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Electrophysiological responses to argument structure violations in healthy adults and individuals with agrammatic aphasia

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Abstract

Sentence comprehension requires processing of argument structure information associated with verbs, i.e. the number and type of arguments that they select. Many individuals with agrammatic aphasia show impaired production of verbs with greater argument structure density. The extent to which these participants also show argument structure deficits during comprehension, however, is unclear. Some studies find normal access to verb arguments, whereas others report impaired ability. The present study investigated verb argument structure processing in agrammatic aphasia by examining event-related potentials associated with argument structure violations in healthy young and older adults as well as aphasic individuals. A semantic violation condition was included to investigate possible differences in sensitivity to semantic and argument structure information during sentence processing. Results for the healthy control participants showed a negativity followed by a positive shift (N400-P600) in the argument structure violation condition, as found in previous ERP studies (Friederici & Frisch, 2000; Frisch, Hahne, & Friederici, 2004). In contrast, individuals with agrammatic aphasia showed a P600, but no N400, response to argument structure mismatches. Additionally, compared to the control groups, the agrammatic participants showed an attenuated, but relatively preserved, N400 response to semantic violations. These data show that agrammatic individuals do not demonstrate normal real-time sensitivity to verb argument structure requirements during sentence processing.

Keywords

verb argument structure; event related potentials; language-related brain potentials; N400; P600; semantic processing; agrammatic aphasia

1. Introduction

Auditory sentence comprehension requires rapid analysis of complex auditory signals and construction of syntactic structures and meaning representations. Models of language

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processing suggest that phonological, syntactic and semantic information is accessed and coordinated within milliseconds in order to successfully understand sentences (Friederici, 2002, Friederici & Kotz, 2003; Hagoort, 2003; Kaan & Swaab, 2002). In particular, integration of information associated with verbs is essential for successful sentence comprehension. Verbs are central elements in this process because they specify the number of arguments that appear in the sentence, the thematic roles of these arguments (e.g., *agent*, the performer of an action; *theme*, the recipient of the action), the syntactic positions in which they occur (subject, direct object, etc.) and their syntactic realization (noun phrase, prepositional phrase, clause, etc.; This information is also referred to as *subcategorization* information). For instance, the intransitive verb *sneeze* requires only one, external, argument (an agent) as in: *John sneezed.* In contrast, the transitive verb *fix* requires two arguments (an agent and a theme) as in: *John fixed the car.* Other verbs take three arguments, requiring an agent, a theme, and a goal (e.g., *John gave the book to the teacher).*

A growing number of studies demonstrate that argument structure information of verbs is immediately and automatically activated during sentence processing (Carlson & Tannenhaus, 1988; MacDonald, Pearlmuter, & Seidenberg, 1994; Mauner & Konig, 2000; Shapiro, Brookins, Gordon, & Nagel, 1991; Shapiro, Gordon, Hack, & Killackey, 1993; Shapiro & Levine, 1990; Trueswell & Kim, 1998). For example, in a series of studies using a cross-modal lexical decision task, Shapiro and colleagues showed that lexical decision times to visually presented targets were longer when presented in the vicinity of verbs with more argument structure/subcategorization options. In addition, it has been shown that verbs prime for their arguments (Ferreti, McRae, & Hatherell, 2001), and that a verb's thematic specifications are used to pro-actively restrict the domain of subsequent reference (Altmann & Kamide, 1999).

Verb argument structure processing ability in individuals with Broca's (agrammatic) aphasia, however, is unclear. Several studies have found impairments in producing verbs and sentences with complex argument structures. For example, Kim and Thompson (2000) found that for English-speaking agrammatic individuals, three-argument verbs were more difficult to produce than two-argument verbs. A similar deficit was found in sentence production, evidenced by greater difficulty when producing sentences with more arguments as compared to those with fewer arguments (Thompson et al., 1997; Thompson, Dickey, Cho, Lee, & Griffin, 2007). These effects have been observed across different languages including English (Kim & Thompson, 2004; Thompson, 2003) German (De Blesser & Kauschke, 2003), Dutch (Jonkers & Bastiaanse, 1996, 1998), Italian (Luzzatti et al., 2002), Hungarian (Kiss, 2000), and Russian (Dragoy & Bastiaanse, 2009)

The nature of this deficit, however, is not completely understood. Some findings suggest that the lexical representation of verb argument structure may be preserved in individuals with agrammatic aphasia. For example, studies have shown normal activation of argument structure and subcategorization information in cross-modal lexical decision tasks such as the ones discussed above (Shapiro et al., 1990, 1993). In addition, the agrammatic participants in Kim & Thompson (2000, 2004) showed no effect of argument structure complexity on comprehension in a word-to-picture matching task, performing at normal levels.

In two studies, Kim and Thompson (2000, 2004) also tested patients' ability to detect verb argument structure violations in a grammaticality judgment task in sentences with a missing obligatory argument (e.g. **The woman is giving the sandwich*; **The boy is carrying*) or with a noun phrase following an intransitive verb (e.g. **The dog is barking the girl*). In both studies, agrammatic participants performed at near normal level (means 93.6% correct, 92.1% correct, respectively). Grodzinsky & Finkel (1998) found a similar pattern in a study testing verb argument structure (and other syntactic) violations. In that study some sentences contained violations similar to those of Kim and Thompson: transitive verbs lacking an obligatory direct object (**The children threw*). In addition, they included verbs with semantically inappropriate complements (**The children sang the football over the fence*). Results showed mean performance at 91% correct.

Notably, grammaticality judgment is an off-line task, where participants make their responses after sentences have been fully presented. In contrast, on-line measures allow observation of the sentence processing as it unfolds in time. Event-related potentials (ERPs), in particular, provide continuous records of cognitive activities associated with language processing, and can thus offer more direct information as to the underlying cause of sentence processing impairments in agrammatic aphasia.

ERPs have been used extensively to investigate the time course of semantic and syntactic processes involved in language comprehension. Processing of semantic anomalies has been shown in many studies to be associated with a centro-parietally distributed negativity peaking around 400 msec post stimulus onset, labeled the 'N400'. In a pioneering study, Kutas & Hillyard (1980) found that the N400 component is elicited by presentation of semantic anomalies, indicating that it is sensitive to the semantic relations between individual words in the preceding language input. Subsequent studies in both auditory and visual domains found similar effects, suggesting that N400 amplitude reflects semantic processing, associated with restrictions resulting from sentence or discourse context (Connolly & Phillips, 1994; Friederici, Pfeifer, & Hahne, 1993; Holcomb & Neville, 1190; Munte, Heinze, & Mangun, 1993; Rosler et al., 1993; Osterhout & Nicol, 1999; vanBerkum et al., 1999). The N400 component also has been associated with lexical-semantic integration (Brown & Hagoort, 1993; Osterhout & Holcomb, 1992), with increasing semantic integration demands associated with increases in N400 amplitude.

In contrast to N400 semantic violations, manipulations of syntactic structure are associated with two main ERP components: a left anterior negativity (LAN) between 100 and 500 msec, and a late centro-parietal positivity peaking at around 600 msec, labeled the 'P600'. The P600 component has been found to be sensitive to a variety of syntactic anomalies, including phrase structure violations (Neville, Nicol, Barss, Foster, & Garrett, 1991; Friederici, Hahne, & Mecklinger, 1996), errors of agreement (Coulson et al., 1998; Osterhout & Mobley, 1995), verb inflection (Gunter & Friederici, 1999; Osterhout & Nicol, 1999), and subcategorization violations (Ainsworth-Darnell, Shulman, & Boland, 1998; Osterhout, Holcomb, & Swinney, 1994). The P600 also has been found for garden-path sentences as well as other grammatical, but syntactically nonpreferred, constructions (Osterhout & Holcomb, 1992, 1993; Osterhout, Holcomb, & Swinney, 1994). More recently, the P600 component has been conceived of as an index of syntactic reprocessing cost (Osterhout, Holcomb, & Swinney, 1994), syntactic complexity or ambiguity (van Berkum, Brown, & Hagoort, 1999), or syntactic integration difficulty in general (Kaan, Harris, Gibson, & Holcomb, 2000). Based on these findings, it has been proposed that this late positivity reflects processes of syntactic reanalysis and repair (Friederici et al., 1996; Friedrici & Meyer, 2004; Friederici & Kotz, 2003; Friederici & Weissenborn, 2007; Gunter, Stowe, & Mulder, 1997).

Several ERP investigations have found distinct electrophysiological signatures for different aspects of verb processing. Specifically, violations of subcategorization requirements (e.g. **The cousin visited <u>to the violinist</u>* instead of *The cousin visited <u>the violinist</u>*) are associated with a LAN-P600 pattern, related to syntactic processing, as mentioned above. In contrast, violations of the correct number of arguments (e.g. *The cousin dawdled *<u>the violinist</u>*) elicit a biphasic N400-P600 pattern (Friederici & Frisch, 2000; Frisch, Hahne, & Friederici, 2004; Friederici & Meyer, 2004), reflecting both semantic and syntactic violations. This latter pattern has been interpreted to reflect different aspects of lexical-thematic integration process. The N400 results from difficulty in integration of thematic information when obligatory arguments are missing (e.g., **John gives a car*), or when illicit arguments are present (e.g., **John sleeps a bed*), whereas the P600 reflects an attempt at syntactic reanalysis or repair following thematic integration failure. This interpretation is consistent with Frisch and Schlesewsky (2001) who found an N400-P600 pattern for German sentences with two noun phrases marked as grammatical subjects, arguably causing a similar failure of thematic integration. It is likewise consistent with the idea that the P600 effect does not reflect the detection of outright syntactic or semantic violations. Rather, it reflects accommodation processes arising from a surprising or dispreferred sentence continuation, as argued in Friederici & Frisch (2000).

Event-related potentials also have been used to study language deficits in aphasia. Several ERP studies investigated aphasic participants' lexical-semantic processing. In one such study, Swaab, Brown, and Hagoort (1997) investigated ERP responses to auditorily presented sentences containing a semantically anomalous word in sentence final position (e.g., **The girl dropped the candy on the sky*). The authors found that as a group, patients showed a preserved N400 effect to semantic violations. However, these effects were modulated according to the degree of comprehension deficit, such that individuals with severe comprehension deficits showed a reduced and delayed N400 effect, whereas those with mild deficits showed N400 patterns similar to those of normal controls. Similar results are reported in Hagoort, Brown, & Swaab (1996) in a study using unrelated and related word pairs. In another study in Dutch, Wassenaar and Hagoort (2005) reported a reduced and delayed N400 effect to semantic violations for patients with Broca's aphasia in the visual modality. Finally, Kitade, Enai, Sei, & Morita (1999) found a delayed N400 effect in aphasic participants in a visual word recognition oddball paradigm. It seems thus to be the case that in general, aphasic participants display an N400 effect in the same conditions as healthy speakers do, but the effect is often delayed and attenuated, in correlation with the severity of their language deficits.

Syntax related ERP effects also have been shown to be modified in aphasic patients. In a series of studies, Hagoort and colleagues (Hagoort, Wassenaar, & Brown, 2003; Wassenaar, Brown, & Hagoort, 2004) recorded ERPs in healthy control and agrammatic participants while they listened to sentences that were either syntactically correct or contained violations of subject verb agreement (e.g., **The girls pay the baker and takes the bread home*). They found that healthy adults showed a P600 effect in response to this manipulation, whereas Broca's aphasic individuals did not. In addition, Broca's aphasic individuals have been found to display a reduced and delayed P600 effect to phrase structure violations (Wassenaar & Hagoort, 2005).

To our knowledge, no previous studies have investigated electrophysiological responses to argument structure violations in aphasic individuals. However, the results of a recent ERP study by Wassenaar & Hagoort (2007), investigating on-line thematic role assignment in a sentence-picture matching is relevant in this respect. In this study, ERPs were recorded while participants decided whether an auditorily presented sentence (e.g. *The cat licked the dog*) matched a visually displayed picture (e.g. of a dog licking a cat). Neurologically unimpaired individuals showed on-line sensitivity to thematic role assignment, displaying an early negative effect followed by a later positive shift in response to thematic mismatches between the picture and the sentence. In contrast, the ERP effects for agrammatic individuals in response to the mismatches were either significantly delayed or absent. However, they showed off-line behavioral sensitivity to the sentence-picture mismatches, suggesting that although they were able to detect the mismatch, this detection did not occur on-line. In addition, prolonged reaction times in the Broca's participant group indicate the need of these participants to use off-line response strategies for sentence interpretation.

1.1 The Present Study

The present study investigated how individuals with agrammatic aphasia process verb argument structure information in real time, using ERPs and a grammaticality judgment task. A semantic violation condition was also included, to determine whether participants evinced the classical N400 effect to semantic anomalies, and to track possible differences in sensitivity to semantic and argument structure information during sentence processing. The ERP signatures of aphasic speakers were compared to those of neurologically intact young and older controls. ERPs were recorded while participants engaged in an auditory grammaticality judgment task.

The argument structure violation condition was realized by placing intransitive verbs (e.g., *sneeze*), in an NP-V-NP string (e.g., **John sneezed the doctor*). We surmised that if argument structure information is automatically activated when the verb is presented, then the post-verbal NPs, which do not match the verb's argument structure requirements, would not be lexically integrated, and this mismatch would be mirrored as a modulation of the ERP waveform. Following the results of Friederici et al. (2000, 2004) in German, it was predicted that, for healthy volunteers, detection of a mismatch between the number of arguments a verb requires and the actual number of nouns appearing in the sentence will be reflected by a negativity followed by a later positive shift. Furthermore, if agrammatic individuals are impaired in on-line access to argument structure information, then these participants should be less sensitive to argument structure violations and display a deviant pattern of ERP responses.

Following Kutas & Hillyard (1980) and Swaab et al. (1997), the semantic anomaly condition was developed by placing a contextually anomalous word in the sentence final position. We anticipated that difficulty integrating the semantically incongruent word with the preceding sentence context would elicit an N400 effect in unimpaired participants. With respect to the agrammatic participants, we hypothesized that they would show an N400 effect in response to semantic anomalies. However, this effect may be reduced or delayed reflecting impaired on-line use of lexical-semantic information, as documented in previous studies (Swaab et al., 1997; Wassenaar & Hagoort, 2005).

2. Methods

2.1 Participants

ERP responses and grammaticality judgments were acquired from three groups of participants: young adults (n = 15), older adults (n = 23), and agrammatic aphasic individuals (n = 15). The study was approved by the IRB at Northwestern University and all participants gave their written informed consent prior to the study. All volunteers were compensated for their participation in the study.

Non-brain-damaged volunteers were recruited from the Northwestern University community and the greater Chicago area. Both groups of neurologically unimpaired participants were native speakers of English. All young (age: $M = 22$ years, $SD = 3$; education: $M = 15.3$ years, $SD = 1.4$) and older controls (age: $M = 60$ years, $SD = 11$; education: $M = 17$ years, $SD = 3$) were right handed and had normal hearing and normal or corrected-to-normal vision. Participants had no history of neurological, psychiatric, speech, language, or learning disorders and none were taking neuroleptic or mood altering medications at the time of the study.

Aphasic participants (10 males) were recruited from the subject pool of the Aphasia and Neurolinguistics Research Laboratory at Northwestern University. Mean age was 55.4 years (SD = 12), and mean education was 16.6 years (SD = 3). All of the aphasic participants suffered left-hemisphere strokes, on average 6 years and 4 months prior to the study. All were right handed, native English-speaking individuals with normal hearing and normal or corrected-to-normal vision. Aphasic participants were matched with the group of healthy older individuals for age ($F(1, 37) = 1.47$, $p > .05$) and education ($F < 1$).

Participants were classified as agrammatic based on their performance on the *Western Aphasia Battery* (WAB, Kertesz, 2007), and the *Northwestern Assessment of Verbs and Sentences* (NAVS, Thompson, 2011), as well as narrative language samples and other tests. Aphasic participants presented with effortful spontaneous speech, consisting of simple phrases and marked by omission and substitution of grammatical morphemes. Analysis of their narrative production revealed reduced phrase length (MLU (words): $M = 6.47$, SD =1.98; range: 3–10), and high proportions of ungrammatical sentences (grammatical sentences produced: $M = 42\%$, $SD = 15\%$). Participants presented with mild-to-moderate aphasia (WAB-AQ: $M = 76.1$, Range: 56.4 – 93), with relatively preserved verb ($M = 98\%$, $SD = 6\%$) and sentence comprehension ($M = 72\%$, $SD = 15\%$, see Table 1).

All aphasic participants presented with left hemisphere lesions due to a cerebral vascular accident in the vicinity of the left middle cerebral or anterior temporal artery. Anatomical scans were performed for 12 of the 15 participants, showing variation in the location of the lesion and its extent across participants. Four of the patients presented with large lesions involving frontal, parietal and temporal regions, and one presented with additional subcortical involvement. Selected slices from these patients' T1 MRI images are presented in Figure 1, and a brief description of their lesions is provided in Table 2.

2.2 Materials

Thirty-five transitive and 35 intransitive verbs were selected to form sentence stimuli. The transitive verbs were obligatory two-argument verbs that take either animate or inanimate objects (e.g., *pull*). The intransitive verbs all were obligatory one-argument verbs with no possible direct or indirect object arguments (e.g., *sneeze*). Note that intransitive verbs can be followed by a noun phrase superficially resembling a direct object in two constructions – the cognate object construction (1a) and the intransitive resultative construction (1b):

1. **a.** John sneezed a cute baby sneeze.

b. John sneezed the napkin off the table.

Despite appearances, linguistic evidence reveals that in both cases, the post-verbal NP is not a direct object of the verb, but rather an adjunct (see e.g. Carrier & Randall, 1992, 1993; Jones, 1988; Mittwoch, 1998; Zubizarreta, 1987). For example, unlike true objects of transitive verbs, these NPs cannot be passivized (2), pronominalized (3) or questioned (4). There is thus a clear distinction in the argument structure information associated with the two verb types.

2. **a.** A baby carriage was pulled.

b. *A cute baby sneeze was sneezed.

3. **a.** John pulled a baby carriage and then his brother pulled it.

b. *John sneezed a cute baby sneeze and then his brother sneezed it.

4. **a.** What did John pull?

b. *What did John sneeze?

Both transitive and intransitive verbs required a human agent in subject position (i.e., unaccusative verbs, psych verbs, etc. were excluded). The complete list of the verbs used in the experiment is provided in the Appendix.

The verbs were embedded in sentences to comprise the experimental stimuli. All sentences were active constructions that included a human/animate subject and an object, which was realized as a coordinated NP (*the N and the N*). Correct sentences (e.g. *Anne visited the doctor and the nurse*) contained a transitive verb and a semantically congruent object. Sentences with argument structure violations (e.g., **Anne* *sneezed* *the doctor and the nurse*) were realized by replacing the transitive verb in the well-formed sentence with an intransitive verb. In the semantic violation condition (e.g., **Anne visited the doctor and* *the socks*), the terminal word of each sentence was semantically inappropriate, resulting in a semantic mismatch. There were 35 sentences in each condition, for a total of 105 critical sentences.

All critical verbs were matched across conditions with respect to frequency ($p > .05$; $\log_{10}$ lemma frequency of occurrence per million according to the CELEX database, Baayen, Piepenbrock, & Van Rijn, 1993), and number of syllables (1–2 syllables, $p > .05$). Nouns used to form the final NP were also matched for frequency and number of syllables across conditions (ps > .05).

One hundred sixty additional filler sentences were created in order to counterbalance the number of correct and incorrect sentences and to avoid strategic effects. Out of these, 67 sentences contained violations, resulting from an illicit omission of an obligatory object or of the conjunction *and*. Ninety three sentences were grammatical sentences with intransitive, transitive or ditransitive verbs.

All sentences were spoken by a female native speaker of English and recorded onto a digital recorder in a sound-attenuating booth. Sound files were separated into words, digitized at a sampling rate of 44 kHz and stored as separate files. The duration of the sound files varied with word length, with determiner files taking between 400 and 500 ms, and longer words taking up to 750 ms. Praat software (Boersma & Weenink, 2009) was used to normalize sound files. Each experimental sentence was seven words long, with each word file presented for 900 msec, and sentence duration was 6300 msec.

2.3 Procedure

The experiment was programmed and presented using E-prime experimental presentation software (Schneider, Eschman, & Zuccolotto, 2007) on a Lenovo desktop computer running Windows XP Professional with an Intel Core 2Quad CPU processor. Participants were seated in a dimly illuminated sound-attenuating booth and were instructed to move as little as possible. On each trial a fixation cross was displayed at the center of the computer screen, while an auditory sentence was presented over loudspeakers. Eight hundred milliseconds after the offset of the sentence, a visual cue presented in the center of the screen instructed the participants to perform an acceptability judgment task. They were instructed to press the green button if they thought the sentence was correct, and the red button if they thought it was incorrect. The visual response cue was presented for 5000 msec or until a response was made. The next trial started 1500 msec after the participants' button press. This delayed judgment task was used to eliminate effects of motor response preparation on the ERPs of interest. The order of presentation was randomized and counterbalanced across participants. Before the main experiment, participants performed a 10-item practice session with feedback to ensure that they understood the task. Practice items were not used during the experiment.

2.4 ERP data Recording and Analysis

EEG data were acquired using a high impedance physiological measurement system (ANT: Advanced NeuroTechnology). ERPs were recorded from 32 scalp sites by means of Ag/AgCl electrodes attached to an elastic cap according to the International 10–20 System (Fp1, FPz, FP2, F7, F5, F4, F3, F8, Fz, FC5, FC1, FC2, FC6, T7, T8, C3, C2, C4, CP5, CP1, CP2, CP6, P7, P3, P4, P8, Pz, POz, O1, O2, Oz, M1, M2). AFz served as ground electrode (see Figure 2 for channel layout). Recordings were referenced to the average of two mastoid electrodes (M1 and M2).

In order to control for eye movements, horizontal electro-oculogram (EOG) was monitored by placing electrodes at the outer cantus of each eye. Vertical eye movements were recorded by placing two electrodes above and below participants' left eye. Electrode impedances were kept at or below 5 kΩ. EEG and EOG signals were amplified using an ANT Refa-8 32-channel EEG amplifier by TMSI, and data were recorded continuously with a low pass filter of 100 Hz, and digitization rate of 256 Hz.

The waveforms were screened for amplifier and movement artifacts, which were rejected prior to averaging. Single trials with eye blinks were corrected for blink artifacts using the Principal Component Analysis method described by Ille, Berg, & Scherg (2002). Overall rejection rate was 9.02% for young participants, 8.91% for older controls, and 10.32% for agrammatic participants. For all participant groups, rejected trials were evenly distributed among experimental conditions.

ERPs were time locked to the onset of the critical word in each sentence. In the argument structure violation condition the waveforms were time locked both to the determiner immediately following the verb (e.g. *John sneezed* <u>*the*</u> *doctor*) and to the noun following it (e.g. *John sneezed the* <u>*doctor*</u>). In principle, when the verb in the sentence is intransitive, it specifies that it cannot take a direct object, and thus, the violation can be detected at "the". As explained in section 2.2., at "the", a grammatical continuation of the sentence is still possible (as in e.g., the intransitive resultative construction, John *sneezed the napkin off the table*). In this case, "the" does not signal a violation of grammaticality, but rather of preference (see also Friederici & Frisch, 2000). However, by the time the following noun is heard, a clear violation arises. The waveform at the determiner was compared to that of the determiner in the grammatical sentence condition, and the waveform of the noun was compared to that of the corresponding noun in the grammatically correct condition. For the semantic violation condition waveforms were time locked to the sentence final noun, and compared to the ERPs elicited by the congruent sentence final noun in the grammatical sentences.

ERPs were obtained by dividing trials into epochs from −100 to 900 msec relative to the target word onset. ERP averages were baseline corrected to the 100 ms pre-stimulus interval and low-pass filtered at 30 Hz using a 24dB/oct zero phase shift digital filter. On the basis of visual inspection and previous studies, two latency windows from 300 to 700 msec were defined for statistical analysis: 300–500 msec for negativity effects (LAN/N400), and 500–700 msec for late positivities (P600). Where warranted by visual inspection of the waveforms, an additional time window of 700–800 msec was included.

Statistical analyses were performed using repeated measures ANOVAs on the mean ERP amplitudes computed for each participant, violation condition and electrode site in the selected latency windows. To investigate the different topographical distribution of ERP effects and to reduce the number of multiple comparisons performed, electrodes were divided into eight subsets by region: FC (Fz, Fpz), CC (Cz, Pz), PC (POz, Oz), RCP (C4, CP2, CP6), LCP (C3, CP5, CP1), RP (P4, P8, O2), LP (P3, P7, O1), RF (F4, F8, FC2, FC6), and LF (F7, F3, FC1, FC5). To protect against Type I error resulting from a large number of comparisons, the Huynh & Feld (1970) correction was applied when evaluating effects with more than one degree of freedom in the numerator. In these cases the original degrees of freedom are reported with the corrected probability levels.

To test for possible differences in variability between the different participant groups (e.g. whether responses of the young control group were more homogenous than those of the older group and patients), we compared the variances in the three groups on the mean amplitude of the difference waves and the time-to-peak, using Levene's test for homogeneity of variance. Comparisons were carried out for each electrode and condition in each time window where between-group differences were found.

3. Results

3.1 Behavioral Results

Mean response latencies and accuracy for the three participant groups across different experimental conditions are presented in Table 3.

A group (young, older, agrammatic) x condition (correct sentences, argument structure violations, semantic violations) repeated measures ANOVA revealed a significant main effect of group ($F(2, 50) = 40.72$, $p < .001$) and condition ($F(2, 100) = 11.65$, $p < .001$), and a condition x group interaction ($F(4,100) = 10.46$, $p < .001$), indicating that aphasic participants and controls showed different patterns of response accuracy across different experimental conditions. Post-hoc comparisons revealed a significant difference between the agrammatic patients and the two control groups (*p*s < .001), such that the overall accuracy of the agrammatic participants was lower than that of control participants, but no difference was found between the two control groups ($p = .975$). Further, in the agrammatic group, argument structure violations were judged significantly less accurately than grammatical sentences ($F(1, 14) = 10.34$, $p < .01$) and than semantic violations ($F(1, 14) = 19.48$, $p < .01$). However, there was no significant difference in accuracy between grammatical sentences and sentences with semantic violations ($F < 1$) for these participants.[1] The two control groups were equally accurate in responding to the different sentence types (all *p*s > .05, corrected for multiple comparisons).

Similar analysis for the reaction time data revealed a main effect of group ($F(2, 50) = 41.44$, $p < .001$), but no effect of condition and no interaction between condition and participant group (both *F*s < 1). Post-hoc comparisons revealed that agrammatic participants had significantly prolonged response latencies, compared to both control groups (all *p*s < .01, corrected for multiple comparisons), but there were no significant differences in reaction times between the two control groups ($p > .05$).

3.2 ERP results

The results of omnibus ANOVAs with condition and electrode site as within subject factors for each participant group at the two latency ranges are presented in Table 4. Table 5 summarizes the results of statistical tests performed for each participant group at different electrode regions and conditions in the specified time intervals.

3.2.1 Argument structure violations—The ERP effects for the argument structure violation for each participant group at the position of the determiner are presented in Figure 3 and results at the critical noun are shown in Figure 4.

[1]This indicates that participants did not exhibit a general 'yes-bias', leading them to accept ungrammatical sentences.

Young control participants: For the target word "the", in the early time window (300–400 msec) an omnibus ANOVA revealed an effect of condition, $F(1, 14) = 4.08$, $p = .06$. The regional analyses revealed a significant negativity at the right frontal-central sites (RFC, $F(1, 14) = 4.85$, $p < .05$), and left central-parietal sites (LCP, $F(1, 14) = 4.82$, $p < .05$). This negativity was followed by a positive shift at the posterior sites (PC, $F(1, 14) = 4.73$, $p < .05$; LP, $F(1, 14) = 4.33$, $p = .05$). No significant ERP effects were found in the 500–700 time window.

Analysis of the waveforms time locked to the critical noun following the verb revealed a significant main effect of electrode site in the two time windows (300–500 msec: $F(29, 406) = 2.89$, $p < .05$; 500–700 msec: $F(29, 406) = 3.05$, $p < .05$), but no significant main effect of condition or interaction was found. The regional analyses revealed negativity restricted to the central and right parietal electrodes in the 300–500 msec time window (CC, $F(1, 14) = 5.78$, $p < .05$; RP, $F(1, 14) = 6.80$, $p < .05$), and to central sites in the 500–700 msec time interval (CC, $F(1, 14) = 5.72$, $p < .05$).

Older control participants: For the target word 'the' in the early time window the omnibus ANOVA revealed no significant main effect of condition or electrode and no interaction. However, at the later time window (500–700 msec) there was a significant main effect of condition, $F(1, 22) = 7.17$, $p < .01$. The regional analyses revealed that the argument structure violations at the determiner elicited a *positive shift* with a predominantly central-parietal distribution (CC, $F(1, 22) = 11.16$ $p < .05$; LCP, $F(1, 22) = 5.29$, $p < .05$; RCP, $F(1, 22) = 5.10$, $p < .05$; PC, $F(1, 22) = 6.67$, $p < .01$; RP, $F(1, 22) = 7.69$, $p < .05$).

In the 700–800 msec time window there was a significant main effect of condition, $F(1, 22) = 14.89$, $p < .01$, and electrode, $F(29, 638) = 2.21$, $p < .05$, and an electrode x condition interaction, $F(29, 638) = 4.02$, $p < .05$, indicating that the positive effect elicited by the argument structure violation continued to be present in this time window, and was distributed mainly over central and parietal sites (CC, $F(1, 22) = 33.98$, $p < .01$; PC, $F(1, 22) = 8.74$, $p < .01$; LCP, $F(1, 22) = 11.33$, $p < .01$; RCP, $F(1, 22) = 9.89$, $p < .01$; RP, $F(1, 22) = 6.05$, $p < .05$).

The analysis of the waveform time locked to the critical noun revealed a significant main effect of electrode, $F(29, 638) = 12.11$, $p < .01$, and a condition x electrode interaction, $F(29, 638) = 3.00$, $p < .05$, in the 300–500 msec time window. The violation elicited a sustained negativity, which was most pronounced at the central and parietal sites (CC, $F(1, 22) = 5.52$, $p < .05$; LCP, $F(1, 22) = 6.97$, $p < .05$; LP, $F(1, 22) = 9.18$, $p < .01$; RP, $F(1, 22) = 6.44$, $p < .05$). In the 500–700 msec time interval the omnibus ANOVA showed a main effect of electrode, $F(29, 638) = 5.54$, $p < .01$. The regional analyses revealed a negative shift that was largest at the central and parietal electrodes (CC, $F(1, 22) = 7.00$, $p < .05$; LCP, $F(1, 22) = 10.54$, $p < .01$; RCP, $F(1, 22) = 5.84$, $p < .05$; LP, $F(1, 22) = 7.12$, $p < .05$).

Agrammatic participants: For the determiner in the argument structure violation, at the early time window the omnibus ANOVA revealed no significant main effect of condition or electrode and no interaction. However, in the 500–700 msec latency interval there was a significant main effect of electrode, $F(29, 406) = 2.33$, $p < .05$. The regional ANOVAs revealed that the violation elicited a positive shift. This effect was not widely distributed, but restricted mainly to the central sites (CC, $F(1, 14) = 6.36$, $p < .05$; RCP, $F(1, 14) = 5.07$, $p < .05$). The critical noun in the verb argument structure violation condition did not elicit significant ERP effects at any of the time windows for the agrammatic participants.

3.2.2 Semantic Violations—The ERP effects for the semantic violation for each participant group are presented in Figure 5.

Young control participants: In response to semantic violations young participants displayed a negative-going wave with a centro-parietal distribution, peaking at about 400 msec. For the 300–500 msec latency window, the omnibus ANOVA revealed a significant main effect of condition, $F(1, 14) = 18.12$, $p < .01$, and a condition x electrode interaction, $F(29, 406) = 4.20$, $p < .01$. The subsequent regional ANOVAs revealed a negativity, largest at the central and parietal sites (CC, $F(1, 14) = 11.80$, $p < .01$; LCP, $F(1, 14) = 9.86$, $p < .01$, PC, $F(1, 14) = 8.84$, $p < .05$; LP, $F(1, 14) = 13.47$, $p < .01$; RP, $F(1, 14) = 20.90$, $p < .01$).

In the 500 to 700 msec time window, the omnibus ANOVA revealed significant main effects of condition, $F(1, 14) = 19.16$, $p < .01$ and of electrode, $F(29, 406) = 3.63$, $p < .01$, and a significant electrode x condition interaction, $F(29, 406) = 4.30$, $p < .01$. The regional analyses indicated that the negativity elicited by the semantic violation continued into this time-window, and was the strongest at the central and parietal sites (CC, $F(1, 14) = 8.61$, $p < .05$; PC, $F(1, 14) = 7.02$, $p < .05$; LCP, $F(1, 14) = 22.48$, $p < .01$; RCP, $F(1,14) = 7.80$, $p < .05$; LP, $F(1, 14) = 9.99$, $p < .01$).

Older control participants: A centro-parietal negativity peaking at around 400 msec was also observed for older adults. For the early latency window the omnibus ANOVA revealed significant main effects of condition, $F(1, 22) = 10.98$, $p < .01$ and electrode, $F(29, 638) = 5.96$, $p < .01$, and a significant condition x electrode interaction, $F(29, 638) = 4.81$, $p < .01$. The negativity elicited by the semantically anomalous word was most pronounced at the central and parietal sites (CC, $F(1, 22) = 9.18$, $p < .01$; RCP, $F(1, 22) = 23.07$, $p < .01$; LCP, $F(1, 22) = 9.17$, $p < 01$; PC, $F(1, 22) = 13.74$, $p < .01$; RP, $F(1, 22) = 8.06$, $p < .05$), and was observed also over the right frontal-central sites (RF, $F(1, 22) = 7.93$, $p < .05$). In addition, there was a positive shift at the left parietal sites (LP, $F(1, 22) = 9.07$, $p < .01$).

In the 500–700 msec latency window, the ANOVA again showed a significant main effect of condition, $F(1, 22) = 7.67$, $p < .05$ and electrode, $F(29, 638) = 3.51$, $p < .05$, and an electrode x condition interaction, $F(29, 638) = 2.53$, $p < .05$. The negativity elicited by the semantic violation was distributed mainly over central and parietal sites (PC, $F(1, 22) = 6.87$, $p < .05$; RCP, $F(1, 22) = 26.90$, p < .01), as well as right frontal-central sites (RFC, $F(1, 22) = 5.85$, $p < .05$), and the positive shift at the left parietal sites was also significant (LP, $F(1, 22) = 8.43$, $p < .01$).

Agrammatic participants: In the early latency window, the omnibus ANOVA revealed a significant main effect of condition, $F(1, 14) = 5.02$, $p < .05$. Planned comparisons revealed a negativity elicited by the semantic violation, at the left central and right parietal sites, (LC, $F(1, 14) = 7.64$, $p < .05$; RP, $F(1, 14) = 4.81$, $p < .05$). Similarly, there was a significant main effect of condition ($F(1, 14) = 4.54$, $p = .05$) in the 500–700 msec time interval. Once again, regional analyses revealed that the negative shift elicited by the semantic violation condition was significant at the central and parietal electrodes (LC, $F(1, 14) = 5.11$, $p < .05$; RCP, $F(1, 14) = 4.34$, $p = .05$; RP, $F(1, 14) = 7.77$, $p < .05$).

3.2.3 Between Group Analyses—To explore between group differences in ERP effects, pairwise comparisons between the agrammatic group and the two control groups were performed at different electrode regions, as described below. Table 6 summarizes the results of statistical tests performed for each violation condition at different electrode regions in the different time intervals. The results are presented in detail below.

Variability in amplitude and latency is characteristic of ERPs of abnormal populations (as reported for example in Iraqui, Kutas, & Salmon, 1996; Swaab et al., 1997). To assess whether differences in variability around the mean might have influenced our results, we compared the variances in the three participant groups on the mean amplitude of the difference waves and on the time-to-peak measure. These measures were calculated for each electrode over each participant group, and group variances were compared using Levene's test for homogeneity of variance. The results for relevant electrodes, namely electrodes showing an effect of condition in any of the participant groups, are presented in Table 7. Results for a representative electrode and condition are illustrated in Figure 6. As can be seen in Table 7, in the vast majority of cases, the variance around the mean was not significantly different between the three participant groups, neither for the mean amplitude of the difference wave nor for the time-to-peak, suggesting that the between-group differences to be discussed below are not due to differences in variance (namely homogenous responses in one group and variable responses in another).

Agrammatic participants vs. young controls: For the argument structure violation at the determiner, a group (young, agrammatic) by condition (correct, semantic violation) ANOVA revealed a significant main effect of group ($F(1, 28) = 4.34$, $p < .05$) and a marginally significant group by condition interaction ($F(1, 28) = 4.09$, $p = .053$) at the left central-parietal sites in the 300–500 msec time window. These results indicate that in response to verb argument structure violations, negativity was present for younger controls, whereas participants with aphasia showed a positive shift. At the critical noun, the analysis showed a significant main effect of group at the central and parietal sites (CC, $F(1, 28) = 8.98$, $p < .01$; LCP, $F(1, 28) = 10.39$, $p < .01$; RCP, $F(1, 28) =$, $p < .05$), which reflected presence of negativity for young participants but not for participants with aphasia.

For the semantic violation, the ANOVA revealed a significant interaction between group and condition at the central and parietal sites in the 300–500 msec time window (RP, $F(1, 28) = 6.13$, $p < .05$; PC, $F(1, 28) = 5.46$, $p < .05$; LP, $F(1, 28) = 4.54$, $p < .05$). This interaction was due to the reduced negativity elicited by semantic violations in this time window for the agrammatic participants. In addition, significant group effects were obtained in the 500–700 msec time window, indicating significantly larger negativity for young controls compared to agrammatic participants at the central and parietal electrodes (CC, $F(1, 28) = 6.10$, $p < .05$; LCP, $F(1, 28) = 5.49$, $p < .05$, LP, $F(1, 28) = 12.72$, $p < .01$).

Agrammatic vs. older controls: For the argument structure violation at the determiner, the between group ANOVAs revealed a significant effect of group at the central and parietal sites (LCP, $F(1, 36) = 5.86$, $p < .05$; LP, $F(1, 36) = 6.80$, $p < .05$) in the early time window, and a significant group x condition interaction at the left central sites (LC, $F(1, 36) = 4.19$, $p < .05$) in the 700–800 msec time interval. These results reflected larger positivity observed at this word in response to verb argument structure violation for older control participants.

At the critical noun, significant group effects were obtained in the 300–500 msec window at the parietal and central sites, reflecting greater negativity present for older controls compared to aphasic participants (CC: $F(1, 36) = 14.69$, $p < .01$; PC: $F(1, 36) = 10.51$, $p < .01$; LCP: $F(1, 36) = 10.92$, $p < .01$; RCP: $F(1, 36) = 12.60$, $p < .01$; LP: $F(1, 36) = 7.68$, $p < .01$; RP: $F(1, 36) = 10.49$, $p < .01$). Similarly, in the 500–700 msec time interval, significant group x condition interactions were observed at the central and parietal sites (LCP: $F(1, 36) = 8.58$, $p < .05$; LP: $F(1, 36) = 4.45$, $p < .05$). This interaction reflected the finding that a negativity was elicited by verb argument structure violations at the position of the noun in older healthy controls, but not in participants with aphasia.

For the semantic violation condition, statistical comparison of the agrammatic and age-matched participants revealed a significant group effect in the 500–700 msec time window (RCP, $F(1, 36) = 6.15$, $p < .05$), indicating larger negativity for older controls compared to agrammatic participants.

4. Discussion

In this study we investigated event-related potentials (ERPs) associated with verb argument structure and semantic violations in sentence contexts. The main goal was to investigate how individuals with agrammatic aphasia process verb argument structure information in real-time during sentence comprehension. We also wanted to examine possible differences in sensitivity to semantic and argument structure information during sentence processing. Argument structure violations were realized by introducing a mismatch between the verb's thematic properties and the number of arguments in the sentence, whereas semantic violations were realized by placing a contextually incongruous noun in the sentence final position.

Behaviorally, agrammatic participants were less accurate than control participants in their grammaticality judgments. The difference was most pronounced in the argument structure violation condition, where grammaticality judgment accuracy was at chance. These results contrast with previous studies, showing near normal performance on grammaticality judgments of structures with argument structure violations, e.g. Grodzinsky & Finkel (1998), Kim & Thompson (2000, 2004). Low accuracy in the argument structure condition in the present study may be explained by the fact that argument structure violations occurred at mid-sentence (whereas in previous studies some violations were sentence final), and were followed by a grammatical five-word noun phrase. Additionally, there were 800 msec of silence beginning at sentence offset, only after which participants were allowed to respond. In contrast, in previous studies participants could provide their judgments at any point during the presentation of the sentence. The delayed judgment required in our task may have caused a working memory load or allowed for interference effects.

The ERP results showed that argument structure and semantic violations led to different electrophysiological responses, and they elicited a distinct pattern of electrophysiological signatures in healthy participants and individuals with aphasia. Young healthy adults showed online sensitivity to the mismatch between the number of arguments required by the verb and the actual arguments appearing in the sentence. As soon as the post-verbal determiner following an intransitive verb was heard, signaling an illegal theme argument (noun phrase), a fronto-central negativity was elicited at central sites, and a positive shift was seen at posterior sites. These results indicate that during normal processing, as sentence structure is built on-line, the verb's argument structure properties place restrictions on the arguments that can follow it. The response pattern found in our study is similar to the N400-P600 pattern found in previous studies investigating verb argument structure processing, and in particular violation of the number of arguments (Friederici & Frisch, 2000). As suggested in previous studies (Friederici & Frisch, 2000; Frisch et al., 2004), when arguments cannot be assigned thematic roles by the verb, lexical-semantic integration problems arise, which are reflected in the N400 effect, whereas subsequent attempts at reanalysis and repair of the sentence structure are reflected in the P600 effect. Friederici & Meyer (2004) take this late positivity to reflect second-pass controlled processes of revision after violations have been detected. Note that for young participants, this pattern was observed at the determiner immediately following the verb, while the waveforms time-locked to the onset of the subsequent noun did not show this pattern, indicating that young healthy adults show sensitivity to verb argument structure information as soon as an inconsistent word is heard and that they resolve this anomaly in real time. The present findings are thus consistent with previous ERP and behavioral studies showing an effect of verb information on the processing of incoming arguments (Ferreti et al., 2001; Osterhout et al., 1994; Trueswell & Kim, 1998).

Results for the older control group indicated somewhat different processing patterns compared to young healthy listeners, albeit the ERP data showed online sensitivity to verb argument structure processing. The older control group did not show an N400 effect on the determiner, indicating that assignment of thematic roles and lexical integration is less automatic and immediate in older listeners. At the determiner site the older participants showed a centro-parietal positive shift, reflecting reanalysis or repair processes arising from a dispreferred sentence continuation, but failed to acknowledge an outright inconsistency between the verb's thematic specifications and the incoming material, as evidenced by the lack of negativity at the determiner. In addition, a left-parietal negative effect was observed on the following noun, which may suggest that the acknowledgement of the violation was delayed in this group until the full lexical item was processed. It can be noted that negativities on the noun in some electrode sites may have been influenced by the sustained effect on the preceding word, i.e., the determiner, which was used as a baseline for the noun event. Since the positivity observed on the determiner for older participants extended even up to 800 msec post stimulus onset on some sites, it is possible that the negativity found on the following noun was exaggerated. Note however that a strong negativity was observed also in left parietal-central sites, where no sustained effect was found in the determiner condition.

Delayed ERP effects related to aging have been reported in previous studies (Kutas & Iragui, 1998; Federmeier & Kutas, 2005; see review in Wlotko, Lee, & Federmeier, 2010). For example, in Federmeier et al. (2003), older adults displayed a qualitatively similar but substantially delayed response to constraints imposed by sentence context. As concluded by Wlotko et al. (2010), older adults are less likely to use active prediction during comprehension, and are thus less efficient in using sentence context information to facilitate processing. Note, that reaction time data cannot reflect this delayed processing, since responses were obtained only after the entire sentence was heard.

The ERP responses elicited by the verb argument structure violations in the agrammatic group were different from those of both young and older controls, indicating that participants with agrammatic aphasia are impaired in on-line processing of verb argument structure information. The agrammatic participants showed an attenuated and restricted positivity at the position of the determiner, and no negative shift. The finding of a late positive shift at the position of the determiner indicates that, as older controls, these participants attempted to integrate the surplus incoming material with the preceding sentence context. This result is similar to that of Friederici et al. (1998) in which a Broca's patient was presented with sentences containing word-category violations. In contrast to healthy controls showing a biphasic LAN-P600 response to these violations, the agrammatic participant displayed only a late positivity. The authors suggested that the absence of the early negativity indicates a loss of fast and automatic processing, but the presence of a P600 reveals that secondary syntactic processes are still available.

In addition, no ERP responses were elicited at the critical noun in the argument structure violation condition, suggesting that aphasic participants were not able to detect the mismatch between the requirements of the verb and the actual incoming arguments even at this later stage, as reflected also by their higher error rates in this condition. These findings indicate that agrammatic individuals are impaired in using verb information on-line to integrate individual arguments into an overall sentence context. Verb information may not be available with the sufficient level of activation to enable integration between sentence constituents at a normal speed. This interpretation is consistent with Wassenaar and Hagoort (2005) who suggested that incomplete or delayed availability of word-class information hinders Broca's aphasic listeners' ability to construct a phrasal structure of the sentence.

The lack of online sensitivity to argument structure information in the agrammatic group contrasts with evidence for retained sensitivity to semantic information, as revealed by their responses to semantic violations. In the semantic condition, the three participant groups showed qualitatively similar ERP responses, though the effects formed a continuum with regard to distribution and the size of the effects. Younger adults showed a broadly distributed centro-parietal negative shift, most pronounced from 300 to 500 msec, in keeping with the classic N400 effect found in correlation with lexical-semantic integration difficulties (Connolly & Phillips, 1994; Kutas & Hillyard, 1980; Rosler et al., 1993).[2] The amplitude of the N400 effect was attenuated in older adults, consistent with previous reports of decreases in amplitude of the N400 effect (as well as other ERP components) with advancing age (Faustmann, Murdoch, Finnigan, & Copland, 2007; Gunter, Jackson, & Mulder, 1992; Kutas & Iragui, 1998). This decrease in N400 amplitude with advanced age has been associated with less efficient integration of lexical items with the semantic context (Iraqui et al., 1996; Wassenaar & Hagoort, 2005), possibly due to slower access to semantic memory, which becomes larger and more interconnected with age, or due to reduced neural processing speed (Kutas & Iraqui, 1998). Another related possibility is that less effective inhibitory mechanisms in older adults lead to poor integration resulting in smaller N400 effects (Cameli & Phillips, 1999).[3] The N400 response to semantic violations was further attenuated in the agrammatic group, and restricted to the central sites. The effects were also flatter, without clearly defined peaks. A reduction of the N400 amplitude has been reported in other studies of sentence comprehension in individuals with aphasia (Swaab, Brown, & Hagoort, 1997, 1998; Wassenaar & Hagoort, 2005). Hagoort and colleagues (Hagoort et al., 1996; Swaab et al., 1997) argued that slower and inefficient lexical integration processes could cause a degraded or incomplete representation of the sentence preceding the final word. This may lead to a less defined representation of the sentence context, and reduce the difference between congruent and incongruent conditions, hence causing an attenuated N400 effect. Importantly, however, the N400, though attenuated, was found in the agrammatic group. This finding is in line with the agrammatic participants' behavioral results, showing above chance accuracy on grammaticality judgments for semantic violations.

ERP studies using linguistic anomaly paradigms are a powerful way to examine online language processing in healthy and impaired systems. More recently it has been recognized that other types of information are embedded in the EEG signal. In particular, spectral analysis techniques can reveal changes in the amplitude of ongoing oscillations within specific frequency bands. Time-frequency analysis of oscillatory activity can detect task-related neural activity that is not necessarily phase-locked to a stimulus, and would not be detectable in time-domain averaging (Mouraux & Iannetti, 2008; Le Van Quyen & Bragin, 2007). Therefore, it is possible that, using such fine-grained methods, neural activity of aphasic participants, not detectible using time-domain averaging, may be present but not

[2]The negativity observed in response to semantic violations in our participants was sustained, remaining significant at the later time window (500–700 msec). Similar effect was observed in previous studies that presented violations at the end of the sentence (Connolly & Phillips, 1994; Connolly et al., 1992).

[3]In addition, for older participants, the N400 was followed by a positivity at the posterior sites. A similar pattern has been observed in a few previous studies in correlation with processing of semantic anomalies (Friederici & Frisch, 2000; Gunter et al., 1997; Wassenaar & Hagoort, 2005). It has been suggested that this late positive effect reflects processes of reanalysis and repair, which can be elicited in response to both semantic and syntactic anomalies. A similar account has been put forward by Kaan, Harris, Gibson, & Holcomb (2000), who consider this late positivity a reflection of general integration difficulty resulting from syntactic or thematic processing difficulties. The finding that older, but not young adults, showed this positive effect in response to semantic incongruity indicates that for older adults lexical-semantic integration processes are less efficient, the late positive shift reflecting an attempt at repair of semantic incongruity after it has been detected.

precisely time locked to the onset of a temporal event. We are currently investigating how different violation conditions may trigger transient power modulations in the ongoing EEG activity by mapping the ERP signal into a two dimensional time-frequency representation. In the aphasic participants, the non-phase-locked modulations of the ERP signal should be reflected in changes in the power of oscillatory activity as a function of time and frequency.

5. Conclusions

Sentence comprehension requires fast and efficient access to and integration of lexical-semantic and syntactic information. Information encoded in the verb's lexical entry is crucial for this process because verbs specify the characteristics of their arguments, such as their number and type. In the present study, we used ERPs to investigate the sensitivity of healthy controls and agrammatic aphasic individuals to argument structure violations embedded in sentence contexts. Results showed that the agrammatic participants were impaired on grammaticality judgments of sentences, especially those with argument structure violations, to an extent exceeding the deficits reported in previous behavioral studies (Grodzinsky & Finkel, 1998; Kim & Thompson, 2000, 2004). Furthermore, agrammatic participants displayed reduced electrophysiological responses to argument structure violations compared to control participants. Both control groups displayed an N400-P600 pattern (although this effect appeared on the determiner for the young group and on the noun for the older group). In contrast, argument structure violations elicited only an attenuated P600 effect on the determiner in participants with aphasia, and no negativity was observed. In contrast to argument structure violations, the agrammatic participants' response to semantic violations was not qualitatively different from control participants'. Less impaired semantic processing was reflected also in agrammatic participants' grammaticality judgments to semantic violations, which were significantly more accurate than those for argument structure violations.

The present results show that agrammatic individuals do not demonstrate normal real-time sensitivity to mismatches between the argument structure requirements of a verb and the incoming linguistic information accompanying it. While these participants are aware of semantic incongruity in real time, the same does not hold for verb-argument incongruity, as evidenced by the lack of an N400 component, and by grammaticality judgment accuracy. The present results suggest that sentence comprehension difficulties in individuals with aphasia may result from incomplete or inefficient access to lexical information associated with verbs, and impaired online integration of that information within the context of sentences.

Highlights

- An ERP acceptability judgment experiment was run with aphasic and control subjects.
- Semantic violations elicited an N400 effect in young and older controls.
- Argument structure violations elicited a biphasic N400-P600 pattern in controls.
- Aphasics exhibited a reduced, delayed N400 in response to semantic violations.
- Aphasics did not show normal biphasic responses to argument structure violations.

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Appendix Verbs used in the experiment

Transitive	Intransitive
bite	blink
bury	bowl
carry	jog
catch	cough
chase	crawl
cover	cry
drag	frown
follow	fish
grab	travel
hit	kneel

Transitive	Intransitive
hold	laugh
hug	sweat
join	march
kick	nod
kiss	pray
lick	run
lift	scream
paint	shiver
pet	sit
pull	sleep
punch	smile
push	snore
save	stand
scrub	swim
spend	walk
squeeze	weep
touch	whisper
visit	sneeze
wash	wink
watch	yawn
weigh	dive
injure	drool
poke	ski
betray	skate
pinch	spit

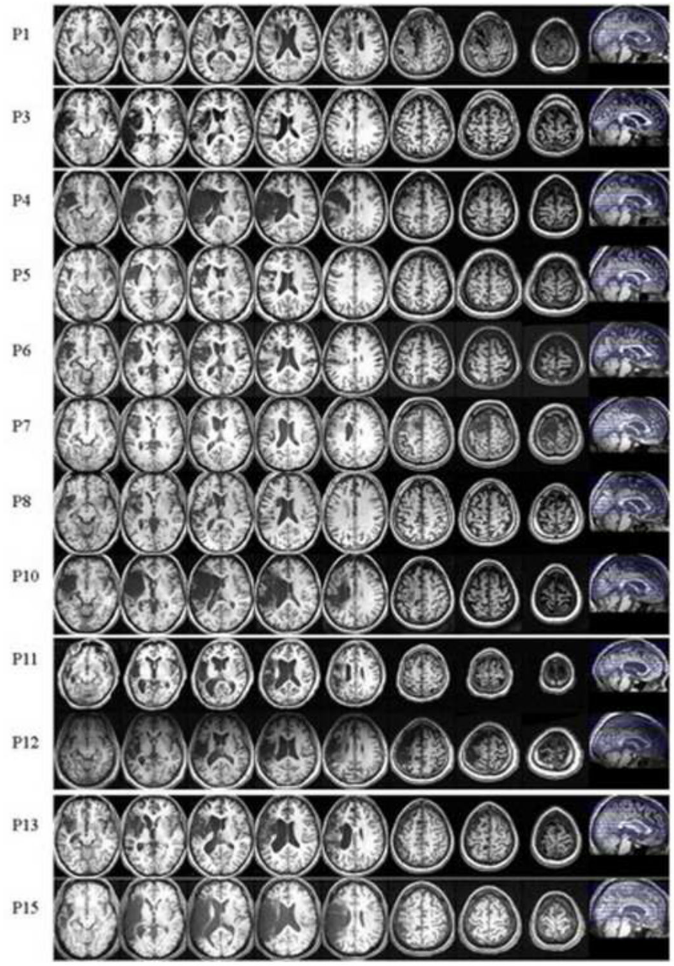

Figure 1.
Selected slices from T1 MRI images of aphasic participants showing lesion sites. MRI scans were not available for patients P2, P9 and P14

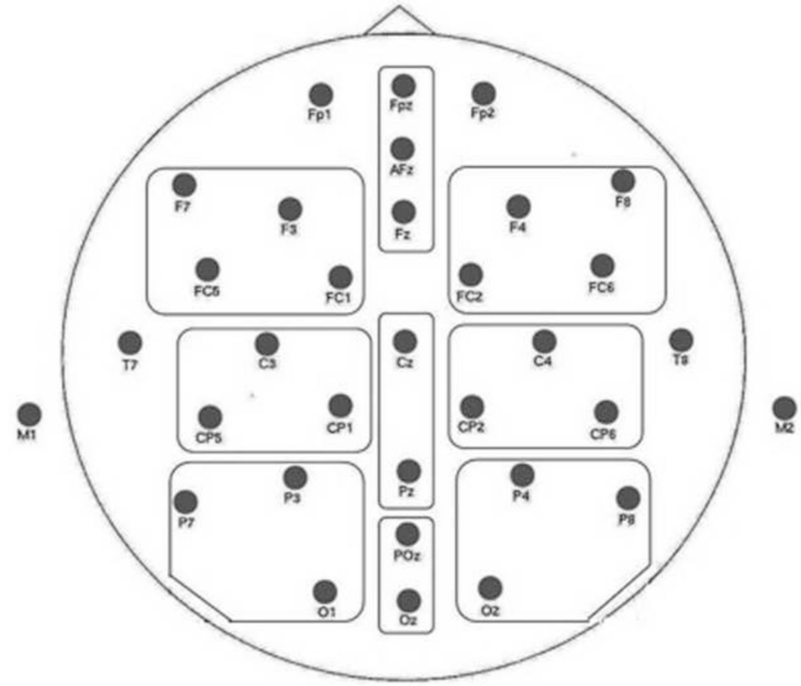

Figure 2.
Electrode layout. The 32 channel montage representing grouping of the electrodes into 9 regions. The data from the electrodes indicated by the solid line were used in the analysis: FC (Fz, Fpz), CC (Cz, Pz), PC (POz, Oz), RCP (C4, CP2, CP6), LCP (C3, CP5, CP1), RP (P4, P8, O2), LP (P3, P7, O1), RF (F4, F8, FC2, FC6), LF (F7, F3, FC1, FC5). The data from the remaining electrodes were used for visualization of the ERP effect using isovoltage maps.

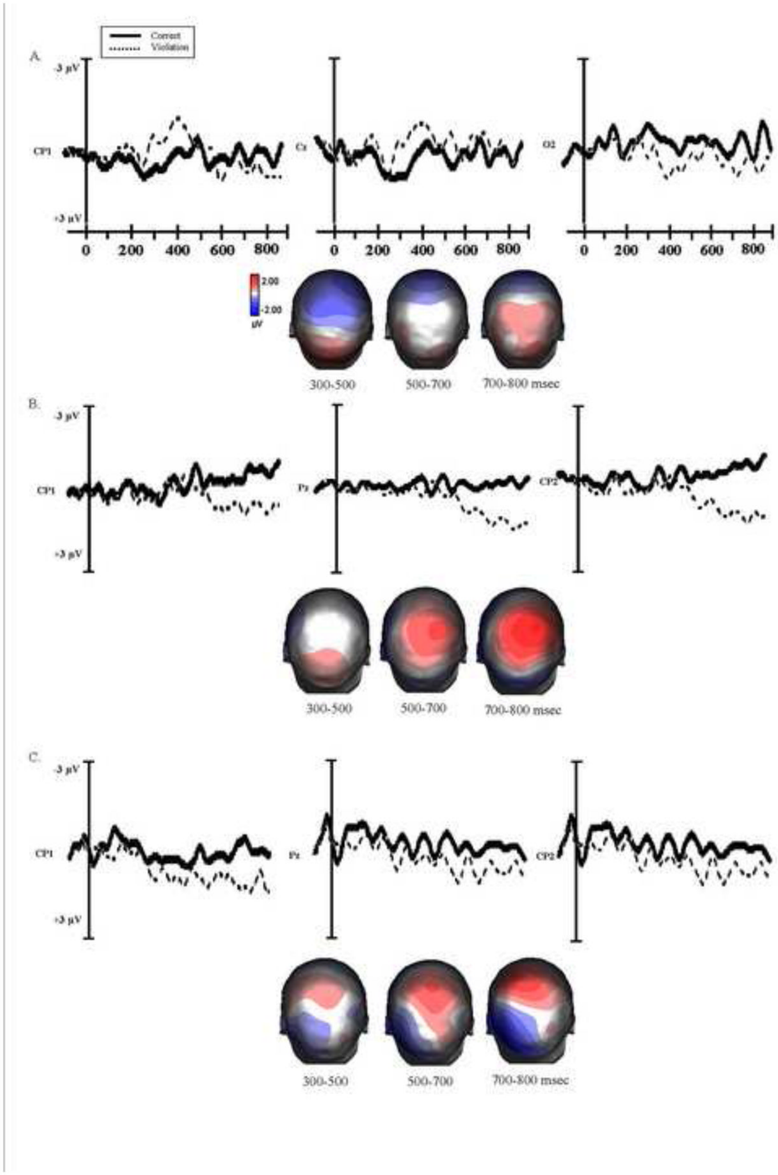

Figure 3.
Grand average ERPs at the representative electrodes for each participant group (A. Young Controls B. Older Adults and C. Agrammatic patients) elicited by the correct sentences (solid line) and verb argument structure violation (broken line) at the position of the deteminer. The voltage maps show topographical distribution of ERP effects across the scalp based on the difference waveforms (violation-correct) at 300–500, 500–700 and 700–800 msec time intervals.

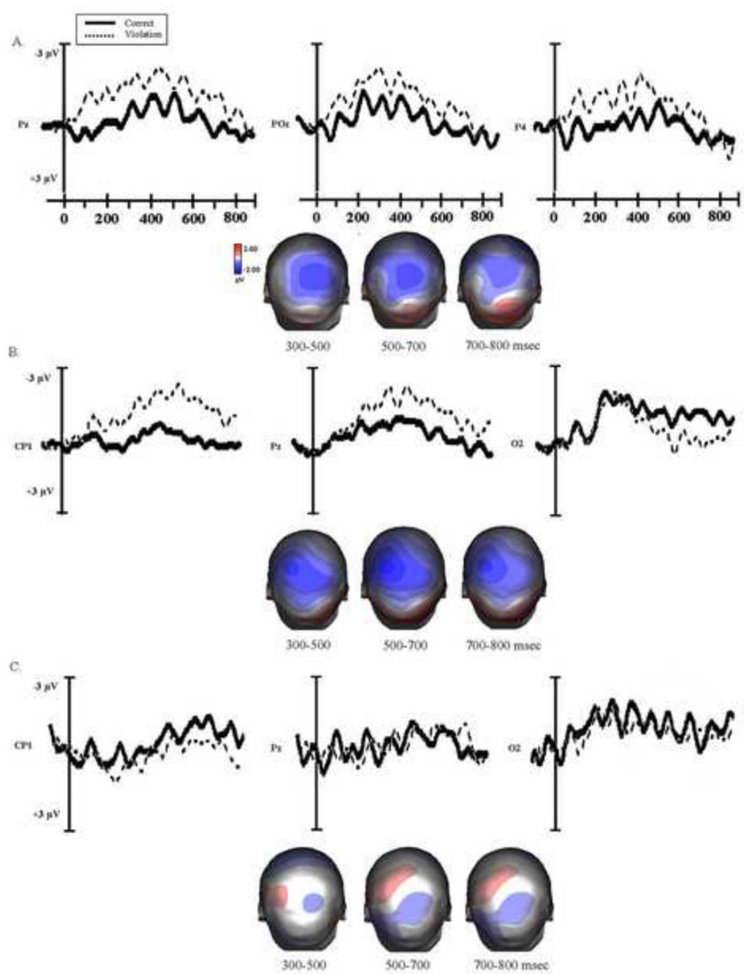

Figure 4.

Grand average ERPs at the representative electrodes for each participant group (A. Young Controls B. Older Adults and C. Agrammatic patients) elicited by the correct sentences (solid line) and verb argument structure violation (broken line) at the position of the critical noun. The voltage maps show topographical distribution of ERP effects across the scalp based on the difference waveforms (violation-correct) at 300–500, 500–700 and 700–800 msec time intervals.

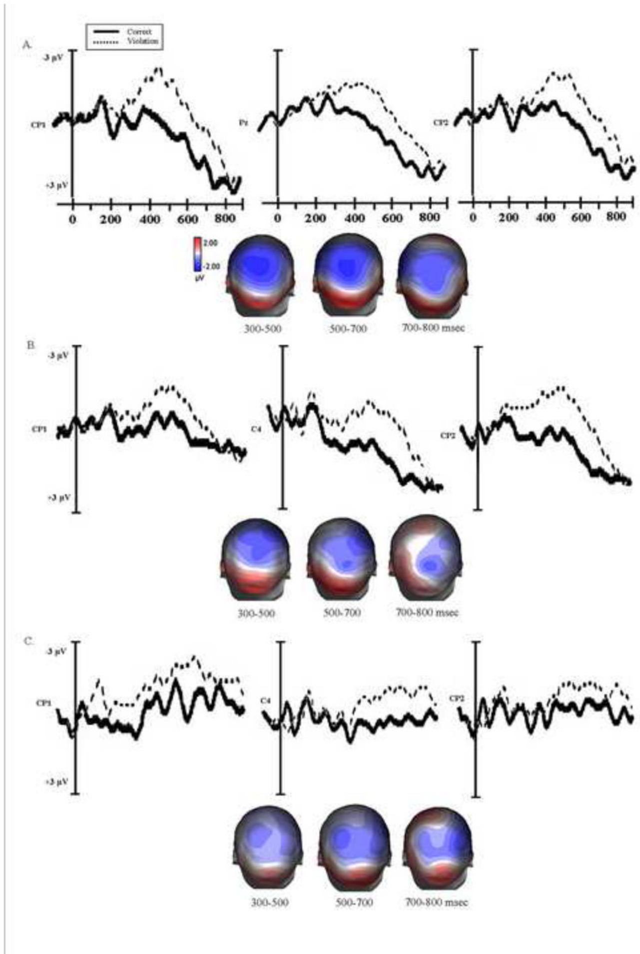

Figure 5.

Grand average ERPs at the representative electrodes for each participant group (A. Young Controls B. Older Adults and C. Agrammatic patients) elicited by the correct sentences (solid line) and semantic violation (broken line) at the position of the critical word. The voltage maps show topographical distribution of ERP effects across the scalp based on the difference waveforms (violation-correct) at 300–500, 500–700 and 700–800 msec time intervals.

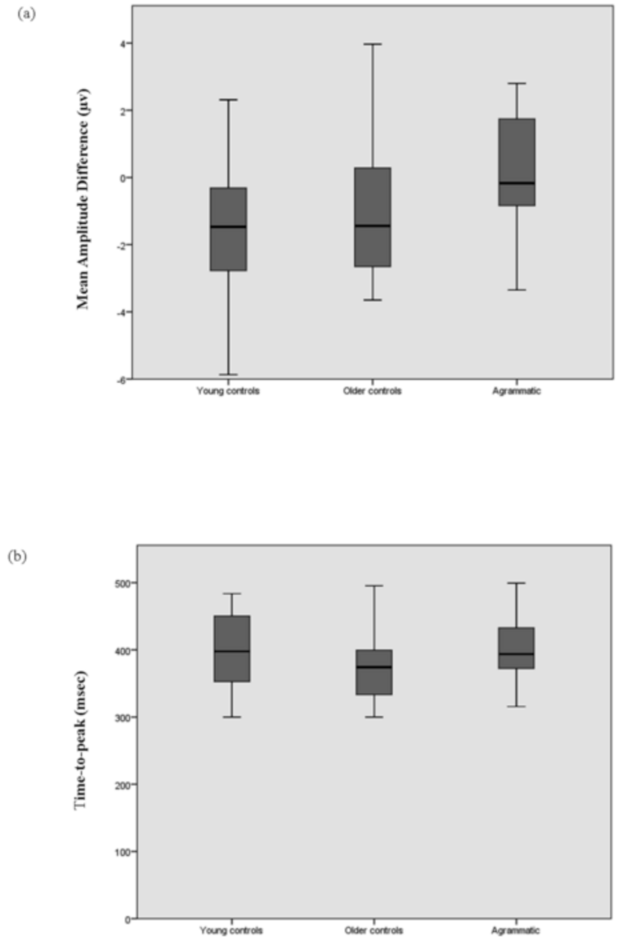

Figure 6.
Variability of the three participant groups in the semantic violation condition, in the 300–500 msec window, at electrode Pz: (a) Mean amplitude of the difference wave (microvolts); (b) Time-to-peak (msec).

Table 1

Language scores for agrammatic participants

Participant	WAB- AQ	NAVS			Narrative production	
		SCT	VCT	ASPT	MLU (words)	% grammatical sentences
P1	60.2	77	100	66	4.83	50
P2	66.3	73	77	81	4.5	0
P3	93	80	100	100	7.09	60.56
P4	56.4	50	100	94	3	0
P5	80.6	87	100	94	7.27	57.14
P6	89	70	94	88	4.09	33.33
P7	86	97	100	100	8.77	78.57
P8	81.2	NC	100	100	6.8	61.29
P9	81.4	53	100	97	8.29	47.54
P10	74	80	100	94	6.07	11.54
P11	75.2	47	100	84	7.9	56
P12	76.7	90	100	81	8.04	53.57
P13	78	60	100	88	6.07	64.29
P14	83	73	100	97	9.93	78.57
P15	65	NC	100	56	4.47	0
Mean (SD)	76.4 (10.49)	72.1 (15.7)	98.1 (6.03)	88 (12.9)	6.47 (1.98)	42.1 (14.65)

Abbreviations: WAB = Western Aphasia Battery; AQ = aphasia quotient; NAVS = Northwestern Assessment of Verbs and Sentences; SCT = sentence comprehension test; VCT = verb comprehension test; ASPT = argument structure production test; MLU = mean length of utterance; NC = not completed

Table 2

Lesion characteristics for agrammatic participants

Participant	Lesion localization
P1	Left hemisphere superior frontal and premotor cortex (BAs 6 and 8) extending to subcortical regions
P3	Left pars orbitalis of the IFG, middle and superior temporal gyrus, extending to the fusiform gyrus
P4	Extensive lesion involving left hemisphere inferior frontal (BAs 44, 45, 47) gyrus, middle superior frontal gyri (BA 46), premotor cortex, extending to the anterior superior temporal gyrus
P5	Left pars opercularis, pars orbitalis of IFG and premotor cortex, extending to the anterior temporal lobe
P6	Left pars opercularis, premotor cortex, inferior precentral and postcentral gyri, extending to the anterior temporal lobe
P7	Left pars opercularis of the IFG, superior frontal cortex, including primary motor and premotor cortex
P8	Left pars orbitalis, pars opercularis of the IFG, middle and anterior superior temporal gyri, extending to subcortical regions
P10	Large left hemisphere lesion involving inferior frontal gyrus (BAs 45 and 47) and prefrontal cortex, extending to the primary somatosensory cortex (BA 2), and including anterior middle and superior temporal gyri,
P11	Left pars opercularis, premotor cortex, including part of primary auditory cortex
P12	Left hemisphere superior frontal gyrus, pre- and postcentral gyrus, and premotor cortex
P13	Left hemisphere inferior frontal and prefrontal gyri, extending to the anterior middle and superior temporal gyri,
P15	Large lesion involving inferior frontal gyrus, extending to the motor and premotor cortex, and left hemisphere somatosensory cortex, involving superior temporal gyrus, angular and supramarginal gyri, as well as primary and association auditory cortex

Table 3

Mean (standard deviation) accuracy (%) and mean reaction times (msec) for control groups and agrammatic participants across the different experimental conditions.

Participant group	Grammatical		AS violations		Semantic violations	
	Accuracy	RT	Accuracy	RT	Accuracy	RT
Young controls	95.9 (4.4)	537.54 (160.93)	97.7 (5.2)	533.57 (185.85)	98.8 (2.7)	508.33 (178.14)
Older controls	96.8 (5.2)	596.36 (256.88)	96.9 (5.1)	580.58 (188.70)	98.9 (1.8)	566.19 (176.72)
Agrammatic	84.3 (13.2)	1124.82 (348.54)	59.7 (27.3)	1166.25 (330.31)	81.4 (17.4)	1147.62 (336.49)

Abbreviations: AS = argument structure

Table 4

Results of statistical tests performed on the mean amplitude of ERP waveforms for different experimental conditions and participant groups in the specified latency ranges

Time window	Young Controls								
	Condition			Electrode			C*E		
	df	F	p	df	F	p	df	F	p
AS violation ('the')									
300–400	1, 14	4.08	0.063	29, 406	1.13	0.355	29, 406	1.11	0.358
500–700	1, 14	0.23	0.636	29, 406	0.66	0.647	29, 406	0.5	0.723
AS violation ('doctor')									
300–500	1, 14	2.22	0.158	29, 406	2.89	0.025	29, 406	0.85	0.512
500–700	1, 14	2.878	0.112	29, 406	3.05	0.021	29, 406	0.56	0.718
Semantic violation									
300–500	1, 14	18.12	0.001	29, 406	1.1	0.361	29, 406	4.2	0.003
500–700	1, 14	19.16	0.001	29, 406	3.63	0.003	29, 406	4.3	0.001
	Age Matched								
	Condition			Electrode			C*E		
	df	F	p	df	F	p	df	F	p
AS violation ('the')									
300–500	1, 22	0.35	0.56	29, 638	1.87	0.094	29, 638	0.96	0.42
500–700	1, 22	7.17	0.014	29, 638	1.2	0.315	29, 638	1.93	0.089
700–800	1, 22	14.89	0.001	29, 638	2.21	0.044	29, 638	4.02	0.012
AS violation ('doctor')									
300–500	1, 22	1.5	0.233	29, 638	12.11	<.001	29, 638	3.00	0.038
500–700	1, 22	3.79	0.064	29, 638	5.54	<.001	29, 638	1.68	0.174
Semantic violation									
300–500	1, 22	10.98	0.003	29, 638	5.96	0.001	29, 638	4.81	0.002
500–700	1, 22	7.67	0.011	29, 638	3.51	0.018	29, 638	2.53	0.049
	Nonfluent								

Time window	Young Controls								
	Condition			**Electrode**			**C*E**		
	df	**F**	**p**	**df**	**F**	**p**	**df**	**F**	**p**
	Condition			Electrode			C*E		
	df	F	p	df	F	p	df	F	p
AS violation (‘the’)									
300–500	1, 14	0	0.965	29, 406	1.93	0.069	29, 406	0.59	0.672
500–700	1, 14	0.18	0.676	29, 406	2.33	0.036	29, 406	1.08	0.379
AS violation (‘doctor’)									
300–500	1, 14	0.05	0.833	29, 406	1.13	0.354	29, 406	0.56	0.672
500–700	1, 14	0.01	0.94	29, 406	1.48	0.209	29, 406	0.45	0.775
Semantic violation									
300–500	1, 14	5.02	0.042	29, 406	1.28	0.278	29, 406	0.991	0.44
500–700	1, 14	4.54	0.051	29, 406	1.67	0.156	29, 406	0.82	0.498

Table 5

Statistical analyses of ERP effects across experimental conditions and electrode regions in the specified time intervals

Time window	Electrode Region							
	CC	PC	LCP	RCP	LP	RP	LF	RF
	Young controls							
AS violation (‘the’)								
300–500msec	n.s.	4.73*	4.82*	n.s.	4.33*	n.s.	n.s.	4.85*
500–700msec	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
AS violation (‘doctor’)								
300–500msec	5.78*	n.s.	n.s.	n.s.	n.s.	6.80*	n.s.	n.s.
500–700msec	5.72*	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Semantic violation								
300–500msec	11.80**	8.84*	9.86**	n.s.	13.47**	20.90**	n.s.	7.66*
500–700msec	8.61*	7.02*	22.48***	7.80*	9.99**	n.s.	n.s.	7.53*
	Age-matched controls							
AS violation (‘the’)								
300–500msec	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
500–700msec	11.16**	6.67*	5.29*	5.10*	n.s.	7.69*	n.s.	n.s.
700–800msec	33.98***	8.74**	11.33**	9.89**	n.s.	6.05*	8.46**	n.s.
AS violation (‘doctor’)								
300–500msec	5.52*	n.s.	6.97*	n.s.	9.18**	6.44*	n.s.	6.03*
500–700msec	7.00*	n.s.	10.54**	n.s.	7.12*	5.84*	n.s.	4.83*
Semantic violation								
300–500msec	9.18**	13.74**	9.17**	23.07***	9.07**	8.06*	n.s.	7.93*
500–700msec	n.s.	6.87*	n.s.	26.90***	8.43**	n.s.	n.s.	5.85*
	Agrammatic							
AS violation (‘the’)								
300–500msec	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

Time window	Electrode Region							
	CC	**PC**	**LCP**	**RCP**	**LP**	**RP**	**LF**	**RF**
500–700msec	6.36 *	n.s.	n.s.	5.07 *	6.12 *	n.s.	n.s.	n.s.
AS violation ('doctor')								
300–500msec	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
500–700msec	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Semantic violation								
300–500msec	n.s.	n.s.	7.64 *	n.s.	n.s.	4.81 *	n.s.	n.s.
500–700msec	n.s.	n.s.	5.11 *	4.34 *	n.s.	7.77 *	n.s.	n.s.

Note:

* p < 05;

** p < .01,

*** p < .001.

Table 6

Results of group comparisons between the agrammatic and the two control groups across experimental conditions and electrode regions in the specified time intervals

msec	Effect	Electrode Region							
		CC	PC	LCP	RCP	LP	RP	LF	RF
		Agrammatic vs. Young Controls							
AS violation (‘the’)									
300–500	GxC	ns	ns	4.09*	ns	ns	ns	ns	ns
	Group	ns	ns	4.34*	ns	ns	ns	ns	ns
500–700		ns	ns	ns	ns	ns	ns	ns	ns
AS violation (‘doctor’)									
300–500	GxC	ns	ns	ns	ns	ns	ns	ns	ns
	Group	8.98**	ns	10.39**	4.64*	ns	ns	ns	ns
500–700		ns	ns	ns	ns	ns	ns	ns	ns
Semantic violation									
300–500	GxC	ns	5.46*	ns	ns	4.54*	6.13*	ns	ns
	Group	ns	ns	ns	ns	ns	ns	ns	ns
500–700	GxC	ns	ns	ns	ns	ns	ns	ns	5.40*
	Group	6.10*	ns	5.49*	ns	12.72*	ns	ns	ns
		Agrammatic vs. Age Matched							
AS violation (‘the’)									
300–500	GxC	ns	ns	ns	ns	ns	ns	ns	ns
	Group	ns	ns	5.86*	ns	6.80*	ns	ns	ns
500–700	GxC	ns	ns	ns	ns	ns	ns	ns	ns
	Group	ns	ns	ns	ns	ns	ns	ns	ns
700–800	GxC	ns	ns	4.19*	ns	ns	ns	ns	ns
	Group	ns	ns	5.64*	ns	ns	Ns	9.61**	7.03*
AS violation (‘doctor’)									
300–500	GxC	ns	ns	ns	ns	4.67*	ns	ns	ns

msec	Effect	Electrode Region							
		CC	PC	LCP	RCP	LP	RP	LF	RF
	Group	14.70***	10.51	10.92**	12.60***	7.68**	10.49**	ns	ns
500–700	GxC	ns	ns	8.58**	ns	4.45*	ns	ns	ns
	Group	ns	ns	ns	ns	ns	ns	ns	ns
Semantic violation									
300–500		ns	ns	ns	ns	ns	ns	ns	ns
500–700	GxC	ns	ns	ns	ns	ns	ns	ns	ns
	Group	ns	ns	ns	6.15*	ns	ns	ns	7.88**

Note:

* p < 05;

** p < .01,

*** p < .001

Table 7

Comparison of variability around the mean of time-to-peak (TTP) and mean amplitude of difference waves (MAdiff) between the three participant groups

Condition	Electrode site		Levene Statistic	Significance
Argument Structure Determiner, 300–500	CP1 (LCP)	TTP	0.867	0.427
		Madiff	1.751	0.184
	CP5 (LCP)	TTP	4.465	0.016
		Madiff	0.141	0.868
	C3 (LCP)	TTP	1.307	0.280
		Madiff	3.473	0.039
	CP6 (RCP)	TTP	0.694	0.504
		Madiff	2.117	0.131
	Pz(CC)	TTP	1.648	0.203
		Madiff	2.88	0.066
	POZ (PC)	TTP	1.069	0.351
		Madiff	2.155	0.127
	Oz (PC)	TTP	1.031	0.364
		Madiff	0.317	0.729
	P3 (LP)	TTP	0.723	0.496
		Madiff	0.252	0.779
	P7 (LP)	TTP	5.156	0.009
		Madiff	0.048	0.953
	P4 (RP)	TTP	0.805	0.453
		Madiff	0.126	0.882
	P8 (RP)	TTP	0.945	0.407
		Madiff	2.395	0.102
Argument Structure Determiner, 500–700	CP1 (LCP)	TTP	1.013	0.371
		Madiff	0.071	0.932
	CP2 (RCP)	TTP	2.342	0.107
		Madiff	0.095	0.91
	CP6 (RCP)	TTP	2.814	0.70
		Madiff	0.986	0.38
	CZ (CC)	TTP	0.184	0.833
		Madiff	2.923	0.063
	PZ (CC)	TTP	1.465	0.241
		Madiff	0.86	0.241
	POZ (PC)	TTP	1.55	0.221
		Madiff	2.74	0.074
	Oz (PC)	TTP	0.885	0.419
		Madiff	0.217	0.806
	P3 (LP)	TTP	0.036	0.965
		Madiff	0.217	0.806

Condition	Electrode site		Levene Statistic	Significance
	P7 (LP)	TTP	0.192	0.826
		Madiff	0.791	0.459
	P8 (RP)	TTP	0.659	0.522
		Madiff	0.496	0.612
Argument Structure Noun, 300–500 msec	CP1 (LCP)	TTP	0.646	0.529
		Madiff	1.138	0.329
	CP2 (RCP)	TTP	0.078	0.925
		Madiff	0.354	0.704
	CP6 (RCP)	TTP	0.411	0.665
		Madiff	0.366	0.695
	CZ (CC)	TTP	0.809	0.451
		Madiff	1.71	0.191
	PZ(CC)	TTP	0.084	0.92
		Madiff	1.992	0.147
	POZ(PC)	TTP	0.03	0.971
		Madiff	3.468	0.039
	Oz(PC)	TTP	1.647	0.203
		Madiff	0.377	0.688
	P3(LP)	TTP	1.332	0.273
		Madiff	0.204	0.816
	P7(LP)	TTP	2.382	0.103
		Madiff	0.322	0.726
	P8(RP)	TTP	0.326	0.723
		Madiff	0.302	0.741
Semantic Violation 300–500 msec	CP1 (LCP)	TTP	0.011	0.989
		MAdiff	1.361	0.266
	CP2 (RCP)	TTP	0.462	0.633
		Madiff	3.072	0.055
	CP6 (RCP)	TTP	2.146	0.128
		Madiff	1.642	0.204
	CZ (CC)	TTP	1.182	0.315
		Madiff	0.451	0.639
	PZ (CC)	TTP	0.473	0.626
		Madiff	0.013	0.987
	POZ (PC)	TTP	0.032	0.968
		Madiff	0.921	0.405
	Oz (PC)	TTP	2.151	0.127
		Madiff	1.844	0.169
	P3 (LP)	TTP	0.526	0.594
		Madiff	0.628	0.538
	P7 (LP)	TTP	0.756	0.475

Condition	Electrode site		Levene Statistic	Significance
		Madiff	6.161	0.004
	P4 (RP)	TTP	4.753	0.013
		Madiff	1.331	0.273
	P8 (RP)	TTP	0.318	0.729
		Madiff	2.611	0.083