch, & Halliday, 1994; Baddeley, 1986; Baddeley & Hitch, 1974; Besner, 1987; Johnston & McDermott, 1986; Richardson, 1987; Wilding & White, 1985). That is, the underlying processes for making rhyming judgments for pairs of words (i.e., prime and target) include retrieving the phonologic representation of a prime, holding it in working memory via the articulatory loop, and segmenting it into its onset and rime elements (Besner, 1987). Similar processes would then occur for processing the target word in the pair. In order to complete the rhyme judgment, the rime element of the target must be compared to the rime element of the prime word (Besner, 1987).

Previous ERP studies using visually presented sentences suggest that some neural processes peaking after 250 ms are atypical in adults who stutter. Earlier potentials, peaking before or around 200 ms (N100,

N180, P200), are common to visual linguistic and nonlinguistic stimuli and are thought to be more closely related to sensory, perceptual processes (Mangun & Hillyard, 1991). The latencies and amplitudes of these components were found to be similar in adults who stutter and those who are normally fluent in two visual sentence-processing paradigms (Cuadrado & Weber-Fox, 2003; Weber-Fox, 2001). In contrast, longer latency ERP components elicited by open- and closed-class words, semantic anomalies, and syntactic violations within sentences were found to be different in adults who stutter compared to those who are normally fluent (Cuadrado & Weber-Fox, 2003; Weber-Fox, 2001). The ERPs elicited in adults who stutter were characterized by reduced negative amplitudes for closed-class words (N280), open-class words (N350), and semantic anomalies (N400). Additionally, a late positivity (P600) elicited by syntactic anomalies was reduced in amplitude and distribution compared to the P600 elicited in normally fluent speakers. The timing of neurolinguistic processes associated with reading are not known; they are likely to be overlapping and parallel to some extent and depend on the nature of the stimuli, context, and task requirements (Perfetti, 1999). However, studies of normal adults employing eye-tracking, ERP measures, and brief exposure paradigms provide evidence for a rapid phonologic-processing model in which partial phonologic information is available as early as 60 ms, followed by word identification (200–300 ms) and availability of semantic information (Perfetti, 1999; Rayner & Pollatsek, 1989). Later processes have been associated with decision making or integration of word meaning, such as the N400 elicited by semantic anomalies (Kutas & Hillyard, 1980). Also, later processes occurring from 500–800 ms poststimulus onset, such as those indexed by the P600, are elicited by violations in agreement (such as involving verb or gender), phrase structure violations, and syntactic reanalysis (e.g., Friederici, Hahne, & Mecklinger, 1996; Hagoort, Brown, & Groothusen, 1993; Neville, Nicol, Barss, Forster, & Garrett, 1991; Osterhout & Holcomb, 1992; Osterhout & Mobley, 1995).

Thus, previous studies in normal adults have helped clarify which cognitive processes are associated with various ERP components and aid in the interpretation of the findings in adults who stutter. The ERP findings in adults who stutter to date are consistent with the hypothesis that underlying neural processes mediating lexical access and postlexical analyses during visual sentence processing may operate atypically in adults who stutter in the absence of overt speech (Cuadrado & Weber-Fox, 2003; Weber-Fox, 2001). One mediating process common to visual processing of different word classes as well as syntactic and semantic violations likely involves phonologic encoding (Arthur et al., 1994; Baddeley, Eldridge, & Lewis, 1981).

In order to explore the possibility that aspects of phonologic encoding may have contributed to processing differences observed between adults who stutter and normally fluent speakers in sentence-processing paradigms, the current study was designed to directly examine phonologic processing in the absence of sentence processing. The rhyming paradigm we chose allowed us to determine whether differences in language processing in adults who stutter are observed in a task that relies primarily on phonologic encoding, rather than processing of syntactic or semantic information in sentences.

Our experimental design also allows assessment of the effects of additional cognitive loading, or "cognitive stress," on neural processes mediating phonologic encoding for rhyme decisions. Previous evidence indicates that cognitive stress results in increased numbers of disfluencies and temporal disruptions in the speech of individuals who stutter compared to controls (Caruso, Chodzko-Zajko, Bidinger, & Sommers, 1994). Furthermore, studies of language processing indicate that additional cognitive loads or complexity may enhance differences between normally fluent speakers and individuals who stutter as reflected by a decrease in the number of propositions produced in sentences (Bosshardt et al., 2002), decreased behavioral accuracy for detection of syntactic violations (Cuadrado & Weber-Fox, 2003), and decreased speech motor stability (Kleinow & Smith, 2000). These results are consistent with the hypothesis that language processing and speech production systems of persons who stutter have a greater vulnerability to interference from additional processing demands (Bosshardt et al., 2002; Smith & Kelly, 1997). Our choice of the complexity manipulations was based on behavioral measures and ERP results indicating that the neural processes mediating the rhyming judgments are sensitive to interactions between phonologic and orthographic information contained in the word pairs (Kramer & Donchin, 1987; Polich et al., 1983; Rugg & Barrett, 1987; Weber-Fox et al., 2003). Examples of the phonologic/orthographic congruency manipulations we used are presented in Table 1.

In summary, in this study we employ a rhyming paradigm combining ERP and behavioral measures to examine phonologic processing in adults who stutter in a task that does not involve speech production. The ERP measures provide a means to detect any differences in neural functions for phonologic processing and to specify both temporal and spatial distributional aspects of any differences in neural activity. The information provided by the behavioral measures helps to constrain the interpretation of the ERP findings, as well as to provide functional indexes for the phonologic-processing tasks. Finally, phonologic and orthographic manipulations of the word pairs were used to examine group differences due to additional cognitive load.

Table 1. Examples of phonologic and orthographic combinations for prime and target word pairs.

Phonology	Orthography	
	Similar (O+)	Dissimilar (O–)
Rhyme (R+)	Congruent (R+O+)	Incongruent (R+O–)
	wood, hood	*could, hood*
	thrown, own	*cone, own*
	host, most	*toast, most*
Nonrhyme (R–)	Incongruent (R–O+)	Congruent (R–O–)
	blood, hood	*air, hood*
	gown, own	*cake, own*
	cost, most	*couch, most*

Note. See Weber-Fox et al. (2003) for complete list of word-pair stimuli.

Method

Participants and Screening Procedures

Participants were 11 adults who stutter and 11 normally fluent speakers. Participants were matched according to age, gender, and educational background (Table 2). All participants had normal or corrected-to-normal vision and were right-handed as determined by the Edinburgh Inventory for assessment of handedness (Oldfield, 1971). All participants were native English speakers with no reported history of neurological, language, or hearing impairments. At the time of testing, the Stuttering Severity Instrument for Children and Adults—Third Edition (SSI–3) was administered to each of the participants who stutter (Riley, 1994). The stuttering severity measures derived from this instrument are also reported in Table 2. It should be noted that the SSI severity measures were based on only one standard sample of conversation and reading, and thus may not capture the variations of stuttering severity observed across situations. All of the adults who stuttered reported a history of treatment for their stuttering. However, the types of treatment and treatment durations, as well as the ages of participation in treatments, varied considerably across the individuals.

Four subtests of the Test of Adolescent and Adult Language—Third Edition (TOAL–3; Hammill, Brown, Larsen, & Wiederholt, 1994) were administered to assess speaking and listening language skills for both vocabulary and grammar. These scores are listed in Table 3. The groups did not differ on these measures, between: group $F(1, 20) = 2.71$, $p = .12$; within: subtest $F(3, 60) = .44$, Huynh-Feldt (H-F) $p = .66$; subtest × group $F(3, 60) = .57$, H-F $p = .58$). The language scores were not used to match individual participants across the two groups. Oral structures and nonspeech oral motor skills were within normal limits for all participants as assessed by the Oral Speech Mechanism Screening Evaluation—Revised (OSMSE–R; St. Louis & Ruscello, 1987). Participants also exhibited hearing sensitivity within normal limits for both ears (screened at 20 dB HL at 500, 1000, 2000, 4000, and 6000 Hz).

Stimuli for Rhyming Judgment Task

Stimuli were 124 rhyming word pairs and 124 nonrhyming word pairs that were previously used in a study of typically developing children and adults (Weber-Fox et al., 2003). Each of the word pairs consisted of

Table 2. Characteristics of participants.

Participant	Adults who stutter				Normally fluent speakers		
	Age	Gender	Education	Severity	Age	Gender	Education
1	20	M	HS	Moderate	20	M	C2
2	36	M	BA	Very mild	36	M	C5
3	19	M	HS	Moderate	19	M	HS
4	21	F	C2	Very mild	21	F	C3
5	19	F	C2	Mild	19	F	C1
6	32	F	C1	Moderate	32	F	HS
7	44	F	BA	Very mild	44	F	BA
8	17	M	HS⁰	Very mild	17	M	HS⁰
9	26	M	C2	Very severe	26	M	C4
10	19	M	HS	Very mild	19	M	HS
11	23	M	C4	Mild	23	M	C4
M	25.09				25.09		
SD	8.65				8.65		

Note. HS = high school graduate; BA = bachelor degree completed; C1 = 1 year of college completed; C2 = 2 years of college completed; C3 = 3 years of college completed; C4 = 4 years of college completed; C5 = 5 years of college completed; HS⁰= currently in high school.

Table 3. Standard scores for subtests on the TOAL-3.

Participant	Adults who stutter					Normally fluent speakers			
	LV	LG	SV	SG		LV	LG	SV	SG
1	9	11	8	6		13	12	12	9
2	5	10	10	11		14	12	12	11
3	11	9	12	11		12	7	10	15
4	11	11	12	13		14	13	12	10
5	10	10	10	11		10	12	10	14
6	8	8	12	10		12	8	12	10
7	14	11	12	11		13	12	12	8
8	14	10	13	14		8	10	13	14
9	8	11	12	11		9	10	11	13
10	13	13	NA	7		9	11	11	17
11	12	11	10	6		9	10	11	9
M	10.45	10.45	11.10	10.09		11.18	10.64	11.45	11.82
SD	2.83	1.29	1.52	2.66		2.22	1.86	0.93	2.92

Note. TOAL–3 = Test of Adolescent and Adult Language—Third Edition; LV = listening/vocabulary; LG = listening/grammar; SV= speaking/vocabulary; SG = speaking/grammar; NA = not available.

a prime followed by a target. Rhyming (R+) pairs consisted of two conditions: 62 orthographically similar (R+O+; e.g., *thrown, own*) and 62 orthographically dissimilar (R+O–; e.g., *cone, own*) pairs. Nonrhyming (R–) pairs also consisted of two conditions: 62 orthographically similar (R–O+; e.g., *gown, own*) and 62 orthographically dissimilar (R–O–; e.g., *cake, own*). Thus, for the rhyming and nonrhyming pairs, orthography was congruent (R+O+ and R–O–) or incongruent (R+O– and R–O+) with the phonologically based rhyme decision (Table 1). The word pairs were balanced so that all targets were matched with a prime in each of the four conditions. The primes in the R–O– condition were randomly selected from the primes used in the other conditions (see Weber-Fox et al., 2003, for a complete list of stimulus items). All but one of the target words were open-class words, which are known to elicit an N350 component (Hagoort, Brown, & Osterhout, 1999). The means (and standard deviations) of the word frequencies per million for the R+O+, R–O+, R+O–, and R–O– primes were 384 (1,499), 634 (1,853), 886 (4,804), and 602 (1,784), respectively (Francis & Kucera, 1982). As stated above, the target words were the same across conditions, with a mean frequency per million of 248 (*SD* = 518; Francis & Kucera, 1982). No significant differences were found for word frequency across the primes and targets, $F(4, 291) = .553$, $p = .70$. Therefore, differences in accuracy, RT, and ERP responses across conditions could not be attributed to frequency effects.

Electroencephalographic Recordings

Electrical activity at the scalp was recorded from electrodes secured in an elastic cap (Quik-Cap, Compumedics Neuroscan). Twenty-eight electrodes were positioned over homologous locations of the two hemispheres according to the criteria of the International 10-20 system (Jasper, 1958). Locations were as follows: lateral sites F7/F8, FT7/FT8, T7/T8, TP7/TP8, P7/P8, mid-lateral sites FP1/FP2, F3/F4, FC3/FC4, CP3/CP4, P3/P4, O1/O2, and midline sites FZ, FCZ, CZ, CPZ, PZ, OZ. Recordings were referenced to electrodes placed on the left and right mastoids. Horizontal eye movement was monitored via electrodes placed over the left and right outer canthi. Electrodes over the left inferior and superior orbital ridge were used to monitor vertical eye movement. All electrode impedances were adjusted to 5000 ohms or less. The electrical signals were amplified within a bandpass of 0.1 and 100 Hz and digitized online (Neuroscan 4.0) at a rate of 500 Hz.

Procedures

Participants completed the informed consent document, case history form, and handedness questionnaire (Oldfield, 1971). Also, the visual acuity of each eye of each participant was screened using a standard eye chart. The electrode cap was then placed on the participant, and appropriate impedances were obtained. Participants were then seated comfortably in a sound-attenuating room.

Participants were positioned 64-in. from a 19-in. computer monitor, and the experimental task was explained. Participants were instructed to make the rhyme judgment "as quickly and accurately as possible" and were instructed to refrain from blinking during trials. As the experiment was self-paced, the participant triggered the

beginning of a trial with a button press (Figure 1). A trial began with a centered, white rectangular border appearing on the screen. Following a delay of 1,000 ms, a prime was presented for 300 ms. After a 900-ms interstimulus interval, a target was presented for 300 ms. Visual angles of the word stimuli were 1.5° to 5° horizontally and 0.5° vertically. Following the presentation of the target, participants pressed the "yes" button if the two words rhymed, or the "no" button if the two words did not rhyme. The response hands corresponding to the "yes" and "no" buttons were counterbalanced across participants and within each of the groups. The rectangular border remained on the screen for an additional 3,500 ms following the offset of the target at which point "READY?" appeared in the center of the screen (Figure 1).

Prior to the test blocks, a practice session consisting of 10 word pairs was carried out. In the experiment, participants performed two test blocks each containing 124 prime and target pairs. The word pairs were pseudorandomized across blocks with equal representation from each of the four conditions. Trials with identical target words were separated by at least five intervening trials. The order of the blocks was counterbalanced across participants. Each block lasted approximately 18 min and varied slightly depending on the pace of individual participants.

Data Analysis

Behavioral measures. Rhyming judgment accuracy and RT were obtained from signals generated from the response pad. RT, the time from the target onset to the button press, was calculated for the correct trials that occurred at least 200 ms after stimulus onset but before 1,800 ms, to eliminate spurious button presses (6%). Previous RT findings indicate that this range captures the time needed for rapidly responding to a complex stimulus such as a visual rhyming task (e.g., Grossi et al., 2001). Rhyming judgment accuracies and RTs, averaged across trials for each participant in each condition, were compared using mixed-effects analyses of variance (ANOVAs) with repeated measures that included a between-subject factor (group: adults who stutter, normally fluent speakers) and a within-subject factor (condition: R+O+, R–O+, R+O–, R–O–). Using the MS-error terms of the repeated-measures analysis, post hoc comparisons were made using Tukey's honestly significant difference (HSD) method to determine which comparisons contributed to significant effects (Hays, 1994).

ERP measures. Trials with excessive eye movement or other forms of artifact (10.3% for adults who stutter, 11.1% for normally fluent adults) were excluded from further analyses of the ERP responses. The rejected trials were equally distributed across the four conditions.

Figure 1. Illustration of the time course of the prime and target stimuli used to elicit event-related brain potentials (ERPs) and rhyme judgments.
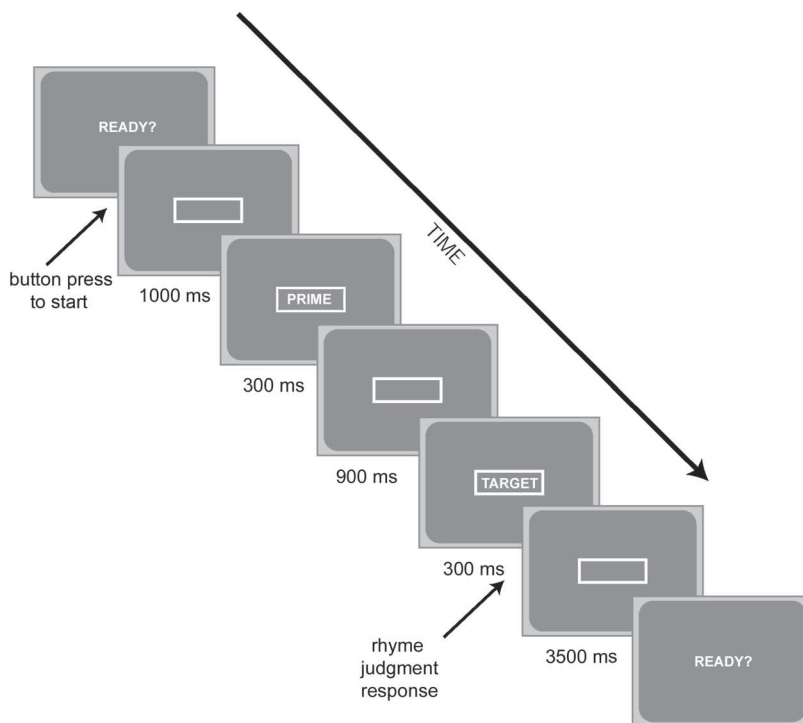
The remaining trials were averaged by condition for each participant. The averages were triggered 100 ms prior to the target onset and included 800 ms after the trigger. The ERP data from the 100-ms interval prior to the target onset served as the baseline activity. The peak latencies of ERP components were computed in relation to the trigger point (0 ms) that marked the stimuli onsets. The peaks were automatically detected using Neuroscan 4.2 software with specified temporal windows that capture the ERP components elicited in this paradigm, as described below.

For ERPs elicited by the targets, the peak amplitudes and latencies of the N100/N180 (N100 elicited over anterior and temporal sites, N180 elicited over parietal and occipital sites) and P200 components were measured within the temporal windows of 50–200 ms and 150–250 ms, respectively. The negative peak latencies and amplitudes of the N350 (Grossi et al., 2001) were measured within the temporal window of 250–600 ms poststimulus onset. Finally, ERP difference waves were formed by subtracting the rhyme from the nonrhyme averages elicited by the orthographically congruent (R–O– minus R+O+) and incongruent (R–O+ minus R+O–) conditions. This difference wave is referred to as the rhyming effect (RE) because it isolates the differences between the rhyme and nonrhyme elicited waveforms (Grossi et al., 2001). The peak amplitudes and latencies of the RE were measured within a temporal window of 250–700 ms.

ERP amplitudes and peak latencies were compared with mixed-effects ANOVAs with repeated measures including a between-subject factor of group (adults who stutter, normally fluent speakers) and three within-subject factors including condition (R+O+, R+O–, R–O+, R–O–), hemisphere (left and right), and electrode site (F7/8, FC3/4, FT7/8, T7/8, TP7/8, CP3/4, P7/8, O1/2). Mixed-effects ANOVAs with repeated measures were applied to the difference waves and included a between-subject factor of group (adults who stutter, normally fluent speakers) and three within-subject factors including condition (congruent, incongruent subtractions), hemisphere (left and right), and electrode sites (same as above). The subset of 16 lateral and midlateral electrode sites was selected for the repeated-measures analyses because it provided a good sample of ERPs from anterior to posterior regions over the left and right hemispheres that allowed for the examination of distributional effects within and between hemispheres. Group comparisons were also completed for the ERP measures obtained at the central electrode sites (FZ, FCZ, CZ, CPZ, PZ, OZ). For the sake of clarity and conciseness in reporting the results, the central electrode analyses were not included in the present report because the results mirrored those for the lateral/midlateral electrode sites

and did not provide additional or novel information. Significance values were set at $p < .05$. For all repeated measures with greater than one degree of freedom in the numerator, the H-F adjusted p values were used to determine significance (Hays, 1994). The effect sizes, indexed by the partial eta-squared statistic (e_p^2), are reported for all significant effects.

Results
Rhyme Judgments

Accuracy. As suggested by the plots in Figure 2 (upper panel), the accuracy of rhyming judgments was not significantly different for adults who stutter and those who are normally fluent in any condition, group $F(1, 20) = 1.05$, $p = .32$; group × condition $F(3, 60) = 1.20$, H-F $p = .31$. Relative to the other three conditions, accuracy was

Figure 2. Means (+*SE*) of rhyming judgment accuracies (top panel) and reaction times (bottom panel) for adults who stutter and normally fluent speakers across conditions.
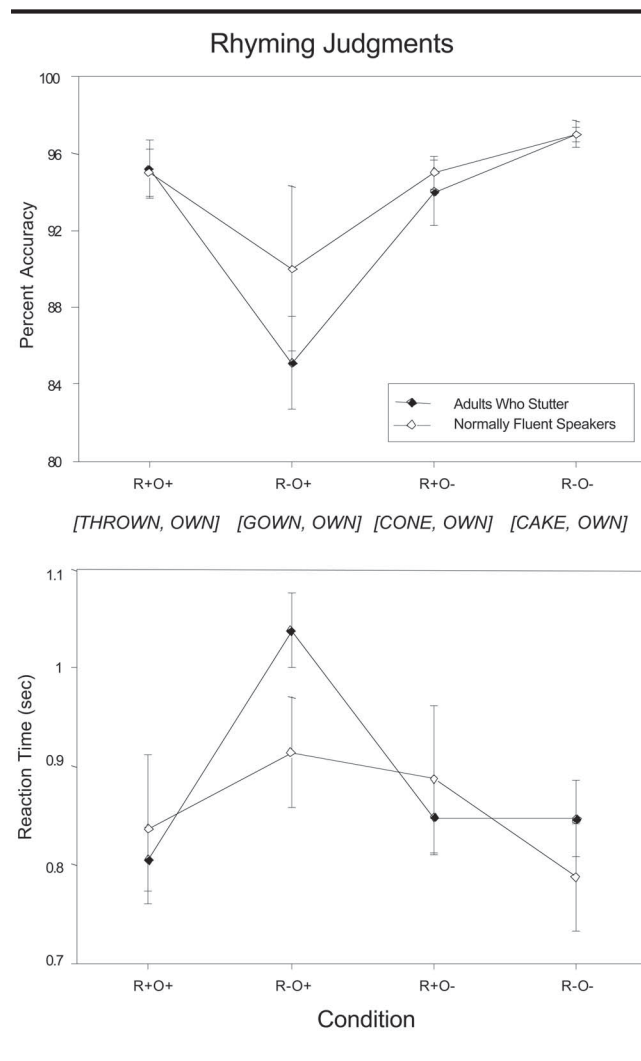
reduced for the R–O+ condition, $F(3, 60) = 9.89$, $H\text{-}F\ p = .001$, $e_p^2 = .33$, Tukey HSD $p < .05$. This condition required encoding different phonologic representations for words with similar orthography (e.g., *gown*, *own*).

Reaction time. Overall group differences in RT were not found, group $F(1, 20) = 0.08$, $p = .78$. Figure 2 (lower panel) shows the condition effects for the measure of RT, $F(3, 60) = 24.72$, $H\text{-}F\ p < .001$, $e_p^2 = .553$. As can be seen, RTs were slower for the R–O+ condition relative to the other three (Tukey HSD $p < .05$). However, the adults who stutter demonstrated greater delays in their RT measure for this incongruent condition (R–O+) and were significantly slower (approximately 100 ms longer) than normally fluent speakers, condition × group $F(3, 60) = 4.27$, $H\text{-}F\ p = .03$, $e_p^2 = .18$, Tukey HSD $p < .05$.

ERP Data

The ERPs (grand averages across 11 participants in each group) elicited by the target words in the congruent and incongruent rhyme conditions are displayed in Figures 3 and 4 for both groups. The ERPs from 10 electrode locations were selected to illustrate the pattern of responses from anterior to posterior regions over both hemispheres. These plots reflect the patterns observed for the full set of 16 electrode sites used in the statistical analyses reported below. The following sections summarize the similarities and differences in the neural responses elicited in the two groups.

N100, N180, P200. There were no significant group differences in the measures of these components, N100/N180: amplitude $F(3, 60) = 1.99$, $H\text{-}F\ p = .17$, latency $F(3, 60) = 0.64$, $H\text{-}F\ p = .43$; P200: amplitude $F(3, 60) = 0.95$, $H\text{-}F\ p = .34$, latency $F(3, 60) = 2.72$, $H\text{-}F\ p = .12$. Consistent with previous studies (Grossi et al., 2001; Weber-Fox et al., 2003), the amplitudes and latencies of the N100/N180 and P200 were not different across conditions of rhyme or phonologic/orthographic congruence, N100/N180: amplitude $F(3, 60) = 0.58$, $H\text{-}F\ p = .60$, latency $F(3, 60) = 0.27$, $H\text{-}F\ p = .84$; P200: amplitude $F(3, 60) = 0.91$, $H\text{-}F\ p = .44$, latency $F(3, 60) = 0.35$, $H\text{-}F\ p = .79$. Thus, these earlier potentials, which are more closely related to sensory perceptual processing, did not distinguish the adults who stutter from those who were normally fluent.

N350. No group differences were found for the peak amplitude of the N350, group $F(1, 20) = 0.19$, $p = .67$; condition × group $F(3, 60) = 1.74$, $H\text{-}F\ p = .17$. The ERPs

Figure 3. ERP grand averages elicited by the target words in the congruent rhyme (R+O+) and nonrhyme (R–O–) conditions. The ERPs are displayed for a sample of lateral/midlateral electrode sites that span from anterior to posterior regions of the left and right hemispheres. Negative potentials are plotted upward. The shading highlights the increased negative amplitudes elicited by the nonrhyme condition relative to the rhyme condition within the 250–600 ms temporal window poststimulus onset.
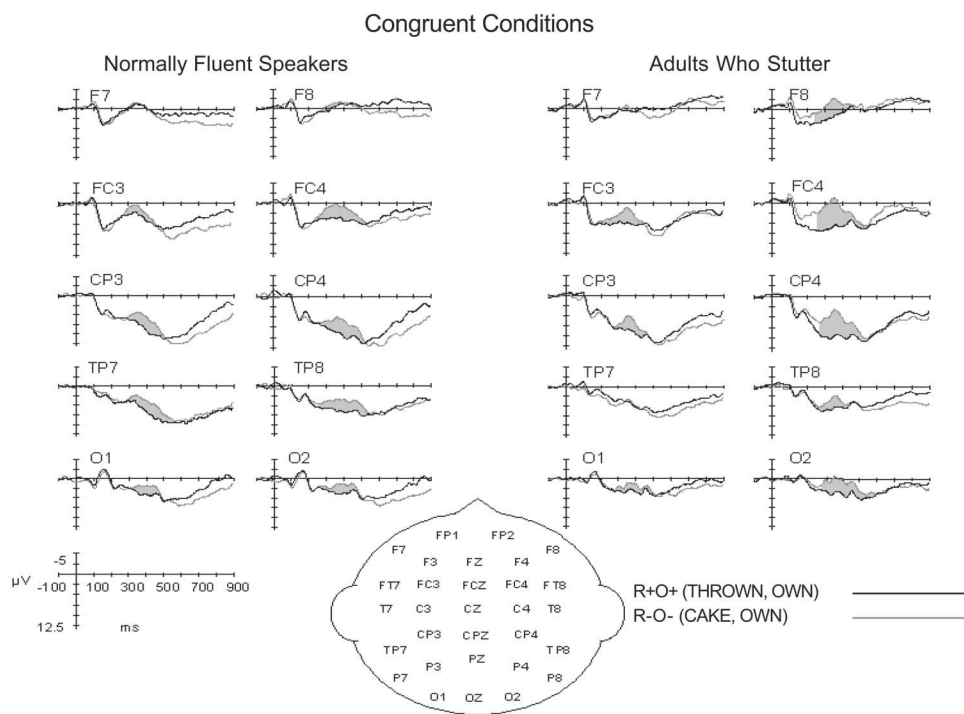
Figure 4. ERP grand averages elicited by the target words in the incongruent rhyme (R+O–) and nonrhyme (R–O+) conditions. In the same format as Figure 3, the ERPs are displayed for a sample of lateral/midlateral electrode sites that span from anterior to posterior regions of the left and right hemispheres. Negative potentials are plotted upward. The shading highlights the increased negative amplitudes elicited by the nonrhyme condition relative to the rhyme condition within the 250–600 ms temporal window poststimulus onset.
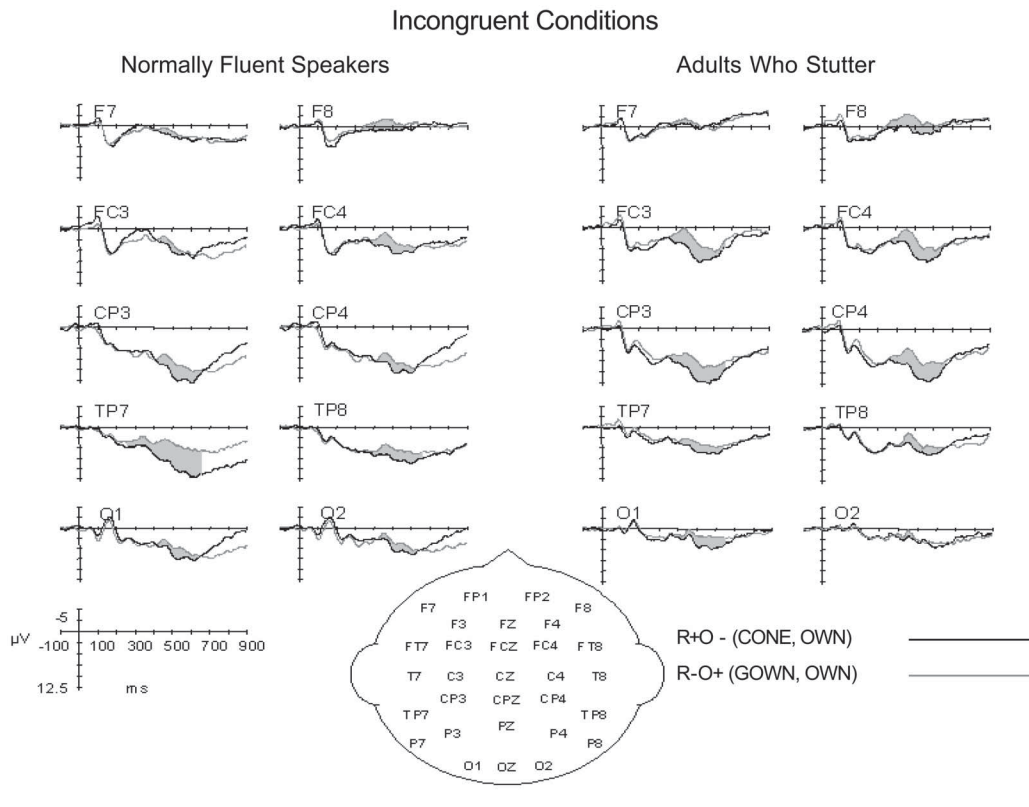
of both groups displayed the typical larger N350 amplitude for nonrhyming targets relative to rhyming targets, condition $F(3, 60) = 7.63$, H-F $p < .001$, $e_p^2 = .28$, Tukey HSD $p < .05$. The condition effects on the amplitude of the N350 can be seen in the shaded areas of the ERP waveforms for the two groups for the congruent and incongruent conditions in Figures 3 and 4.

The peak latencies of the N350 across conditions were similar for the adults who stutter and the normally fluent speakers, group $F(1, 20) = 0.07$, $p = .80$; condition × group $F(3, 60) = 0.14$, H-F $p = .94$. As in previous reports (Kramer & Donchin, 1987; Weber-Fox et al., 2003), a significant effect of condition was found for the peak latencies of the N350. That is, the peak latencies for the incongruent nonrhyme (R–O+, e.g., *gown, own*) elicited longer N350 peak latencies compared to the other three conditions, condition $F(3, 60) = 11.45$, H-F $p < .001$, $e_p^2 = .36$. This effect is illustrated in Figure 5.

Difference wave analyses – RE. The RE components from the difference waves of both groups are illustrated in Figure 6. The averages from midlateral sites were

selected to illustrate how the waveforms compared for the congruent and incongruent REs. These plots reflect the patterns observed across the 16 electrode sites included in the statistical analyses. Group peak latencies were similar for both REs, group $F(1, 20) = 0.49$, $p = .491$; condition × group $F(1, 20) = 0.27$, $p = .61$. As in earlier findings (Weber-Fox et al., 2003), the peak latencies of the REs were longer for the incongruent subtractions compared to the congruent ones, condition $F(1, 20) = 20.92$, $p < .001$, $e_p^2 = .51$. The peak latencies averaged across the lateral/midlateral electrode sites for the congruent difference waves were on average 89 ms earlier than those of the incongruent difference waves ($M = 410.7$ and 499.6, $SE = 15.0$ and 12.2, respectively).

The overall amplitudes of the RE did not differ between the adults who stutter and those who are normally fluent, group $F(1, 20) = 0.04$, $p = .84$; condition × group $F(1, 20) = 0.41$, $p = .51$. While the overall amplitudes of the RE components did not distinguish the groups, the hemispheric distribution differed, hemisphere × group $F(1, 20) = 6.01$, $p = .02$, $e_p^2 = .23$. As can

Figure 5. Peak latency measures (means and *SEs*) of the N350 across the four rhyming conditions. The means depicted in this figure were collapsed across all participants since there were no group effects or interactions.

N350 Latency

Figure 7. Mean (+*SE*) peak amplitudes of REs averaged across the lateral and midlateral electrode sites for the adults who stutter and those who are normally fluent, plotted for the left and right hemispheres for each group.

RE Peak Amplitude

be seen in Figure 7, the peak amplitude of the RE of the adults who stutter was larger over the right hemisphere compared to their response over the left hemisphere, while the RE of the adults who are normally fluent was similar in amplitude across the hemispheres. Unlike the latencies of the RE components, the peak amplitudes of the RE components did not differ for the congruent and incongruent difference waves, condition $F(1, 20) = 0.31$, $p = .58$.

Discussion

Our goal in this experiment was to determine whether phonologic processing differs for adults who stutter compared to normally fluent speakers under conditions that do not require production of overt speech.

Figure 6. ERP grand averages of the difference waves for the normally fluent speakers and adults who stutter. The congruent and incongruent rhyming effects (REs) are plotted for the midlateral electrode sites FC3/4 and CP3/4. Negative potentials are plotted upward.

The stimulus set also allowed us to address whether phonologic processing in adults who stutter is more susceptible to increased cognitive loads or complexity. Taken together, the findings from ERP, RT, and accuracy measures in this visual rhyme paradigm suggest that phonologic processing is fundamentally similar in adults who stutter and those who are normally fluent. There were no differences between the groups in latencies of ERP responses, nor in amplitudes of specific ERP components. The only robust difference between the groups were observed in behavioral measures when task demands were highest (when different phonologic representations must be encoded from similar orthographic symbols; e.g., *gown, own*); the participants who stutter exhibited greater slowing in their responses compared to their normally fluent peers. The only ERP measure that differentiated the two groups was the RE component from the difference waves. A right hemisphere asymmetry was observed for the group of adults who stutter, suggesting a greater role in right hemispheric activation for accomplishing the rhyme judgments. Given that the similarities in ERP and behavioral responses far outweigh the differences observed in this task, the present results do not support models of stuttering in which generally slowed phonologic processes and errors in phonologic planning are implicated as the core cause of stuttering (Postma & Kolk, 1993). Rather, we demonstrate that adults who stutter engage greater right hemisphere involvement for late cognitive processes mediating rhyme decisions. Further, the current behavioral findings suggest that later stages of processing, perhaps related to response selection, are more vulnerable to increased cognitive loads.

Behavioral Measures of Phonologic Processing

Rhyme judgment accuracy across all the conditions and RTs for three of the four conditions indicated that underlying phonologic-encoding abilities are similar for adults who stutter and normally fluent speakers when no overt speech production is required. This finding is consistent with the behavioral results of Bosshardt et al. (2002), who reported that accuracy and RTs for rhyme judgments were similar for adults who stutter and normally fluent speakers. The question remains as to whether phonologic encoding is atypical for persons who stutter when overt speech production is required.

Consistent with previous findings (Kramer & Donchin, 1987; Polich et al., 1983; Rugg & Barrett, 1987; Weber-Fox et al., 2003), judgment accuracy decreased and RTs were prolonged when different phonologic representations had to be encoded from similar orthographic strings (e.g., *gown, own*). However, the RTs of the adults

who stutter showed a greater sensitivity to this type of phonologic/orthographic incongruence. This condition has been likened to a Stroop effect (Stroop, 1935), wherein irrelevant features of the stimuli are hypothesized to be difficult to suppress and lead to decreased performance accuracy and efficiency (Kramer & Donchin, 1987). The current behavioral findings are consistent with previous reports that adults who stutter are more susceptible to increased processing demands, such as those imposed by a Stroop task (Caruso et al., 1994). Overall, the RT results support the hypothesis that language processing systems of adults who stutter have a greater vulnerability to interference from additional processing demands (Bosshardt et al., 2002; Cuadrado & Weber-Fox, 2003; Kleinow & Smith, 2000).

Neurophysiologic Indexes of Phonologic Processing

The measures of neural activity in the rhyme judgment task also suggest that phonologic processing is generally similar in adults who stutter and normally fluent speakers. As in earlier studies of visual sentence-processing paradigms, no group differences were observed for early ERP components (N100, N180, P200; Cuadrado & Weber-Fox, 2003; Weber-Fox, 2001). Thus, converging evidence from this series of studies indicates that early visual-perceptual processes involved in reading do not differ for adults who stutter and normally fluent speakers. There is evidence that at least partial phonologic information is available as early as 60 ms poststimulus onset, with word identification occurring at approximately 200–300 ms poststimulus onset (Perfetti, 1999; Rayner & Pollatsek, 1989). The group similarities in the N100, N180, and P200 amplitudes or latencies provide evidence that the early stages of phonologic processing function normally in adults who stutter.

Furthermore, the amplitudes and latencies of the N350 across each of the four conditions also did not distinguish the adults who stutter from those who are normally fluent. The amplitudes of the N350 for both groups showed the well-known effect of increased negativity for nonrhyming targets relative to rhyming targets (Grossi et al., 2001; Kramer & Donchin, 1987; Polich et al., 1983; Rugg, 1984; Rugg & Barrett, 1987; Weber-Fox et al., 2003). Consistent with previous reports (Kramer & Donchin, 1987; Polich et al., 1983; Weber-Fox et al., 2003), the incongruent nonrhyme condition (e.g., *gown, own*) resulted in longer N350 peak latencies. The peak latency of this component is sensitive to the phonologic-orthographic incongruency that requires different phonologic representations be encoded from similar orthographic symbols. Our results for the N350 latencies and amplitudes indicate the neural processes mediating the

phonologic encoding necessary for the rhyme judgment task operated similarly for adults who stutter and those who are normally fluent.

As reported above, peak latencies of the incongruent difference wave REs were prolonged relative to the peak latencies of the congruent difference wave REs in both groups; this reflects the increased processing load imposed by orthographic stimuli that interfered with phonologic encoding necessary for making the nonrhyme decision (Weber-Fox et al., 2003). However, the adults who stutter exhibited a right hemisphere asymmetry for the RE that was not found for the normally fluent speakers, suggesting a greater right hemisphere involvement in the rhyme decision process. This finding was independent of the behavioral results. While a right hemisphere asymmetry was observed for the adults who stutter even for the congruent rhyme subtraction, the behavioral measures of accuracy and RT for the congruent rhyme conditions did not distinguish the groups. The RE derived from the difference wave analyses serves to isolate the differences between processing a nonrhyming target and a rhyming target (Grossi et al., 2001; Rugg & Barrett, 1987). This difference RE, characterized as a broadly distributed negative component that peaks around 400 ms, has been considered a part of the family of N400-like potentials that are sensitive to contextual manipulations (Grossi et al., 2001; Rugg & Barrett, 1987). It has been hypothesized that the RE reflects cognitive processes mediating the comparisons of the phonologic representations of words, that is, the processes that underlie the ability to determine whether words rhyme or not (Grossi et al., 2001).

The right hemisphere asymmetry that we observed for adults who stutter is consistent with evidence from magnetic resonance imaging and positron-emission tomography showing overactivation of the right hemisphere in adults who stutter, not only for overt speaking tasks but also for tasks that did not engage the speech motor system (e.g., Braun et al., 1997; Fox et al., 1996, 2000; Ingham, Fox, Ingham, & Zamarripa, 2000; Preibisch et al., 2003). Preibisch and colleagues interpreted the atypical right hemisphere activity they observed in the right frontal operculum during reading aloud and a silent semantic decision task as reflecting compensatory processes for the reduction of white matter underlying the left sensorimotor cortex in the tongue and larynx regions in adults who stutter (Sommer, Koch, Paulus, Weiller, & Buchel, 2002). In our earlier ERP studies of sentence processing, we have not observed consistent right hemisphere overactivations for adults who stutter; however, the latencies of the negativities (N280 and N350) elicited by closed- and open-class words in sentences were later over the right hemisphere for adults who stutter compared to normally fluent adults

(Weber-Fox, 2001). The implications of previous and present ERP results are that, at least for some cognitive operations, adults who stutter may engage right hemisphere functions differently than normally fluent speakers, even for tasks that do not require overt speech.

Conclusion

In summary, the findings from ERPs, RTs, and behavioral accuracy for the rhyme judgment task converge to indicate that phonologic-encoding systems are similar for adults who stutter as well as for normally fluent speakers, at least under conditions in which no overt speech production is required. However, the efficiency of later stages of phonologic processing, as indexed by the RTs, indicates that phonologic encoding is more vulnerable to increased cognitive loads in adults who stutter, specifically when rhyme judgments are most taxing on the covert phonologic processes, as in the R–O+ condition. Thus, the data from this experiment do not support the covert repair hypothesis. If phonologic-encoding processes were slower and more error-prone in persons who stutter (Postma & Kolk, 1993), then we would predict decreased response accuracy, increased RTs, increased ERP peak latencies, and atypical ERP amplitude patterns in adults who stutter across all conditions. While the current and previous studies have shown that overt speech is not necessary to detect differences in language processing between adults who stutter and those who are normally fluent (Cuadrado & Weber-Fox, 2003; Ingham et al., 2000; Weber-Fox, 2001), it is possible that differences in phonologic encoding may be enhanced when overt speech production occurs. We are currently examining this question in a study of speech kinematics in a nonword repetition task in children and adults who stutter.

Also, we note that the literature on the co-occurrence of phonologic and fluency disorders is based on findings from young children (Conture et al., 1993; Louko, 1995; Melnick & Conture, 2000; Paden et al., 1999; Ratner, 1995; Wolk, 1998). An important question that remains is whether atypical phonologic-encoding processes appear in children who stutter but not in adults under conditions that do not require overt speech production. We have an ERP study of children who stutter and normally developing peers underway to examine this question.

Taken together with the findings from earlier sentence-processing studies (Cuadrado & Weber-Fox, 2003; Weber-Fox, 2001) and evidence of greater vulnerabilities in semantic coding systems in adults who stutter (Bosshardt et al., 2002; Bosshardt & Fransen, 1996), the differences in ERPs and behavioral effects between adults who stutter and those who are normally fluent

are not attributable to fundamental deficiencies of phonologic encoding. Group differences in previous ERP studies of sentence processing in adults who stutter (Cuadrado & Weber-Fox, 2003, Weber-Fox, 2001) revealed reduced amplitudes and distributions of ERP components that index processing of open- and closed-class words, and semantic and syntactic anomalies. These group differences occurred within temporal windows thought to include processes of lexical access (Perfetti, 1999) and postlexical syntactic analyses (Friederici et al., 1996; Hagoort et al., 1993; Osterhout & Holcomb, 1992). Thus, processing differences between adults who stutter and those who are normally fluent were more pronounced and qualitatively different in the sentence-processing tasks (Cuadrado & Weber-Fox, 2003; Weber-Fox, 2001) compared to processing word-pair stimuli for the rhyming task of the present study. As suggested by Bosshardt et al. (2002), we conclude that processing differences between adults who stutter and normally fluent speakers are the result of interactions between multiple factors such as language constraints and cognitive loading. This interpretation is consistent with a multifactorial model of stuttering (Smith, 1990; Smith & Kelly, 1997).

Acknowledgments

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