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Stuttering and Natural Speech Processing of Semantic and Syntactic Constraints on Verbs

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Abstract

Purpose—Previous findings from event-related brain potentials (ERPs) indicate that adults who stutter (AWS) exhibit processing differences for visually presented linguistic information. This study explores how neural activations for AWS may differ for a linguistic task that does not require preparation for overt articulation and/or engage the articulatory loop for silent speech.

Method—Syntactic and semantic processing constraints were examined in AWS and adults who are normally fluent (AWNF) by assessing their behavioral performance and ERPs in a natural speech listening task.

Results—AWS performed similarly to AWNF in identifying verb-agreement violations and semantic anomalies, but ERPs elicited by syntactic and semantic constraints indicated atypical neural functions for AWS. ERPs of the AWNF displayed an expected N400 for reduced semantic expectations and a typical P600 for verb-agreement violations. In contrast, both N400s and P600s for the semantic and verb-agreement conditions were observed in the ERPs of the AWS.

Conclusions—The findings suggest that AWS may engage semantic-syntactic mechanisms more generally for semantic and syntactic processing. These findings converge with earlier studies using visual stimuli to indicate that, while linguistic abilities are normal in AWS, underlying brain activity mediating some aspects of language processing may function differently.

Keywords

verb-agreement; semantic anomalies; stuttering; language; ERPs

Introduction

Stuttering is characterized by involuntary disruptions in the flow and rhythm of speaking even though the individual knows exactly what he/she wants to say. These uncontrolled interruptions in producing speech, commonly perceived as sound prolongations, syllable repetitions, and silent blocks, can be brief or last for many seconds (Conture, 2001; Yairi & Ambrose, 2005). The foci of many earlier studies of stuttering were on speech motor control variables as they relate to overt fluent and non-fluent speech production, and in many cases examined atypical motor activations in the articulatory, laryngeal, and respiratory systems (e.g., Denny & Smith, 1992; McClean & Runyan, 2000; Peters & Boves, 1988; Smith et al. 1993; Zimmerman, 1980; Zocchi et al., 1990). While stuttering manifests as a disorder of overt speech production, it is becoming increasingly clear that other factors that interact with the development of the speech motor system play a role in its epigenesis. 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). Converging evidence from a large body of literature indicates 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; Ratner, 1997; Bosshardt, Ballmer, & de Nil, 2002; Howell, 2004; Paden, Ambrose, & Yairi, 2002; Kleinow & Smith, 2000; Weber & Smith, 1990; Weber-Fox, 2001; Wolk, Edwards, & Conture, 1993; Yaruss, 1999; Zelaznik, Smith, Franz, & Ho, 1997).

Working within a framework in which multiple factors are thought to interact during development to contribute toward the emergence of stuttering, our research in recent years has focused on language processing as one of these factors. Kinematic and EMG findings indicate that, compared to normally fluent adults, the speech motor coordination of adults who stutter (AWS) is more sensitive to increased linguistic demands, indicating an interaction between cognitive loads associated with language formulation and the motor control of speech (Kleinow & Smith, 2000; van Lieshout, Starkweather, Hulstijn, & Peters, 1995). The current study is in line with a series of experiments designed to examine how neural processes occurring during linguistic tasks differ between individuals who stutter and those who are normally fluent (Cuadrado & Weber-Fox, 2003; Weber-Fox, 2001; Weber-Fox, Spencer, Spruill, & Smith, 2004). These experiments tap more general language processing abilities of adults who stutter when their speech production systems are not engaged, rather they are reading silently or listening to linguistic stimuli.

A growing body of evidence from brain imaging studies indicates that AWS exhibit atypical brain functions in perisylvian areas related to speech, language, and auditory processing. AWS displayed a hemispheric asymmetry characterized by overactivation of right cortical areas for speaking and for tasks that do not overtly engage the speech motor system (e.g., Braun et al., 1997; Fox et al., 1996; Fox et al., 2000; Ingham, Fox, Ingham, & Zamarripa, 2000; Preibisch et al., 2003). White matter volumes were observed to be reduced in left sensorimotor regions (Sommer, Koch, Paulus, Well, & Buchel, 2002), while increased white matter volumes were observed in right hemisphere perisylvian, prefrontal and sensorimotor areas in adults who stutter (Jancke, Hanggi, & Steinmetz, 2004). Preibisch and colleagues (2003) interpreted the atypical hemisphere activity they observed in the right frontal operculum during reading aloud and a silent semantic decision task as reflecting compensatory processes related to atypical functions in the left hemisphere as indicated by a reduction of white matter underlying the left sensorimotor cortex in the tongue and larynx regions in AWS (Sommer et al., 2002). Additionally, recent findings by Giraud et al. (In press) indicate that activity of the basal ganglia may be correlated with the severity of persistent stuttering. Functionally, fronto-temporal and temporal-parietal activations in the left hemisphere involving auditory functions were decreased in AWS, particularly during stuttering (Braun et al., 1997; Fox et al., 1996; Fox et al., 2000). Magneto-encephalography (MEG) findings in AWS further indicate atypical activation patterns in left perisylvian regions in preparation for speaking (Salmelin, Schnitzler, Schmitz, & Freund, 2000). In contrast to the sequence of activation observed in normally fluent speakers, the left inferior frontal area involved in speech planning became active after the rolandic areas involved in motor execution (Salmelin et al., 2000).

Recent findings from a MEG study of speech perception indicate that language processing in the auditory modality differs for AWS and adults who are normally fluent (AWNf). Biermann-Ruben and colleagues (Biermann-Ruben, Salmelin, & Schnitzler, 2005) examined neural activation during speech perception prior to overt repetition of a spoken word and sentence, and a sentence transformation task (Biermann-Ruben et al., 2005). The speaking task was delayed 500 ms after the offset of the word or sentence in order to observe activation patterns

during the speech perception phase. The findings indicated that compared to AWNF, AWS had greater activation of left inferior frontal areas, thought to be important for speech preparation, during the temporal window of 95–145 ms post-word and sentence onsets. In addition, between 315–1000 ms post-stimulus, activations of the right rolandic areas, thought to be involved in sensorimotor processing, were larger for single-word compared to sentence tasks for the AWNF, but the opposite pattern was seen for the AWS. These recent findings suggest that neural activation patterns of AWS differ from AWNF during speech perception (Biermann-Ruben et al., 2005). However, because the speech perception phase was followed by a delayed speaking task, it is not known whether the differences in activation would occur even without requirements to prepare for overt articulation. A previous study in normally fluent adults which did not require speaking following speech perception did not elicit activation in the temporo-parietal, inferior-frontal, and rolandic areas (Helenius, Salmelin, Service, & Connolly, 1998). Taken together, these findings suggest the possibility that the differences between the AWS and the AWNF observed by Biermann-Ruben and colleagues could have been to some degree due to activations for preparing to speak. The current study extends the work of Biermann-Ruben and colleagues by utilizing a natural speech processing paradigm that only requires a delayed button press for a sentence judgment task, thus, no preparation for overt articulation is necessary.

Earlier studies of language processing in AWS employing measures of event-related brain potentials (ERPs) revealed that language processing is subtly altered in AWS, even in the absence of overt speech production requirements (Weber-Fox, 2001; Cuadrado & Weber-Fox, 2003; Weber-Fox et al., 2004). These studies utilized visual language stimuli and revealed that, despite possessing language abilities that are within normal limits, some neural processes peaking after 250 ms are atypical in adults who stutter. Early latency cortical potentials (N100, N180, P200), thought to be more closely related to sensory, perceptual processes (Mangun & Hillyard, 1991), did not distinguish AWS and AWNF (Cuadrado & Weber-Fox, 2003; Weber-Fox, 2001; Weber-Fox et al., 2004). In contrast, endogenous, longer latency ERPs elicited in adults who stutter were characterized by reduced amplitudes. Both the N400 elicited by semantic anomalies and the late positivity (P600) elicited by verb-agreement violations were smaller in amplitude for AWS compared to AWNF. Thus, processes associated with integration of word meaning (indexed by the N400, e.g., Kutas & Hillyard, 1980) and syntactic re-analysis (indexed by the P600, e.g., Friederici, Hahne, & Mecklinger, 1996; Hagoort, Brown, & Grothusen, 1993; Neville, Nicol, Barss, Forster, & Garrett, 1991; Osterhout & Holcomb, 1992; Osterhout & Mobley, 1995) point to processing differences in AWS for both semantic and syntactic constraints, despite solid language skills indexed by standardized measures.

In order to understand the significance of these processing differences, it will be necessary to determine whether atypical ERPs are due to underlying distinctions in processing linguistic constraints, or whether they are due to processes mediating the conversion of orthographic symbols to phonological representations. Behavioral evidence suggests that reading involves phonological encoding of orthographic symbols for lexical access and may include processes of sub-vocal rehearsal or inner speech via an articulatory loop (Baddeley, 1992; Baddeley, Eldridge, & Lewis, 1981; Perfetti, 1999). Therefore, the question remains whether AWS process auditory language stimuli differently from AWNF. If the differences in neural functions observed in the visual studies were due primarily to silent “inner speech” processes (e.g., Baddeley, 1992), then natural speech may not elicit the same language processing differences. Converging evidence from the sentence processing ERP studies (Cuadrado & Weber-Fox, 2003; Weber-Fox, 2001) and findings from a visual rhyming study that manipulated orthographic and phonological congruence suggest that sentence processing constraints, rather than reading pairs of words, elicit more robust differences in ERPs between AWS and AWNF (Weber-Fox et al., 2004). These findings suggest that processing differences between AWS and AWNF are the result of interactions between multiple factors that are likely

to include language constraints and cognitive loading (Bosshardt, Ballmer, & de Nil, 2002; Weber-Fox et al., 2004). The current study was designed to investigate how AWS process auditory language stimuli, thus excluding the need for phonological encoding of grapheme symbols and the engagement of the “inner speech” articulatory loop. If differences in language processing for AWS include functions other than (or in addition to) those associated with the encoding of orthographic symbols, then their ERPs elicited by the natural speech stimuli should also display atypical patterns.

Therefore, we used a natural speech, sentence processing paradigm in the current study to examine both semantic and syntactic constraints. Further, the critical words for analysis were the verbs in each of the conditions. This allowed us to examine both semantic and syntactic processing for the same word class, verbs, at the same point in each sentence. It has been suggested that use of verbs may be particularly challenging for young children who stutter, and recent evidence indicates that these children may lag in the number of different verbs and total number of verbs produced in spontaneous speech (Wagovich & Ratner, 2007). Like nouns, verbs are conceptually rich and provide semantic information in a sentence, but in addition, they provide relational information for integrating inflections and argument structures across the sentence (Hirsh-Pasek & Golinkoff, 2006; Langacker, 1987; Osterhout, Kim, & Kuperberg, In press). Verb processing engages distinctive neural activations compared to nouns as indexed by measures of ERPs and functional magnetic resonance imaging (fMRI) in both children and adults (Federmeier, Segal, Lombrozo, & Kutas, 2000; Weber-Fox, Hart, & Spruill, 2006; Yokoyama et al., 2006). In a study utilizing class-ambiguous verbs/nouns (e.g., drink, smoke, hammer), Federmeier and colleagues (2000) noted that the role of words in a given context impacts the neural activations for processing that word. It has been suggested that verbs should engage syntactic and semantic processing streams (Osterhout et al., In press). Accordingly, the design of the current study allows for comparison of syntactic and semantic processing in AWS for the same critical verbs across conditions.

In summary, the current study builds on previous findings that suggest language processing differences between AWS and AWNF. Further, the design of the study allows us to explore the neural functions elicited for linguistic processing in the absence of preparation for overt articulation and/or engaging the internal articulatory loop. In addition, the focus on verbs as the critical comparative words across conditions provides indices of both syntactic and semantic constraints at the same point in sentence processing. Finally, employing natural speech stimuli (auditory modality) allow us to determine whether previously described differences in language processing are modality specific, or whether AWS exhibit differences in brain functions related specifically to linguistic operations.

Method

Participants and Screening Procedures

Participants were 9 adults who stutter (AWS) and 9 adults who are normally fluent (AWNF) between the ages of 18 and 45 years. Participants were matched according to age, gender, and educational background (Table 1). All AWS reported a history of developmental, childhood stuttering. All participants were right handed as determined by the Edinburgh Inventory for assessment of handedness (Oldfield, 1971) and were native English speakers with no reported history of neurological, language, reading, or hearing impairments. Stuttering behaviors were verified during administration of The Stuttering Severity Instrument for Children and Adults (SSI-3; Riley, 1994), which were video recorded, and during interactions over the course of the experiment. The SSI-3 was administered by speech-language pathology graduate students who had clinical training in stuttering, and were supervised by a certified speech-language pathologist.

The language abilities of the participants were assessed and all participants scored within normal limits on four subtests of the Test of Adolescent and Adult Language, including the listening and speaking grammar and vocabulary subtests (TOAL-3, Hammill, Brown, Larsen, & Wiederholt, 1994). The composite standard scores for the 4 subtests are displayed in Table 2 for the AWS and the AWNF (Group Standard Scores: $F(1, 16) < 1$). All participants also exhibited normal hearing in each ear as confirmed by hearing screening at a level of 30 dB HL at 500, 1000, and 2000 Hz presented via headphones. Also, each participant demonstrated normal or corrected-to-normal vision according to self-report and confirmed by a visual acuity screening of each eye using a standard eye chart.

Stimuli for the Sentence Processing Task

The stimuli were 180 naturally spoken sentences produced by a female speaker and digitized at a rate of 16 kHz. For each word up to and including the critical word (verb), the visual display of the auditory waveform was used to pick the onsets and offsets and then perceptually checked to make sure the word was not clipped (Cool Edit). The wave files for each word, converted to sound files, were then presented (Neuroscan STIM program) with a 50 ms interval interjected between each word up to and including the word following the critical verb comparison. Thus, onsets of each word were clearly discernable while maintaining a natural sounding rate, rhythm, and prosody. The sentence stimuli consisted of three conditions. In all cases the verb was the critical word. The conditions included a control (e.g., Everyday, the children *pretend* to be superheroes), a verb agreement violation (e.g., Everyday, the children **pretends* to be superheroes), and a semantically unexpected verb (e.g., Everyday the children **rust* to be superheroes). A sample of the sentence stimuli are listed in Table 3. These sentences were designed so that all the words leading up to the critical word (the verb) were identical across the three conditions so that the ERPs elicited by the verbs in each condition could be directly compared. Also, the sentences were counterbalanced in the following ways: first, half of the noun subjects in the sentences were singular and half were plural, and secondly, each word that served as a control verb also served as a semantically unexpected verb in another sentence. For the semantic condition, the critical word (the verb) does not produce a frank anomaly in many cases, but rather is unexpected. This is an attribute of verbs; unlike nouns, they are quite flexible in usage. However, as the sentence continues, it becomes clear that the meaning of the verb is incorrect. For example, “Everyday the ballerina *submerges* on her pointed toe shoes”. The ERP measures at the point of the verb therefore do not reflect the additional semantic information provided by the completion of the sentence. So, the ERPs elicited by the verbs across the three conditions reflect processing of identical information leading up to the verb, and the additional information following the verb does not confound a comparison of the ERP measures across the three conditions.

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 10–10 system (American Electroencephalographic Society, 1994). 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 linked 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 5 kohms or less. The electrical signals were amplified within a bandpass of .1 and 100 Hz and digitized on-line (Neuroscan 4.0) at a rate of 500 Hz.

Procedures

Each participant completed the informed consent forms and medical/case history forms. All participants were encouraged to ask questions. Once appropriate impedance levels were obtained, the participants were seated comfortably in a sound-attenuating room and positioned 160 cm from a 47.5 cm monitor. The experimental task was explained and headphones were positioned over the electrode cap.

Participants were instructed to listen to each of the sentences and judge whether each sentence was a good English sentence and made sense. They were also asked to refrain from blinking during trials. As the experiment was self-paced, the participant triggered the beginning of a trial with a button press. A fixation point appeared on the screen and, following a delay of 1000 ms, the sentence was presented binaurally through headphones at 70–75 dB SPL. Following the presentation of the sentence, there was a delay of 500 ms, followed by a “Yes/No?” presented on the screen to cue the participant to press the “Yes” button if the sentence was a good English sentence and made sense. Otherwise, they were instructed to press “No”. The response hands corresponding to the “Yes” and “No” buttons were counterbalanced across participants, gender, and within each of the groups. The sentence stimuli were presented in 5 blocks with 36 sentences in each block. The sentences were pseudo-randomized so that each condition was equally represented in all blocks. Because the task was self-paced, the time for completion varied across participants between ~45–55 minutes.

Data Analyses

Behavioral Measures—Sentence judgment accuracy was obtained from signals generated by the response pad. Sentence judgment accuracies for each participant in each condition were compared using mixed effects ANOVAs with repeated measures that included a between-subject-factor (group: AWS, AWF) and a within-subject-factor (condition: control, verb-agreement violation, semantic). Using the MS-error terms of the repeated measures analysis, post-hoc comparisons were made using the Tukey HSD method to determine which comparisons contributed to significant effects (Hays, 1994).

ERP Measures—Trials with excessive eye movement or other forms of artifact (29%) were excluded from further analyses of the ERP responses. The rejected trials were equally distributed across the three conditions. The remaining trials were averaged by condition for each participant. The averages were triggered 100 ms prior to the verb in each sentence and included 1500 ms post stimulus onset. The ERP data from the 100 ms interval prior to the prime and target onsets served as the baseline activity. The peak latencies of ERP components were computed in relation to the trigger point (0 ms) that marked the verb onsets. The peak latencies and peak and mean amplitudes were automatically detected using Neuroscan 4.2 software within specified temporal windows that captured the ERP components elicited in this paradigm, as described below.

For ERPs elicited by the verbs in each of the three conditions, the peak and mean amplitudes and peak latencies of the N400 were measured within the temporal window of 300–550 ms post stimulus onset. The mean amplitude of the later, broader positive component (P600) was measured within the temporal window of 850–1150 ms. ERP peak and mean amplitudes and peak latencies were compared with mixed effects ANOVAs with repeated measures. For analyses of the ERP responses elicited at lateral and mid-lateral electrode sites, ANOVAs with repeated measures included a between-subject factor of group (AWS, AWF) and 3 within-subject factors including condition (control, verb-agreement violation, semantic), hemisphere (left and right) and electrode site (FC3/4, T7/8, TP7/8, C3/4, CP3/4, P3/4). For analyses of ERPs elicited at midline sites, the repeated measures ANOVAs included a between-subject-factor of group (AWS, AWF) and 2 within-subject-factors including condition (control, verb-

agreement violation, semantic), and electrode site (FCZ, CZ, CPZ, PZ, OZ). The subset of electrode sites used for the comparisons provided a distribution of sampling from anterior to posterior midline sites in addition to sites over the left and right hemispheres where reliable peaks could be measured. Significance values were set at $p < .05$. For all repeated measures with greater than one degree of freedom in the numerator, the Huynh-Feldt ($H-F$) adjusted p -values were used to determine significance (Hays, 1994). The effect sizes, indexed by the partial-eta squared statistic (e^2_p), are reported for all significant effects. Interactions involving Group ($H-F p < .08$) were followed-up with step-down ANOVAs for each group to determine effects specific to the AWNF and AWS. The repeated measures ANOVAs were identical in design as described above without the between-subject-factor of group. Tukey HSD post hoc comparisons, which utilize the MS Error term from the repeated measures ANOVA, were calculated for significant interactions involving multiple variables to determine which comparisons contributed to the significant F values (Hays, 1994).

Results

Sentence Judgment Accuracy

The AWS and the AWNF performed with high and similar accuracy on the detection of verb-agreement and semantic violations, $F(1, 16) = 1.143$, $p = .301$. The effect of condition, $F(2, 32) = 9.927$, $H-F p = .001$, $e^2_p = .383$, revealed that the accuracy in detecting verb-agreement violations was reduced relative to the control and semantic conditions for all the subjects combined, Tukey HSD, $p < .05$. As can be seen in Figure 1, mean accuracy appeared reduced for the AWS in the control condition, however, the interaction between group and condition did not reach significance, $F(2, 16) = 2.518$, $H-F p = .11$.

ERPs

The grand average ERPs elicited by the verbs in the three sentence conditions are illustrated in Figures 2 and 3 for the AWNF and the AWS groups respectively. As anticipated on the basis of earlier studies (e.g., Friederici et al., 1993), the verbs in the control, verb-agreement, and semantic conditions elicited distinct waveforms in the AWNF. The N400 elicited in the semantic condition and the P600 elicited in the verb-agreement condition for the AWNF can be observed in Figure 2. Figure 3 illustrates the N400 and P600 responses elicited in the AWS. The similarities and differences of the N400 and P600 across the conditions and groups are summarized below.

N400—The mean (SE) peak latency of the N400 component was 414.2 ms (7.3) over lateral/mid-lateral sites and 409.8 ms (8.4) over midline sites. There were no significant effects of condition or interactions between condition and group on the peak latency of the N400 measured over the lateral/mid-lateral and midline electrode sites, $F(2, 32) < 1$.

The semantic condition elicited larger peak and mean N400 amplitudes compared to the control condition for lateral/mid-lateral sites, $F(2, 32) = 5.229$, $H-F p = .011$, $e^2_p = .246$, $F(2, 32) = 3.304$, $H-F p = .057$, $e^2_p = .171$, and midline sites, $F(2, 32) = 6.950$, $H-F p = .003$, $e^2_p = .303$, $F(2, 32) = 5.339$, $H-F p = .014$, $e^2_p = .250$ (Tukey HSD $p < .05$). While the N400 peak and mean amplitude measures did not result in overall group differences for lateral/mid-lateral or midline sites, $F(1, 16) < 1$, there was a consistent trend for an interaction between condition and group for the peak and mean amplitude measures of lateral/mid-lateral sites, $F(2, 32) = 2.697$, $H-F p = .08$, $e^2_p = .144$, $F(2, 32) = 2.845$, $H-F p = .08$, $e^2_p = .151$, and midline sites, $F(2, 32) = 2.791$, $H-F p = .08$, $e^2_p = .149$, $F(2, 32) = 2.890$, $H-F p = .08$, $e^2_p = .153$. In Figure 4, the peak and mean amplitudes of the N400s are plotted for both groups across conditions to illustrate the nature of these interactions between condition and group.

Step-down ANOVAs confirmed that for the AWNF, the mean amplitudes of the N400 at midline electrode sites were larger, $F(2, 16) = 5.994$, $H-F p = .011$, $e^2_p = .428$, for the semantic condition compared to both the control, Tukey HSD $p = .019$, and verb-agreement conditions, Tukey HSD $p = .025$ (Figure 4). A similar pattern was observed for the peak amplitude N400 measures of midline sites, $F(2, 16) = 3.901$, $H-F p = .042$, $e^2_p = .326$, with post hoc results indicating a tendency for the N400 peak amplitude to be larger for the semantic condition compared to the N400 elicited by the control and verb-agreement conditions, Tukey HSD $p < .07$. The peak and mean amplitudes of the N400 for AWNF at lateral/mid-lateral sites also tended to be larger for the semantic condition compared to the N400 elicited in the control condition, $F(2, 16) = 3.442$, $H-F p = .057$, $e^2_p = .301$, $F(2, 16) = 3.498$, $H-F p = .055$, $e^2_p = .304$, (Tukey HSD $p < .08$). In summary, the N400 amplitudes elicited in the AWNF were, as expected, larger for the semantic condition compared to the control and verb-agreement conditions.

Step-down ANOVAs for the AWS presented an unexpected pattern for the N400 amplitudes. The condition effects for the mean amplitude measures at midline electrode sites did not reach significance, $F(2, 16) = 2.456$, $H-F p = .141$, $e^2_p = .235$. However, a significant condition effect for the peak amplitude measures of the N400 at midline electrode sites for the AWS, $F(2, 16) = 6.076$, $H-F p = .015$, $e^2_p = .432$, revealed that the N400 amplitude was larger for the semantic and verb-agreement conditions relative to the control, Tukey HSD, $p < .03$ (Figure 4). Further, the N400 peak amplitudes elicited by the semantic and verb-agreement conditions were not different, Tukey HSD $p = .94$. The mean amplitude measures for the N400 at lateral/mid-lateral sites did not reach significance, $F(2, 16) = 2.364$, $H-F p = .146$, $e^2_p = .228$. However, a significant condition effect for the N400 peak amplitudes at lateral/mid-lateral sites, $F(2, 16) = 4.981$, $H-F p = .021$, $e^2_p = .384$, revealed that the N400 peak amplitude was larger for the verb-agreement violation relative to the control, Tukey HSD $p = .017$, a comparison that did not reach significance for the N400 elicited by the semantic condition, Tukey HSD $p = .133$. Once again, there were no differences between the N400 peak amplitudes elicited by the semantic and verb-agreement conditions, Tukey HSD, $p = .55$. In summary, unlike the ERPs of the AWNF that displayed a unique N400 amplitude increase for the semantic condition, the N400 amplitudes of the AWS were not distinguishable for the semantic and verb-agreement conditions. Instead, a significant N400 peak amplitude increase was elicited by the verb-agreement and semantic conditions relative to the control at the midline electrode sites; whereas at lateral/mid-lateral electrode sites, only the verb-agreement violations elicited a significantly larger N400 peak amplitude compared to the control condition.

P600—Measures of the mean amplitudes of the P600, illustrated in Figure 5, revealed an effect of condition for both the lateral/mid-lateral electrode sites, $F(2, 32) = 8.329$, $H-F p = .001$, $e^2_p = .342$, and midline sites, $F(2, 32) = 15.689$, $H-F p < .0001$, $e^2_p = .495$. Post-hoc comparisons for the mean amplitude measures at lateral/mid-lateral and midline electrodes sites revealed that the verb-agreement condition elicited a larger amplitude P600 compared to the control, Tukey HSD $p < .003$, and semantic conditions, Tukey HSD $p < .005$.

The mean amplitudes of the P600 did not result in overall group differences, $F(1, 16) < 1.322$, $H-F p > .266$. However, group interacted significantly with condition for the mean amplitude measures for both the lateral/mid-lateral sites, $F(2, 32) = 4.276$, $H-F p = .02$, $e^2_p = .211$, and midline sites, $F(2, 32) = 5.496$, $H-F p = .009$, $e^2_p = .256$. Figure 5 illustrates the nature of these interactions between condition and group.

Step-down ANOVAs revealed that for the AWNF, the mean amplitudes of the P600 at midline electrode sites were larger for the verb-agreement condition, $F(2, 16) = 15.343$, $H-F p < .001$, $e^2_p = .657$, compared to both the control, Tukey HSD $p = .018$, and semantic conditions, Tukey HSD $p = .0003$ (Figure 5). In addition, the mean amplitudes of the P600 for AWNF at lateral/

mid-lateral sites were larger for the verb-agreement condition compared to the P600 elicited in the semantic condition, $F(2, 16) = 7.898$, $H-F p = .004$, $e^2_p = .497$, Tukey HSD, $p = .003$. The P600 mean amplitudes at the lateral/mid-lateral electrode sites for the verb-agreement condition also tended to be larger than the P600 elicited in the control condition, Tukey HSD $p = .10$. Thus, for the AWNF, as expected, the verb-agreement violation elicited a larger amplitude P600 compared to the control (midline electrode locations) and semantic conditions (midline and lateral/mid-lateral electrode locations).

In contrast, follow-up ANOVAs for the AWS presented a somewhat surprising pattern for the P600 amplitudes (Figure 5). Significant condition effects for the mean amplitude measures at midline electrode sites, $F(2, 16) = 7.037$, $H-F p = .006$, $e^2_p = .468$, revealed that the P600 amplitude was larger for the verb-agreement violation compared to the control condition, Tukey HSD $p = .005$; however, the P600 amplitudes elicited by the semantic and verb-agreement conditions were not different, Tukey HSD $p = .12$. The mean amplitude measures for the P600 at lateral/mid-lateral sites followed a similar pattern. The significant condition effects, $F(2, 16) = 4.560$, $H-F p = .047$, $e^2_p = .363$, revealed a larger P600 elicited by the verb-agreement violation compared to the control condition, Tukey HSD $p = .025$. Once again, there were no differences between the P600 peak amplitudes elicited by the semantic and verb-agreement conditions, Tukey HSD $p = .68$. In summary, unlike the ERPs of the AWNF that displayed a typical P600 amplitude increase for the verb-agreement violation condition (and not for the semantic condition), the P600 amplitudes of the AWS were not distinguishable for the semantic and verb-agreement conditions. Instead, the P600 amplitude elicited for the semantic condition was not different from the control or verb-agreement conditions.

Discussion

A natural speech processing paradigm was utilized with adults who stutter (AWS) to examine whether previously described differences for semantic and syntactic processing of visual stimuli were also present for auditorally presented stimuli. AWS performed similarly to adults who are normally fluent (AWNF) in identifying verb-agreement violations and semantic anomalies. However, the cognitive processes involved in the processing of syntactic and semantic constraints, as indexed by the N400 and P600 ERPs, indicated that the neural functions mediating these tasks differ for a significant proportion of AWS. These findings converge with results in the visual modality to indicate that, while AWS display linguistic abilities that are within normal limits on standardized tests of language abilities, the underlying brain activity mediating some aspects of language processing is atypical for a significant number of individuals in this population, even in the absence of preparation for overt speaking. These results are compatible with recent MEG findings that indicate differences in neural activations for speech perception in adults who stutter (Biermann-Ruben et al., 2005).

Modality Specific Effects

The current findings for language processing in the auditory modality reveal underlying distinctions between AWS and AWNF that are qualitatively different than those observed for visual language processing studies (Cuadrado & Weber-Fox, 2003; Weber-Fox, 2001; Weber-Fox et al., 2004) and provide new insights into possible language processing differences between AWS and AWNF. Language processing in the visual modality requires conversion of orthographic symbols into phonological representations and may tap into “articulatory loop” mechanisms not involved for processing in the auditory modality (Baddeley, 1992). The current findings extend the previous work to indicate that AWS exhibit atypical neural activation patterns for language processing even without the additional cognitive load of engaging neural functions that may be involved in “inner speech” when reading. Therefore, differences in language processing between AWS and AWNF are not limited to the visual modality.

The differences observed for ERPs elicited by natural speech processing are, however, qualitatively different. Also, unlike findings for verb-agreement violations presented visually in an ERP paradigm, (Cuadrado & Weber-Fox, 2003), the behavioral measures for the auditory sentences were similar for AWS and AWNF. Thus, the results from the current study indicate that some aspects of the behavioral and ERP differences between AWS and AWNF in visual language studies may have been specific to the encoding requirements of reading. However, given the results of the current study, it is clear that AWS exhibit more general language processing differences as well, despite language skills that are within the normal range as indexed by standard language testing.

Semantic and Syntactic Constraints

Normally Fluent Speakers—These sentences allowed us to examine differences between semantic and syntactic constraints imposed on the processing of the verbs in each sentence. The AWNF displayed robust N400 responses to the verbs that were semantically unexpected. Although the meanings of the verbs did not pose a frank semantic violation at the point in the sentence when the verbs were being processed (e.g., you could imagine a cartoon horse singing), the verbs in this condition were unusual and low probability. Based on previous literature, a relatively small but significant N400, as observed in the current study, would be expected, because the amplitude of the N400 indexes ease of semantic integration (e.g., Kutas & Hillyard, 1980; Friederici, Pfeifer, & Hahne, 1993; Federmeier & Kutas, 2000). In contrast, the verb-agreement violation did not elicit an N400 in the AWNF. Instead a late positivity, known as a P600, characterized the verb-agreement condition. Again, this finding for the AWNF is consistent with previous reports of the P600 indexing syntactic re-analysis (e.g., Friederici et al., 1996; Hagoort et al., 1993; Neville et al., 1991; Osterhout & Holcomb, 1992). Thus, for the normally fluent speakers, an unexpected verb in these simple sentences did not trigger the need for syntactic re-analysis and repair (as indexed by the P600) and the verb-agreement violation did not impose greater difficulty in semantic integration (as indexed by the N400). Rather, for the AWNF, the ERPs elicited by the semantic and syntactic conditions engaged processing streams that were specific to the constraints being challenged.

Adults Who Stutter—The unexpected verbs in the semantic condition elicited N400 responses in AWS similar to those of AWNF, suggesting a similar increase in difficulty with semantic integration. However, a surprising finding for this group was that the verb-agreement violation also elicited an N400, suggesting that the anomalous morphological ending (presence or absence of the “s”) also increased difficulty in semantic integration. The verb-agreement violations also elicited a P600, indicating that this increased difficulty in semantic integration was followed by the more typical syntactic re-analysis process. For the semantic condition, the P600 was not significantly different from the control condition, but also was not different from the P600 elicited by the verb-agreement violation, thus falling somewhere in between the two conditions. Therefore, the general pattern for the AWS reflects a less differentiated processing system compared to their normally fluent peers in that the semantic and syntactic constraints elicited both N400 and P600 components for relatively uncomplicated violations of simple sentences.

It could be argued that it is not surprising that the verb stimuli in the current study elicited a more biphasic pattern (N400-P600) in AWS. As reviewed by Osterhout et al. (In press), the processing of verbs should engage both the semantic and syntactic processing streams because verbs are conceptually and semantically rich while providing relational information for syntax. However, it is not clear why the AWS would engage these processing streams less selectively compared to AWNF. One possibility is that the processing of verbs imposes a greater cognitive load for AWS. From the developmental literature, it is clear that verbs impose high processing loads for sentence comprehension and include integrating inflections and argument structures

(Hirsh-Pasek & Golinkoff, 2006). Further, ERP evidence in school-age children indicate that verbs elicit one of the longest peak latencies of the second negative component, thought to index the initial availability of the word's lexical category (Brown, Hagoort, & Ter Keurs, 1999), compared to other categories, such as nouns and conjunctions (Weber-Fox, Hart, & Spruill, 2006). Further, errors in comprehension and production of verbs are common in children with specific language impairments, and it has been argued that these children have particular difficulty with the additional grammatical complexity that verbs require for sentence processing (Leonard, 1998; Leonard & Deevy, 2003). Recent evidence from language sample analyses indicate that verbs may create a greater challenge for young children who stutter compared to their typically developing peers (Wagovich & Ratner, 2007). Additionally, verb morphological complexity was observed to increase stuttering rates for some children and adults who stutter (Marshall, 2005). The current findings suggest that these early differences in verb usage proficiency may be reflected in adulthood by these more subtle measures of processing semantic and syntactic constraints on verbs. Future ERP studies in children who stutter are needed to explore the nature of the relationships between developmental differences in language abilities at early stages of stuttering and neural online-processing patterns elicited by linguistic stimuli.

The current finding of a biphasic N400-P600 response in AWS may indicate that the disorder of stuttering may be associated with a processing strategy that is only seen for more complex sentence processing in normally fluent adults. Recent investigations of language processing in normal adults have revealed that N400 and P600 can reflect the interface between semantic and syntactic processing under conditions that require complex on-line linguistic operations (e.g., Friederici & Frisch, 2000; Kemmerer, Weber-Fox, Price, Zdanczyk, & Way, 2007; Kim & Osterhout, 2005; Kolk, Chwilla, van Herten, & Oor, 2003; Kuperberg, Kreher, Stinikova, Caplan, & Holcomb, 2007). For example, Friederici & Frisch (2000) observed that thematic role violations were primarily semantic (elicited an N400) and violations of the type of verb arguments were syntactic (elicited a P600). However, a violation in the number of verb arguments (intransitive verb occurred with two arguments) elicited semantic processes followed by syntactic re-analysis and repair (biphasic N400-P600 combination). The findings of Friederici & Frisch (2000) indicated that during sentence processing, the structural and thematic information encoded by the verb is checked against the information that has been formed on-line. Their findings demonstrate that the degree of engagement of semantic and syntactic processing operations for normal speakers is fluid and depends on the type of linguistic information that must be integrated for continuing to process the sentence. The results from the current study suggest that, when processing the information provided by verbs, the processing systems of AWS may be less fluid. That is, the AWS may engage the semantic and syntactic processing streams less efficiently for relatively simple violations that elicit more selective activation patterns in AWF.

Conclusions

ERPs provide a functional measure of neural activity with fine temporal resolution (Nunez, 1995) and allow the examination of specific operations of language processing (e.g., Friederici, 1997; King & Kutas, 1995; Kutas & Hillyard, 1980; Neville, et al., 1991; Osterhout & Holcomb, 1992; Weber-Fox, et al., 2006). The converging evidence from the current study and from the prior series of ERP studies in AWS (Cuadrado & Weber-Fox, 2003; Weber-Fox, 2001; Weber-Fox et al., 2004), indicate that stuttering is associated with differences in language processing activations, even in the absence of overt-speech planning and production. Our results are compatible with multi-factorial models of stuttering (e.g., Smith, 1990; Smith & Kelly, 1997) and indicate that the disorder with its associated differences in brain morphology impacts not only the coordination of the speech-motor system, but may also be reflected in the

efficiency of operations related to the integration and differentiation of semantic and syntactic streams involved in language processing.

Notably, stuttering is a developmental disorder and the differences we observe for language processing in adults who stutter may not reflect processing that distinguishes young children who stutter from their typically developing peers. In a recent study of school-age children who stutter (CWS, Weber-Fox, Spruill, Spencer, & Smith, In press) the behavioral and ERP differences between CWS compared to their normally fluent peers were qualitatively different and much more pronounced than those in AWS observed in an earlier study from our laboratory (Weber-Fox et al., 2004). These findings reinforce the need for developmental stuttering research. Therefore, as a follow-up to the current study, it will be necessary to study syntactic and semantic processing in children who stutter to gain a better understanding about how neural functions for language processing may contribute to the development of the disorder.

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Figure 1.

The percentage correct for judging the sentences is plotted for AWNF and AWS across each condition. While performance was high across the conditions, the accuracy was significantly lower for the verb-agreement condition.

Adults Who are Normally Fluent

Figure 2.

Grand average ERPs elicited by the control, verb-agreement, and semantic conditions for the adults who are normally fluent (AWNf). ERPs from midline electrodes sites and from lateral/mid-lateral sites over the left and right hemispheres included in the statistical analyses are illustrated. Negative potentials are plotted upward. The grand averages for the AWNF show distinctions in the waveforms elicited by each of the 3 conditions, including a clear N400 for the semantic condition and a robust P600 for the verb-agreement condition.

Adults Who Stutter

Figure 3.

Grand average ERPs elicited by the control, verb-agreement, and semantic conditions for the adults who stutter (AWS). ERPs from midline electrodes sites and from lateral/mid-lateral sites over the left and right hemispheres included in the statistical analyses are illustrated. Negative potentials are plotted upward.

Figure 4. N400 peak and mean amplitudes elicited in AWNF and AWS across the three conditions. Just as in the ERP figures, negative potentials are plotted upward.

Figure 5. P600 mean amplitudes elicited in AWN and AWS across the three conditions. Just as in the ERP figures, positive potentials are plotted downward.

Table 1

Characteristics of Participants

Participant	Adults who Stutter			Adults who are Normally Fluent		
	Age	Gender	Education	Age	Gender	Education
1	25	F	6	25	F	6
2	41	M	7	43	M	5
3	34	M	3	35	M	5
4	18	M	1	19	M	2
5	22	F	5	23	F	5
6	21	M	3	22	M	5
7	41	M	5	42	M	5
8	43	M	4	45	M	5
9	26	M	7	26	M	5
Mean	30.11		4.55	31.11		4.78
SE	2.93		0.60	3.06		0.33

Note: Education Levels: 1 = High School Graduate, 2 = 1 yr college, 3 = 2 yrs college, 4 = 3 yrs college, 5 = 4 yrs college, 6 = 1st year graduate school, 7 = Master Degree completed

Table 2

Standard Scores for the TOAL-3

<u>Participant</u>	<u>Adults who Stutter</u>		<u>Adults who are Normally Fluent</u>	
	<u>Standard Score</u>	<u>Percentile</u>	<u>Standard Score</u>	<u>Percentile</u>
1	113	81	108	70
2	107	68	108	70
3	105	63	85	16
4	100	50	90	25
5	102	55	98	45
6	109	73	117	87
7	105	63	108	70
8	90	25	93	32
9	113	81	125	95
Mean	104.89	62.11	103.55	56.67
SE	7.13	17.47	13.09	28.11

Note. Standard Scores were calculated from a composite of 4 subtests of the TOAL-3: Listening Vocabulary, Speaking Vocabulary, Listening Grammar, and Speaking Grammar

Table 3
Sample of Stimulus Sentences

Correct verb (verb-agreement violation, reduced semantic expectation)

1. Everyday the horses *gallop* (*gallops, sing*) to the top of the hill.
 2. Everyday the canaries *sing* (*sings, gallop*) at the top of their lungs.
 3. Everyday the secretary *types* (*type, grazes*) many legal documents.
 4. Everyday the cow *grazes* (*graze, types*) along the fence line.
 5. Everyday the ballerina *dances* (*dance, submerges*) on her pointed toe shoes.
 6. Everyday the submarine *submerges* (*submerge, dances*) to a depth of five hundred feet.
 7. Everyday the beauticians *style* (*styles, slither*) at least 30 heads.
 8. Everyday the snakes *slither* (*slithers, style*) through the fallen leaves.
-