AN INVESTIGATION OF THE EFFECTS OF PROFICIENCY AND AGE OF ACQUISITION ON NEURAL ORGANIZATION FOR SYNTACTIC PROCESSING USING ERPs AND fMRI

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Improvements in neuroimaging techniques have made it possible to answer questions regarding the neural organization for the processing of syntax in normal participants. In this series of experiments we examined the effects of linguistic proficiency and age of second language acquisition on neural organization for syntactic processing. We examined these factors using two complementary methodologies: event-related potentials (ERPs), which affords a temporal resolution on the order of milliseconds, and functional magnetic resonance imaging (fMRI), with spatial resolution on the order of millimeters. In order to compare results across methodologies, we used an auditory syntactic violation paradigm with similar experimental parameters in each methodology. In Chapter II we examined neural organization for syntactic processing using ERPs in monolingual native speakers of higher and lower proficiency and found that violations elicited an early onset (100 ms) anterior negativity (EOAN) followed by a later positivity (P600) in all participants. Compared to lower proficiency participants, higher proficiency participants showed an EOAN that was more focal spatially and temporally, and showed a larger P600. These results were supported by a correlational analysis of a larger group of monolingual native speakers with a wide range of proficiency scores. This analysis also found a relationship between childhood socioeconomic status and the recruitment of the EOAN over left hemisphere sites, raising the hypothesis that effects of childhood experience may endure into adulthood. In Chapter III we examined the effects of age of acquisition on syntactic processing by recruiting a group of late learners of English who were matched for proficiency with a group of monolingual native speakers from Chapter II. While in native speakers violations elicited a robust EOAN, this effect was absent in the late learner group, suggesting that early language exposure is important for the recruitment of resources reflected in this effect and independently of proficiency. In Chapter IV we gathered ERP and fMRI data from monolingual native speakers and found proficiency differences in the recruitment for syntactic processing of left inferior frontal and posterior regions. We linked proficiency-related modulations in the different ERP syntactic effects to specific fMRI activations indexing syntactic processing.

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CHAPTER I

GENERAL INTRODUCTION

Language, and the capacity to acquire and use it with little effort, is one of the most uniquely human of all traits, and one which has given rise to the capacity for the sharing of knowledge and culture which is one of the hallmarks of human society. One of the core properties of this uniquely human ability is that it is limitless with regard to the number of communicative expressions which can be formed by a finite number of symbolic lexical items. This property arises from the organization of the rules which govern the formation of these expressions: it is the hierarchical and recursive organization of these rules which gives rise to the limitless, generative nature of language. This aspect of language that consists of rules which govern structural relations in language is known as syntax. As the core of the generative nature of language, syntax has long been a central issue in linguistics. With improvements in techniques for the study of the neural implementation of language, it has become possible to answer questions regarding the neural organization for the processing of syntax in normal participants. Neural organization for syntactic processing, and the effects of linguistic proficiency and age of second language acquisition on this organization, is the central focus of the series of experiments presented here.

While empirical data bearing on the question of neural organization for language processing used to be limited primarily to that gathered from observations of brain damaged patients, technological advances of the last quarter of the 20th century saw the development of new techniques which allowed for unprecedented investigation of online language processing. One such technique, event-related potentials (ERPs), measures at the scalp electrical activity time-locked to stimuli presentation. While ERPs provide excellent temporal resolution, because they rely on measurements of electrical activity from limited numbers of electrodes on the scalp they are limited in spatial resolution. ERPs are complemented by neuroimaging techniques, such as positron emission tomography and functional magnetic resonance imaging, which feature excellent spatial resolution but, as they are indirect measures of neural activity, are limited in temporal resolution. In the last 20 years these complementary techniques have been used extensively to explore neural organization for language processing.

Event-related potentials are measurements of continuous brain electrical activity time-locked to the presentation of a stimulus. ERPs provide an online, non-invasive index of cognitive processes with a temporal resolution of milliseconds. The ERP response typically consists of a series of positive and negative deflections, known as components. As these components vary on a number of dimensions, such as amplitude, polarity, and latency, ERPs provide a multidimensional index of cognitive processes. This degree of temporal resolution is crucial in the study language given the rapid pace of information processing in natural language processing. While the strength of the ERP technique is the high degree of temporal resolution provided, because electrical activity is recorded at the scalp the ability to localize the source of this electrical activity is limited. This is due primarily to two factors. First, because electrical activity is conducted very well by the brain neural activity at one location could have been generated in a different part of the brain. Second, ERPs sum in a linear fashion at the scalp, and because the skull is a poor conductor of electricity the precise localization of ERP components is further complicated (Rugg & Coles, 1995). ERPs do provide some spatial information via the topographic distribution of components, and the quality of this information can be improved by recording from a greater number of electrode sites. Still, spatial resolution is ultimately limited by the factors described above, and the strength of the ERP methodology lies in its excellent temporal resolution.

In the last two decades, two techniques have been developed which offer a much higher degree of spatial resolution compared to ERPs. The first technique to be developed and used in cognitive neuroscience is positron emission tomography (PET). PET uses a short-lived radioactive isotope which is injected into the bloodstream and whose concentration varies with neural activity in different brain regions. While PET offers spatial resolution on the degree of centimeters as the decay of the isotope is measured across brain regions, the slow timecourse of this decay requires that homogeneous sets of stimuli be presented in blocks of usually a minute or longer. This limit in experimental design, along with the relatively invasive nature of the technique, has seen the PET methodology increasingly limited in use with the development of the second technique offering excellent spatial resolution.

This second technique, functional magnetic resonance imaging (fMRI), also provides excellent spatial resolution, but without the limitations of PET. Functional magnetic resonance imaging uses radio waves and strong magnetic field gradients to measure differences in oxygenated and deoxygenated hemoglobin in the brain. As a measure of brain function, fMRI is based on the increase in blood flow to local vasculature which accompanies neural activity. This is reflected in fMRI by a measure of the increase in the amount of oxygenated hemoglobin supplied to different brain areas, known as the blood oxygen level dependent (BOLD) response (for more detail, see Moonen, Bandettini, & Aguirre, 1999). The BOLD response is typically on the order of 12 seconds; while an improvement over the temporal resolution offered by PET, this still limits the spatial resolution offered by fMRI. However, fMRI provides exquisite spatial resolution, on the order of millimeters. Recent developments in techniques provide for more flexibility in experimental design. In addition to the blocked designs commonly used in PET experiments, it is now possible to use event-related designs which allow for the presentation of randomly intermixed stimulus trials, thus more closely approximating designs used in ERP experiments. This flexibility, combined with its increase in spatial resolution combined with a decrease in invasiveness compared to PET, has seen fMRI become the more widely used methodology for studying online syntactic processing with a high degree of spatial resolution.

Anecdotally, it is clear that there exist differences in the way native speakers use and comprehend their native language. Several studies suggest that language experience can affect linguistic proficiency and a few have reported that proficiency also predicts the brain response to language in monolingual native speakers. Behaviorally, studies of language development in native speakers of English suggest that parents who talk more to their children tend to have children with larger vocabularies (Hart & Risley, 1995).

Research also suggests that parents who talk more to their children tend to have children who score higher on tests of syntactic comprehension, and that teachers who use more complex speech in preschool classrooms tend to have students who score higher on tests of syntactic comprehension (Huttenlocher, Vasilyeva, Cymerman, & Levine, 2002). ERP studies of monolingual children suggest that brain organization is predicted by language proficiency: children with larger vocabularies (Mills, Coffey-Corina, & Neville, 1993) and children who score higher on tests of language comprehension (Adamson-Harris, Mills, & Neville, 2000) show more mature patterns of brain organization for language as compared with children with smaller vocabularies or those who score lower on comprehension tests. ERP studies of deaf adults suggest that early effects of language experience can endure into adulthood, as individuals exposed to American Sign Language (ASL) from an early age recruit right hemisphere areas in addition to left hemisphere language areas when processing ASL, but those not exposed to ASL at an early age do not show this bilateral response to ASL (Neville, Coffey, Lawson, Fischer, Emmorey et al., 1997; Newman, Bavelier, Corina, Jezzard, & Neville, 2002).

While most ERP studies which have examined group differences in monolingual adults have focused on differences in working memory capacity, data from one ERP experiment suggests that significant differences in proficiency do exist in monolingual adults and are linked to altered neural organization as indexed by ERPs (Weber-Fox, Davis, & Cuadrado, 2003). Also, most ERP studies of syntactic processing have used primarily university students as participants. By making theoretical assumptions based on studies of participants drawn from the relatively homogenous participant pool that is the university setting, researchers may be missing an important opportunity for a veridical understanding of neural organization for language processing. The studies of monolingual native speakers presented here include participants recruited from a wide spectrum of society in an attempt to both maximize proficiency differences and provide a more complete picture of the neural systems important in syntactic processing.

An ongoing question in the study of second language acquisition concerns the relative contributions of age of acquisition and ultimate linguistic proficiency on neural organization for second language processing. Several event-related potential (ERP) and neuroimaging studies of second language learners have found that, while subsystems implicated in online semantic processing are relatively invulnerable to delays in second language acquisition, neural organization for syntactic processing is altered by delays in acquisition as short as four years (Dehaene et al., 1997; Hahne, 2001; Hahne & Friederici, 2001; Kim, Relkin, Lee, & Hirsch, 1997; Ojima, Nakata, & Kakigi, 2005; Rossi, Gugler, Friederici, & Hahne, 2006; Wartenburger et al., 2003; Weber-Fox & Neville, 1996). However, such delays in second language acquisition are typically associated with lower language proficiency (Johnson & Newport, 1989), rendering it difficult to access whether differences in age of acquisition or proficiency lead to these effects.

The series of experiments presented here systematically examined the relative effects of proficiency and age of acquisition on neural organization for syntactic processing, using the same auditory syntactic violation paradigm in groups which differ on these dimensions.

In Chapter II, the role of proficiency was explored while keeping age of acquisition constant by examining the ERP response to syntactic violations in monolingual native speakers who differ on tests of English proficiency. The use of monolingual native English speakers kept age of acquisition constant relative to late second language learners of English; as discussed above, evidence from studies of language development suggest that more subtle differences in language experience during development are associated with differences in proficiency and the neural response to language. One of the goals of the experiment presented in Chapter II was to further explore the hypothesis that proficiency differences related to differences in experience in development may endure into adulthood and that such differences in monolingual adults may be related to differences in language experience in childhood. A second goal was to expand the study of neural organization for syntactic processing beyond a sample of university students. To this end, participants were recruited from a wide range of socioeconomic status and educational backgrounds and data concerning their language experience during development was collected. Participants were given a battery of standardized measures of English proficiency, and the ERP responses to phrase structure violations were analyzed using complementary analytical approaches based on both group and individual differences in proficiency scores. In the first approach, participants were divided, based on their average standardized scores, into groups falling into roughly the top and bottom quartiles. The ERP responses to phrase structure violations in English was recorded and quantified by subtracting the response to canonical critical words in sentences to violation critical words, and the ERP grand average waveforms for the groups were directly compared for differences in the amplitude and distribution of ERP components which index syntactic processing. The second approach was a correlational analysis intended to replicate and further explore proficiency effects observed using the group approach by analyzing data from 72 participants with a wide range of standardized proficiency scores. In this analysis average difference amplitudes were calculated by subtracting the average amplitude to canonical target words from the average amplitude to violation target words from the phrase structure violation paradigm described above. The degree to which these difference amplitudes correlated with proficiency scores across different electrode sites and time windows was examined, and a partial correlation analysis was also conducted to control for the possible effects of other variables that typically correlate with proficiency including socioeconomic status, education level, and working memory span.

In the experiment presented in Chapter III, the role of age of acquisition was explored by keeping proficiency constant. The ERP response to syntactic violations was examined in native speakers of German who did not begin learning English until the age of 11 or after but who had achieved a high enough level of English proficiency to study or work at a university in the United States. Crucially, these late learners of English were given the same standardized tests of English given to the monolingual participants from Chapter II, which allowed this group to be matched on English proficiency with the group of lower proficiency monolinguals from Chapter II. While previous ERP studies have examined late second language learners of different proficiency levels, this is the first study to directly compare proficiency-matched groups with vastly different ages of acquisition. This allows for the exploration of the hypothesis that certain neural systems important for syntactic processing may require input during a putative sensitive period, and that late second language learners may recruit different neural systems to achieve a similar level of proficiency to that of native speakers.

While ERPs and fMRI are methodologies which compliment each other in terms of temporal and spatial resolution, few studies have used syntactic processing paradigms in fMRI experiments which are similar to those which have been used in ERP studies (e.g., Friederici, Rüschemeyer, Hahne, & Fiebach, 2003), and only one study to date has examined the neural response to the same violations in the same participants in both methodologies (Kuperberg et al., 2003). In the experiment presented in Chapter IV, the same auditory syntactic violation paradigm was used using both methodologies in the same group of participants to examine neural organization for syntactic processing, and specifically the effects of linguistic proficiency on this organization. This allowed for the use of the excellent spatial resolution afforded by the fMRI methodology as a complement to the excellent temporal resolution of the ERP methodology. These two methodologies were used together to examine auditory syntactic processing using ERPs and fMRI in the same group of participants. Participants in Chapter IV were prescreened with the same battery of standardized behavioral measures used in Chapter II, and ERP-fMRI data were collected only from participants scoring in the upper and lower quartiles. These participants performed the same auditory syntactic processing paradigm under the same task conditions in both ERP and fMRI paradigms. This allowed for both replication of the ERP results from Chapter II and expansion of these results to allow for a characterization of the neural substrates involved in the processing of auditorily presented phrase structure violations. Differences in neural organization for syntactic processing related to differences in proficiency were further explored by examining neural regions in which the neural response to phrase structure violations correlated with standardized proficiency scores. Additionally, as little evidence currently exists with regard to the neural substrates underlying ERP components related to syntactic processing, the paradigm used in Chapter IV is able to provide crucial evidence bearing on this question. This approach takes advantage of having the same ERP and fMRI data from the same participants, and of the proficiency-related modulation of the ERP response to syntactic violations. Regions were identified in which proficiency-related modulations of the neural response to violations occurred and these were correlated with average difference amplitudes related to different ERP components, thereby shedding light on the possible neural generators of these components.

The experiments presented here examined the effects of proficiency and age of acquisition using the same auditory phrase structure violation paradigm with participants who varied on these dimensions, using complementary methodologies and complementary analytical approaches. Taken together, the results from these experiments constitute another step towards a more complete characterization of neural organization for syntactic processing while raising important hypotheses for future study concerning the potentially enduring effects of childhood language environment on adult language proficiency and neural organization for language processing.

CHAPTER II

PROFICIENCY DIFFERENCES IN SYNTACTIC PROCESSING OF NATIVE SPEAKERS INDEXED BY EVENT-RELATED POTENTIALS

Anecdotally, it is clear that there exist differences in the way native speakers use and comprehend their native language. Beginning with Chomsky's (1965) claim that linguistic theory should be concerned with an ideal speaker-listener with perfect linguistic knowledge, differences in linguistic proficiency among native speakers have often been assumed to be the result of resource limitations or performance errors considered to be independent of and irrelevant to grammatical knowledge. Numerous studies of bilinguals, young children, children with specific language impairment, and deaf adults have found that event-related potentials (ERPs) are sensitive to differences in language proficiency (Mills et al., 1993; Neville, Coffey, Holcomb, & Tallal, 1993; Neville, Mills, & Lawson, 1992; Weber-Fox & Neville, 1996). Additionally, several ERP studies have examined differences in language processing in native speakers. However, most of these studies have not separately assessed confounds between language processing and other cognitive resource limitations because they specifically studied complex syntactic structures to examine individuals with differences in working memory capacity (Friederici, Steinhauer, Mecklinger, & Meyer, 1998; King & Kutas, 1995; Mecklinger, Schriefers, Steinhauer, & Friederici, 1995; Vos & Friederici, 2003; Vos, Gunter, Kolk, & Mulder, 2001; Vos, Gunter, Schriefers, & Friederici, 2001). Also, most of these studies looked at university students processing sentences in the visual modality. Because the majority of language use in everyday life occurs in the auditory modality and between speakers with a wide variety of educational backgrounds, there remains the question of the extent to which proficiency differences in syntactic processing may be apparent under conditions which more closely approximate real-world language use. In the current study we tested the hypothesis that differences in grammatical proficiency in native speakers are indexed by differences in ERP components related to the processing of phrase structure violations in auditorily presented sentences. To this end, we examined differences in grammatical processing proficiency in participants recruited from a wide spectrum of society using a natural speech paradigm which does not place high demands on working memory resources. In order to more fully characterize these differences, we conducted two complementary analyses: first, we characterized differences in the ERP response to syntactic violations between two groups which differed in standardized proficiency scores; second, we conducted a correlational analysis with a larger group of participants in order to assess the degree to which the relationship between proficiency and the neural response to syntactic violations held across a wide spectrum of proficiency scores and while controlling for other possible mediating factors.

ERP studies of language processing

ERPs provide an on-line, multidimensional index of cognitive processes with a temporal resolution of milliseconds and thus have emerged as one of the more widely used methodologies to examine on-line language processing. Along with other methods, ERP studies have demonstrated that separate linguistic subsystems are mediated by non-identical neural mechanisms. Following a pioneering report by Kutas and Hillyard (1980), numerous studies in both the visual and auditory modalities have found that semantically unexpected words elicit a negative-going potential peaking around 400 ms (N400) compared to contextually appropriate words (e.g., Friederici, Pfeifer, & Hahne, 1993; Holcomb & Neville, 1991), leading to the hypothesis that the N400 component indexes semantic processes of lexical integration.

While the N400 has consistently been related to aspects of semantic processing, at least two components have been identified which index syntactic processing. One of these is a negative-going wave, typically larger over left anterior electrode sites between 100-500 ms, known as the left anterior negativity (LAN). The LAN has been elicited by a variety of syntactic violation types, such as phrase structure violations (Friederici et al., 1993; Gunter, Friederici, & Hahne, 1999; Hahne & Friederici, 1999; Neville, Nicol, Barss, Forster, & Garrett, 1991; Yamada & Neville, 2007) and morphosyntactic violations (Coulson, King, & Kutas, 1998a; Friederici et al., 1993; Münte, Heinze, & Mangun, 1993). The LAN typically occurs in one or both of two time windows (100-300 ms and 300-500 ms), which has lead some researchers to propose the existence of two distinct, separate components, with the first, termed the early left anterior negativity (ELAN), indexing processes different from those indexed by the second, LAN (Friederici, 1995; Friederici & Mecklinger, 1996; Hahne & Jescheniak, 2001). Two recently proposed theories of online sentence processing account for these components in different ways. Friederici (2002) proposes that the ELAN reflects early and automatic processing of word category violations, a process hypothesized to be autonomous and independent of contextual or semantic influences. In contrast, Hagoort and colleagues (Hagoort, 2003; Hagoort, 2005; van den Brink & Hagoort, 2004) propose that semantic and syntactic information are processed in parallel as soon as they are available and that the timing differences reported between LAN and ELAN effects are a result of differences in the online availability of morphosyntactic and word category information, not as the result of a fundamental functional distinction between them.

The second component which has been observed in ERP studies of syntactic processing is a large positive-going wave usually largest over bilateral posterior regions and peaking between 500-1000 ms., known as the P600 (Osterhout & Holcomb, 1993). The P600 is consistently elicited by syntactic violations (Hagoort, Brown, & Groothusen, 1993; Hagoort & Brown, 2000; Hahne & Friederici, 1999; Osterhout & Holcomb, 1992; Osterhout & Mobley, 1995) as well as by violations of preferred syntactic structure (Osterhout & Holcomb, 1992; Osterhout, Holcomb, & Swinney, 1995) or in well-formed sentences of higher syntactic complexity (Kaan, Harris, Gibson, & Holcomb, 2000; Kaan & Swaab, 2003a, b). While the distribution of the P600 is usually posterior, several studies have reported a late positivity with a more frontal distribution to grammatically correct but non-preferred structures (Friederici, Hahne, & Saddy, 2002; Kaan & Swaab, 2003a, b; Osterhout & Holcomb, 1992). This has led to the proposal that the frontally distributed P600 reflects processing difficulties related to revision in the face of non-preferred structures, while the posteriorally distributed P600 reflects processes related to the failure of a parse and related processes of repair and meaning rescue (Friederici et al., 2002; Hagoort & Brown, 2000) or to syntactic integration difficulty (Kaan et al., 2000). Several studies have sought to clarify the functional interpretation of the P600 by using a so-called "Jabberwocky" paradigm, in which open-class words are replaced with pronounceable nonwords, leaving little or no meaning to be rescued in the face of a syntactic violation. Results from these studies are mixed: while two studies have found a reduced P600 to syntactic violations in Jabberwocky sentences (Canseco-Gonzalez, 2000; Münte, Matzke, & Johannes, 1997), one study did not (Hahne & Jescheniak, 2001).

While overall there is a good deal of consistency in the elicitation of this biphasic response across studies using different violation types in different languages and modalities, there still exists a great deal of variability, in particular with regard to the distribution of the anterior negativity effect. Specifically, several studies have reported an anterior negativity effect in monolingual native speakers which is more extended temporally and/or more bilateral in distribution (e.g., Friederici & Frisch, 2000; Friederici & Mecklinger, 1996; Friederici et al., 1993; Hagoort, Wassenaar, & Brown, 2003; Hahne, 2001; Hahne & Friederici, 2002; Hahne & Jescheniak, 2001; Isel, Hahne, Maess, & Friederici, 2007; Münte et al., 1997; Rossi et al., 2006). While possible sources of this variability are potentially informative for theories of online sentence processing, little is known about this issue. One possible source of this variability is within-group differences in participant characteristics, such as language proficiency. While it is difficult to assess the possibility that such differences may have contributed to the variability observed in previous studies, here we specifically address the possibility that differences in participant characteristics may be reflected in differences in the distribution and timing of ERPs elicited by syntactic violations.

Individual differences and effects of experience

Previous studies of individual differences in adult native speakers have primarily focused on differences in working memory (WM) using paradigms involving garden-path sentences or manipulations of syntactic complexity. Early behavioral studies found that individual differences in WM capacity are predictive of comprehension and speed of processing, as subjects with lower WM spans were slower and less accurate in comprehending complex syntactic constructions compared to subjects with higher WM spans (Just & Carpenter, 1992; King & Just, 1991). Subsequent ERP studies have found that these differences are reflected electrophysiologically as well. The most common finding is that the disambiguating element in object-first relative clauses compared to subject-first relative clauses elicits a P600, but only in subjects who performed faster on sentence comprehension tasks (Mecklinger et al., 1995) or who had high WM spans (Friederici et al., 1998; Vos & Friederici, 2003). While these studies provide evidence that ERPs are sensitive to individual differences in WM and syntactic processing, the focus on differences in WM raises the question of the degree to which individual differences in proficiency may occur independently of other resource limitations such as WM span.

Evidence from studies of language development in monolinguals suggests that language experience can affect linguistic proficiency. Much of this evidence links differences in childhood language experience to differences in socioeconomic status

(SES), a compound variable usually quantified by measuring household differences in parental education level, occupational prestige, and income (Ensminger & Fothergill, 2003). While this is the most common method for measuring SES, many other factors contribute to differences in household environments related to SES, including prenatal care, stress, physical health and nutrition, substance abuse, parenting attitudes, and school and neighborhood characteristics (Bornstein & Bradley, 2003). While the "unpacking" of SES through the assessment of the individual effects of these factors is at present an unanswered question, as is the direct assessment of the role of genetic factors, the aggregate effect of SES on child language environments and language development is substantial. A recent review found consistent cross-cultural evidence for SES differences in maternal speech: higher SES mothers talk more to their children than do lower SES mothers and more frequently use speech for the purpose of eliciting conversation, while the speech of lower SES mothers is more frequently used for the purpose of directing child behavior (Hoff, Laursen, & Tardif, 2002). Furthermore, a large-scale study of in-home conversation between parents and children (Hart & Risley, 1995) found that over the course of a week children of higher SES parents heard 215,000 words while children of lower SES parents heard 62,000 words, and in addition to hearing more words children of higher SES parents heard more different words. These SES-related differences in language input were reflected in differences in child vocabulary, as higher SES children had significantly larger vocabularies, and SES accounted for 36% of the variance in vocabulary. While the magnitude of differences related to SES depend on the range of SES in the sample studied, similar findings of SES-related differences in vocabulary growth have been reported by a number of studies (e.g., Arriaga, Fenton, Cronan, & Pethick, 1998; Dollaghan et al., 1999; Hoff, 2003). A relationship has also been found between SES and grammatical development, as children from higher SES households have been found to score higher on standardized measures of grammatical development (Dollaghan et al., 1999), to score higher on standardized measures of word combination and sentence complexity (Arriaga et al., 1998), and to score higher on measures of productive and receptive syntax (Huttenlocher et al., 2002). Importantly, that study also provided evidence that such differences were specifically related to language experience, as variation in the syntactic complexity of maternal speech significantly explained variation in the syntactic complexity of child speech, and variation in the complexity of teacher speech was also significantly related to the growth of child scores on measures of syntactic comprehension. Studies which have examined the associations between SES and a wider range of measures of cognitive function have reported a predominant association between SES and language in children (Noble, McCandliss, & Farah, 2007; Noble, Norman, & Farah, 2005). While scant evidence exits with regard to the degree to which SES effects endure beyond childhood, some evidence supports this possibility. Differences in preschool vocabulary size related to SES at age 36 months predict subsequent receptive and spoken language scores, as well as academic achievement, in elementary school (Walker, Greenwood, Hart, & Carta, 1994), and lower childhood SES is associated with lower scores on a range of cognitive measures in adulthood, including language, even when educational attainment as adults is controlled for (Kaplan et al., 2001).

Several studies of both monolingual native speakers and of bilinguals suggest that language experience affects both linguistic proficiency and related neural systems indexed in ERP paradigms. ERP studies of monolingual children suggest that brain organization is predicted by language proficiency: children with larger vocabularies (Mills et al., 1993) and children who score higher on tests of language comprehension (Adamson-Harris et al., 2000) show more mature patterns of brain organization for language, including greater focalization, as compared with children with smaller vocabularies or those who score lower on comprehension tests. ERP studies of deaf adults suggest that the effects of early language experience can endure into adulthood, as individuals exposed to American Sign Language (ASL) from an early age recruit right hemisphere areas in addition to left hemisphere language areas when processing ASL. However, those not exposed to ASL at an early age do not show this bilateral response to ASL and score lower on tests of ASL grammar (Neville, Coffey, Lawson, Fischer, & et al., 1997; Newman et al., 2002; Newport, 1990). More evidence from ERP studies of bilinguals suggest that linguistic subsystems are differentially sensitive to the effects of language experience, with the syntactic subsystem displaying less focal neural organization with delays in second language exposure as short as 4-6 years, while the semantic subsystem appears to be affected by delays in second language exposure only after 11-13 years of age (Weber-Fox & Neville, 1996). Similar results have been observed for native and late learners of ASL (Capek et al., 2002).

This evidence of the effects of language experience raises the question of the extent of these effects. Do significant differences in proficiency exist within normal monolingual adults, and would such differences be indexed by ERP components related to syntactic processing? Or do effects of early experience fade with time such that neural systems underlying language processing in adult monolinguals are relatively homogeneous?

Data from one ERP experiment suggests that significant differences in proficiency do exist in monolingual adults and are linked to altered neural organization as indexed by ERPs. Weber-Fox, Davis, and Cuadrado (2003) found that individuals who scored higher on a spoken grammar test had an earlier N280 to closed-class words over left anterior regions, suggesting greater efficiency related to syntactic processing in higher proficiency individuals. If ERP components associated with syntactic processing are sensitive to differences in linguistic proficiency, then the evidence discussed above suggests that components elicited by phrase structure violations in low proficiency participants should be less focal those elicited in higher proficiency individuals.

The present study

The present study sought to further explore the relationship between proficiency and neural organization for language in monolingual native speakers as measured by ERPs during on-line syntactic processing. We attempted to maximize proficiency differences by recruiting participants from a wide spectrum of society. We attempted to minimize the effects of other potential resource limitations such as WM by using a paradigm which examined the brain response to phrase structure violations in simple, single-clause sentences, which were presented auditorily in an attempt to increase ecological validity while minimizing confounds related to literacy. In an effort to fully characterize differences in neural organization related to proficiency, we conducted two complementary analyses. In the first, we examined two groups of participants with scores at or near the upper and lower quartiles on standardized tests of English proficiency, respectively. In the second, we examined the relationship between proficiency and the neural response to syntactic violations in a group of 72 participants with a wide range of proficiency scores, using a correlational approach which allowed us to control for three other possible mediating factors: education level, working memory span, and socioeconomic status of origin.

Method

Participants

Right-handed, normal hearing, native monolingual speakers of English, recruited from both the university and non-university populations, participated in the study. Participants were paid for their time. A total of 116 participants were run in the behavioral testing paradigm described below, and of these 80 were also run in the event-related potential paradigm described below. From this group of 80, eight participants were removed from the final analysis either after being identified as outliers on the behavioral measures or due to excessive ERP artifact. This left a group of 72 participants with good behavioral and ERP data, and from this group 34 were selected for the between-group analysis based on behavioral performance to form Lower Proficiency (LP) and Higher Proficiency (HP) groups. An average standardized score for the three subtests of the Test of Adolescent and Adult Language-3 (TOAL-3; (Hammil, Brown, Larsen, & Wiederholt, 1994) was calculated for all participants, and the LP and HP groups were formed by selecting the participants with the lowest and highest average standardized scores. In order to reduce group differences in WM capacity, an initial selection of the participants with the lowest and highest average standardized scores was modified by removing the two participants from each group with the lowest and highest Carpenter Reading Span scores, respectively.

Behavioral Language Inventories

Three subtests of the TOAL-3 were administered to assess proficiency. The TOAL-3 Listening/Vocabulary subtest is a test which requires participants to match a vocabulary word with two pictures relating to that word (out of four pictures shown). The TOAL-3 Listening/Grammar subtest requires participants to determine, out of three sentences presented auditorily, which two sentences have similar meaning. The TOAL-3 Speaking/Grammar subtest requires participants to repeat exactly sentences said by the examiner; the sentences gradually increase in syntactic difficulty. Participants were also given the Saffran and Schwartz Grammaticality Judgment Test (Linebarger, Schwartz, & Saffran, 1983), a 78-item assessment in which participants are asked to judge the grammaticality of sentences containing a variety of syntactic violations, adapted for purposes of this study into the auditory modality. In order to assess working memory capacity, participants were also given the Carpenter Reading Span Test (Daneman & Carpenter, 1980), a widely-used assessment in which participants must recall the final word of two or more sentences after reading them consecutively. Participants also completed a questionnaire which gathered data about educational attainment, as well as about language usage, television, and video game habits both as children and as adults.

This questionnaire also gathered data used to calculate the socioeconomic status of the family in which participants were raised until 18 years of age or independence. This was measured by the Hollingshead Four Factor Index of Social Status (Hollingshead, 1975), which takes into consideration parental education and occupation.

Stimuli

In the ERP paradigm, participants heard both English sentences and Jabberwocky sentences, in which open-class words were replaced with pronounceable nonwords to greatly reduce the semantic context; only the results for the English stimuli are presented here. The English stimuli were sentences which were canonical (50%) or which contained an insertion phrase structure violation (50%) in which an additional closed-class word was inserted in a sentence-final prepositional phrase. In all cases, the phrase structure violation clearly occurred at the onset of either a demonstrative (50%) or possessive (50%) pronoun directly following the inserted pronoun. The ERPs to the onset of the target word (underlined below) in the canonical and violation (*) sentences were compared:

English: Timmy can ride the horse at <u>his</u> farm.
*Timmy can ride the horse at my <u>his</u> farm.

A number of measures were undertaken in order to provide prosodic variability as well as to insure that subjects listened fully to the sentences and did not focus only on the location of the critical violation. In 5% of the experimental sentences an additional prepositional phrase was added to the beginning of the sentences, and in 20% of the experimental sentences an adjective was placed directly after the target word so that the target word was not invariably in the penultimate position in the sentence. In addition, filler sentences and probe questions were constructed. Filler sentences contained a permutation phrase structure violation in which a main verb and the determiner of the object noun phrase were reversed. Probe questions took the form "Did you hear the word (blank)?" Most participants heard 62 sentences of each condition; a subset (N = 10) heard 40 sentences per condition. Filler sentences (10% of total) were pseudo-randomly interspersed between the experimental sentences, as were probe questions (5% of total), such that filler sentences and probe questions occurred equally across quarter stimulus blocks and were always separated by at least two experimental sentences.

All sentences were recorded using SoundEdit 16 Version 2 with 16-bit resolution and a 16 Khz sampling rate then transferred to a PC for presentation. The sentences were spoken by a female with natural tempo and prosody and critical word onsets were identified and coded by three trained coders using both auditory cues and visual inspection of sound spectrographs for increased accuracy. Any sentences in which codes differed by more than 20 milliseconds between coders were re-coded by all three coders together until a consensus was reached by all three to ensure reliability.

Procedure

Most participants were tested in one three-hour session, with the standardized tests of language administered right before ERP testing. A subset of participants (N = 24) were given the behavioral measures and ERP testing in separate sessions. In each ERP session a 32-channel electrode cap was applied while the participant completed an information sheet which included questions about their education, socioeconomic status, handedness, neurological history, and language habits. Participants were then seated in a comfortable chair in an electrically shielded, sound-attenuating booth. Sentences were presented via a speaker placed centrally on a monitor 70 in. from the participant. Participants were given auditory instructions including examples of both sentence types and emphasizing the need to judge the sentences based on grammatical, and not semantic, correctness. On each trial, participants pushed one of two response buttons to play a sentence. While the sentences were playing, participants were asked to refrain from blinking or moving their eyes as a box with a central fixation cue ('*') was displayed. After each sentence, participants were cued to make a judgment with a display of "Yes or No?" on the screen. The judgment was made with a button press with either the left or right hand, counterbalanced across participants. Participants proceeded at their own pace and were given two regularly scheduled breaks and additional breaks as requested.

EEG Equipment and Analysis

The EEG was recorded using tin electrodes mounted in an appropriately sized elastic cap (Electro-Cap International) over 29 scalp sites based on Standard International 10-20 electrode locations: F7/F8, F3/F4, FT7/FT8, FC5/FC6, T3/T4, C5/C6, CT5/CT6, C3/C4, T5/T6, P3/P4, TO1/TO2, O1/O2, FP1/FP2, Fz, Cz, and Pz. Scalp electrode impedances were kept below 3 Kohms. Data from all scalp electrodes were referenced on-line to the EEG from an electrode placed over the right mastoid and later referenced off-line to the mathematical average of the left and right mastoids. Horizontal eye movements were monitored using electrodes placed at the outer canthus of each eye and referenced to each other, while vertical eye movements were monitored using an electrode placed beneath the right eye and referenced to the right mastoid. The raw EEG signal was collected at a sampling rate of 250 Hz and was amplified using Grass Amplifiers with high- and low-pass filter settings of 0.01 Hz and 100 Hz, respectively.

Only trials on which subjects responded correctly were included in the ERP analyses. The EEG data for each participant were examined for eye movements, muscle artifact, and amplifier saturation and drift, and any trials contaminated by these artifacts were excluded from final data analyses. ERPs were computed for 1200 ms after the onset of the target word relative to a 100 ms prestimulus baseline. ERP waveforms were measured within specific time windows determined by visual inspection of individual and group averages; specific time windows are described in the Results section. Based on *a priori* hypotheses from previous results and on visual inspection of the effects, the anterior negativity effect was characterized by analyzing the 12 anterior electrode sites. Additional analyses conducted on different time windows and electrode sites are noted in the Results section.

For the between-group analysis, mean voltage amplitude was measured within each time window and analyzed using ANOVAs with repeated measures, including two levels of condition (C: canonical, violation), two levels of hemisphere (H: left, right), three levels of anterior-posterior (A: frontal, fronto-temporal, temporal (anterior sites); central, parietal, and occipital (posterior sites)), and two levels of lateral-medial (L: lateral, medial), as well as a between-participants factor, proficiency, with two levels (P: Lower Proficiency, Higher Proficiency). Following omnibus ANOVAs, additional analyses were performed in step-down fashion such that follow-up analyses were performed to isolate any significant interactions, collapsing across factors with which an interaction was not found. When significant between-group interactions were found, separate ANOVAs were performed for each group to better characterize group differences. For all distributional comparisons, analyses were performed on both the raw data and on data normalized following the procedure recommended by McCarthy and Wood (1985); as no differences between the two analyses were found, only analyses performed on the raw data are reported. Greenhouse-Geisser corrections were applied to all ANOVAs with greater than one degree of freedom.

For the correlational analysis, for each of the 72 participants the average difference amplitude (violation – canonical) was calculated for each electrode site. Based on the results from the between-group analysis, three time windows were analyzed to capture the anterior negativity: 100-300 ms, 300-700 ms, and 700-1200 ms. Within these time windows, the average difference amplitude was calculated across left anterior lateral sites (F7, FT7, T3), left anterior medial sites (F3, FC5, C5), right anterior medial sites (F4, FC6, C6), and right lateral sites (F8, FT8, T4). A laterality index was also calculated for anterior lateral sites (left anterior lateral – right anterior lateral), anterior medial sites (left anterior medial – right anterior medial), and anterior sites (left anterior – right anterior). The 300-1000 ms time window was analyzed to capture the P600 effect; within this time window the average difference amplitude was calculated across all 12 posterior sites. Zero-order correlations were then calculated between individual average difference amplitudes and individual proficiency scores, quantified as a composite individual average standardized score for the three subtests of the TOAL-3. In order to control for the possible influence of other variables which significantly correlated with proficiency, partial correlations controlling for these variables were also conducted. Any correlations driven by extreme scores, as defined by lying more than two standard deviations from the mean, are not reported.

Results: between-group analysis

Behavioral Results

Lower Proficiency (LP) and Higher Proficiency (HP) groups were determined by standardized scores on the two TOAL-3 subtests used as described in the methods section. The mean average standardized scores for the resulting LP (M = 8.09, SD = 1.65) and HP (M = 13.06, SD = 1.20) groups were statistically independent ($t(32) = -10.04$, $p < .0001$). The mean scores for each behavioral measure are displayed in Table 2.1. Means for the groups were statistically independent for each language measure. While the groups did not differ significantly on the measure of WM capacity, there was a trend toward a group difference. While all participants were within normal limits for native speakers, the groups were distinct in terms of TOAL-3 standardized scores: the mean scores for the LP group were at or below the 34th percentile on each subtest (below the 25th percentile for the grammar subtests), while the mean scores for the HP group were at or above the 75th percentile for each subtest. In the ERP grammaticality

Table 2.1

Mean scores by proficiency

Group	TOAL-3 L-V**	TOAL-3 L-G**	TOAL-3 S-G**	Saffran and Schwartz*	Carpenter Span+
LP					
(n = 17, 7 F)					
M	23.06	19.00	17.06	74.29	2.79
(SD)	(5.69)	(7.98)	(3.36)	(3.08)	(.53)
Range	14-33	7-32	9-22	67-78	2-4
Percentile	37	25	16	N/A	N/A
HP					
(n = 17, 10 F)					
M	31.18	30.71	22.59	76.12	3.15
(SD)	(2.55)	(4.79)	(1.62)	(.992)	(.66)
Range	27-35	17-35	20-25	75-78	2-5
Percentile	84	75	91	N/A	N/A

* = $p < .05$, ** = $p < .0001$, + = $p = .095$

judgment task, there was a trend for a higher percentage of correct responses by the HP group (M = 98.64, SD = 1.45) compared to the LP group (M = 94.96, SD = 9.94) which did not reach significance (t(32) = 1.512, p = .14). Scores on measures used to insure that participants were listening to the entire sentence indicated that this was indeed the case. The HP group answered 100% of the probe questions correctly and the LP group, while performing significantly worse, still answered 94.18% of the questions correctly (t(32) = 2.411, p < .05).

ERP Results

The ERP data to the critical word in English sentences for both groups are shown in Figure 2.1. Visual inspection of the waveforms revealed clear patterns and clear differences between proficiency groups. Both groups displayed a biphasic response to phrase structure violations: an anterior negativity with onset around 100 ms and a posterior positivity peaking around 600 ms. In the HP group, the anterior negativity effect was short in duration and larger over left hemisphere sites. In contrast, the anterior negativity in the LP group was more extended temporally and spatially, with the effect extending beyond 400 ms and more prominent over right hemisphere sites than in the HP group. In addition, the anterior negativity effect extended to 1200 ms over lateral sites, and a late negativity began at 700 ms over medial sites for the LP group. Group differences were also evident in the P600 effect, which was larger and more broadly distributed in the HP group compared to the LP group.

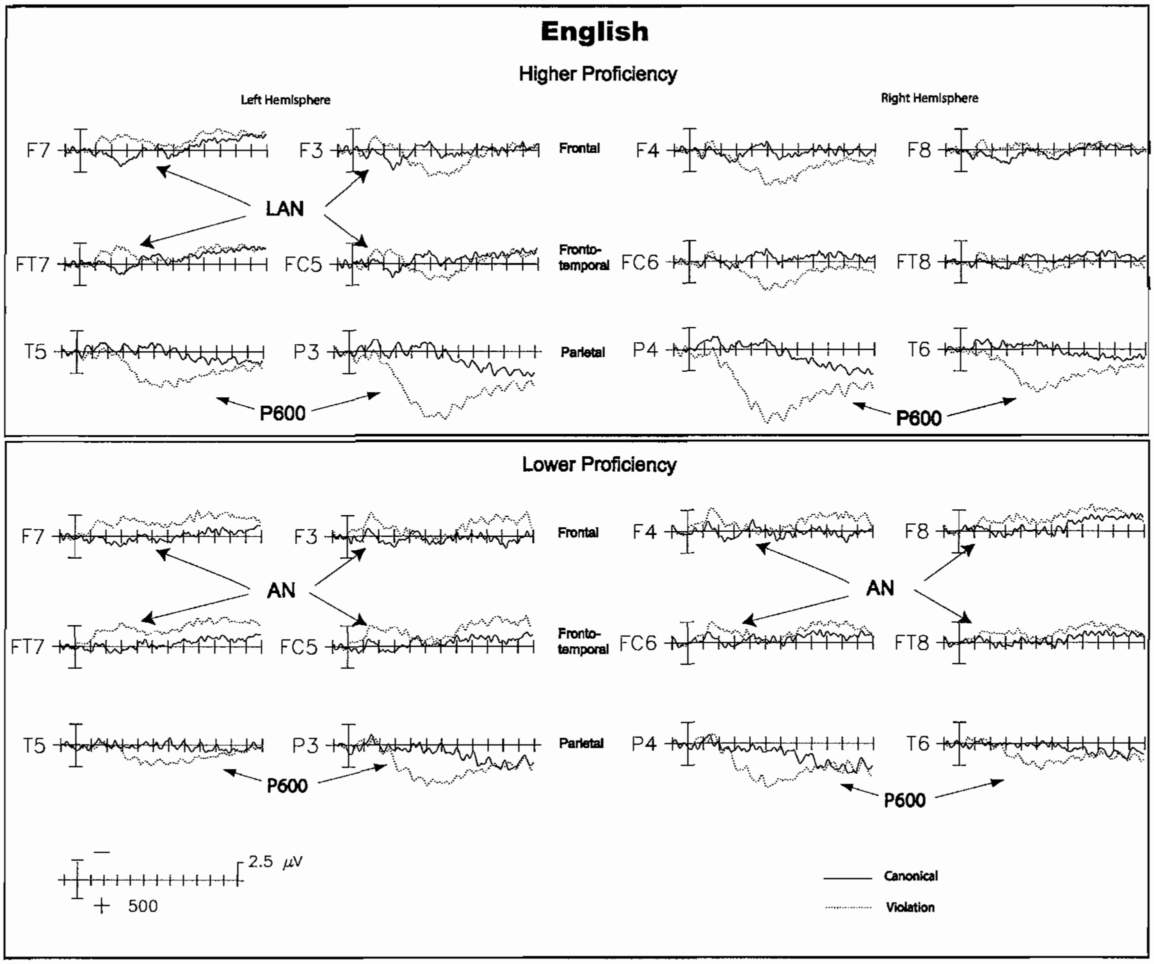

Figure 2.1. ERPs to English phrase structure violations for HP and LP groups showing representative electrode rows illustrating the anterior negativity (frontal and fronto-temporal) and P600 (parietal) effects.

Anterior negativity

Analyses across anterior electrode sites in the 100-300 ms time window revealed a group interaction with the factors hemisphere and lateral-medial (C x H x L x P: F(1, 32) = 4.22, p < .05), reflecting significant differences in the distribution of the anterior negativity effect across proficiency groups. These distributional differences are illustrated by voltage maps in Fig. 2.2. The effect in the HP group was more lateralized

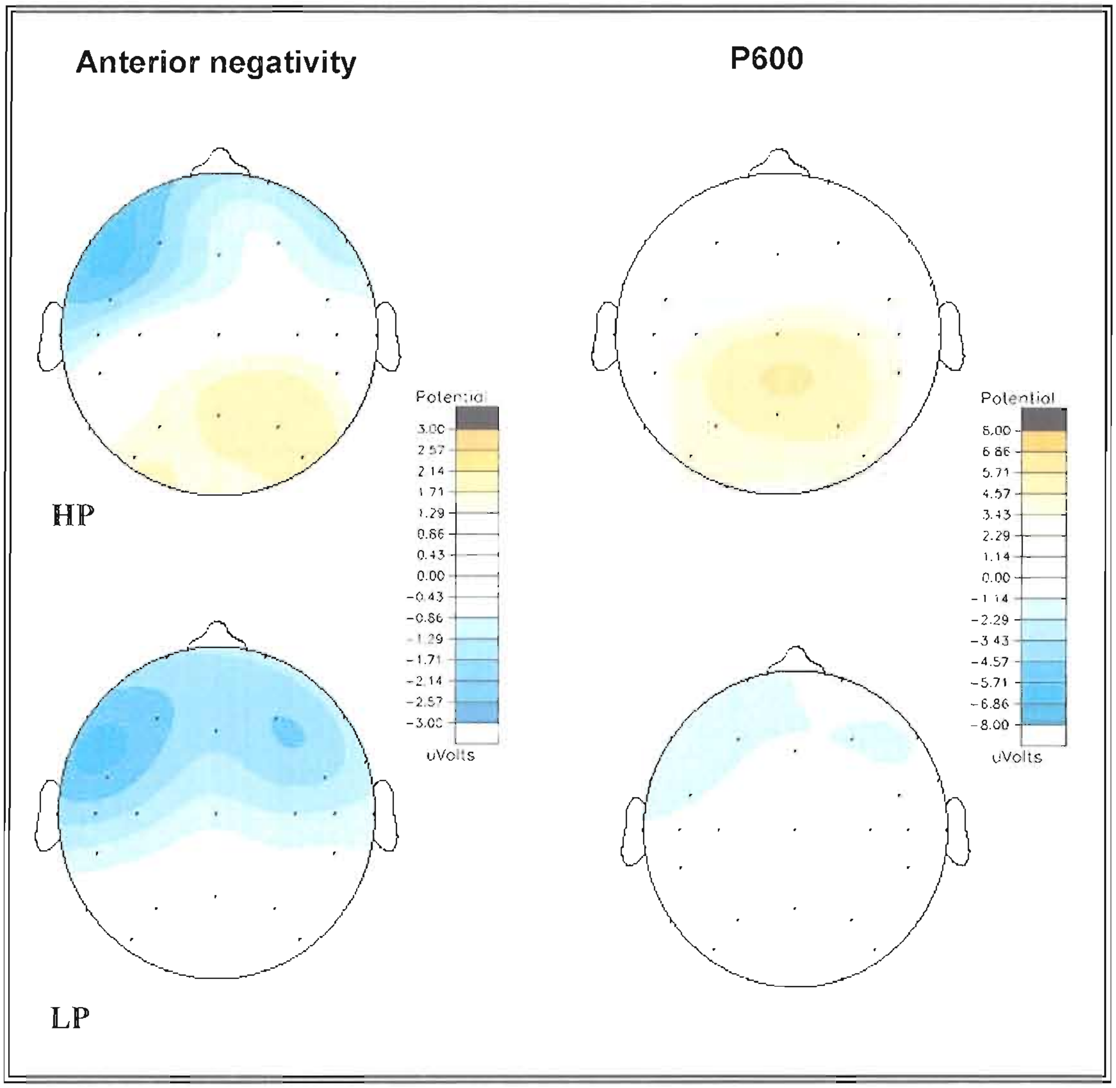

Figure 2.2. Voltage maps for HP and LP groups illustrating the distribution of the anterior negativity effect for English in over the 100-300 ms time window and the posterior positivity (P600) effect over the 300-1000 ms time window.

to left-hemisphere sites, in particular across medial sites, while the effect in the LP group was more widespread and bilateral in distribution. Further analyses of this interaction confirmed this interpretation. In the HP group the effect was significantly larger over left-hemisphere sites overall (C x H: F(1, 16) = 8.71, p < .01). In the LP group, the effect was bilateral overall (C x H: F(1, 16) = 1.81, NS). While there was a greater degree of left lateralization over lateral sites (C x H x L: F(1, 16) = 4.65, $p < .05$) in the LP group, a direct comparison of lateral sites by hemisphere did not reach significance (t(16) = 1.762, p = .097). These further analyses also confirmed distribution differences across lateral and medial sites, as there was a strong trend for the effect to be larger over lateral sites in the HP group (C x L: F(1, 16) = 4.25, p = .056), while it was evenly distributed across lateral and medial sites in the LP group (C x L: F(1, 16) = 0.53, NS). These differences are further illustrated in Figure 2.3.

Visual inspection also suggested group differences in the distribution of the negativity to the central row of electrodes (CT5-6, C3-4), and an interaction in the 100 -300 ms time window across all electrode sites which neared significance confirmed that this effect extended to the central row, maximally over medial sites, in the LP group but not the HP group (C x A x L x P: F(5, 160) = 2.72, p = .055).

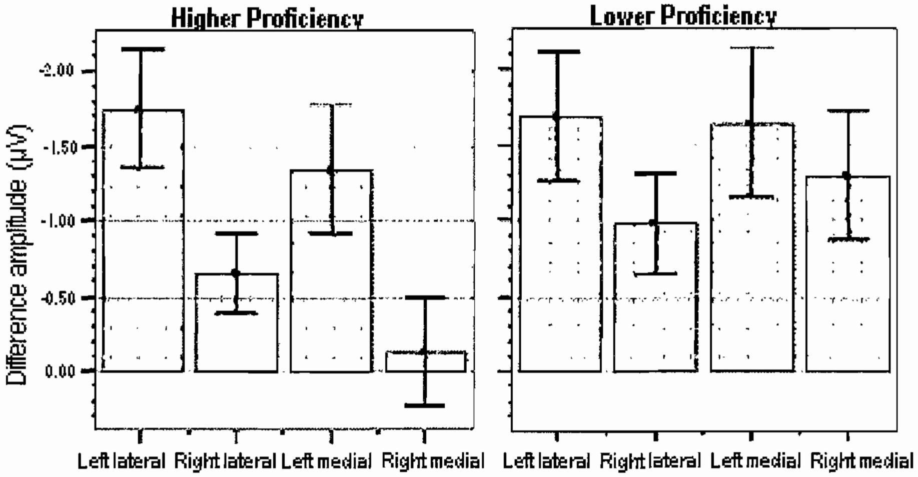

Figure 2.3. Amplitude of the difference ERPs (violation – canonical) in the 100-300 ms time window for the English condition over three anterior rows of electrodes as a function of Proficiency, Lateral-Medial, and Hemisphere.

Late negativity

As visual inspection suggested that the anterior negativity was longer in duration in the LP group, additional analyses across anterior sites were conducted in later time windows. A group interaction between 300-700 ms confirmed that the negativity extended in this time window in the LP group only, maximally over anteriormost lateral sites; in contrast, violations elicited a positivity maximal over medial sites in this time window in the HP group (C x A x L x P: F(2, 64) = 6.27, $p < .01$). As visual inspection revealed an anterior negativity in the 700-1200 time window in the LP group, additional analyses in this time window were conducted. These analyses confirmed that while the negativity extended across this epoch in the LP group, this was not the case in the HP group (C x P: F(1, 32) = 10.41, $p < .005$). This negativity was bilaterally distributed in the LP group in both the 300-700 ms time window (C x H: F(1, 16) = .281, NS) and the 700-1200 ms time window (C x H: F(1, 16) = .434, NS).

Posterior positivity (P600)

Because visual inspection suggested group differences in amplitude and distribution in the posterior positivity effect across all electrode sites, initial analyses were conducted across all sites. An analysis in the 300-1200 ms time window revealed that this effect was larger overall in the HP group than in the LP group (C x H: F(1, 32) = 11.65, $p < .005$) and that it extended to anterior medial sites in the HP group but not in the LP group (C x A x L x P: F(5, 160) = 6.20, $p < .005$).

As individual group analyses confirmed that the posterior positivity was confined to the three posterior rows in the LP group (C x A: $F(5, 80) = 27.66$, $p < .0001$), additional group comparisons limited to these rows were conducted. These analyses revealed that the effect was larger in the HP group compared to the LP group over sites where the effect was present in both groups (C x P: $F(1, 32) = 8.24$, $p < .01$).

Results: correlational analysis

Behavioral Results

In order to limit the number of variables considered in the correlational analysis with average ERP difference amplitudes, the relationship between proficiency and several potentially confounding variables was explored. Proficiency correlated significantly with socioeconomic status of origin (henceforth SES) ($r = .460$, $p < .0001$), working memory span ($r = .561$, $p < .0001$), and education level ($r = .368$, $p < .005$). Proficiency did not correlate significantly with participant age, and analysis by gender revealed no significant differences in proficiency between males ($N = 35$) and females ($N = 37$); therefore age and gender were not included in the ERP correlational analysis. As results from the between-group analysis provided specific hypotheses concerning the direction of the effects, all significance levels reported are one-tailed unless otherwise specified.

The correlational analysis also revealed possible environmental factors contributing to proficiency differences in adult monolingual native speakers. Proficiency correlated with the amount participants reported reading as children ($r = .234$, $p < .05$) and there was a nearly significant correlation with the frequency participants reported being read to when children ($r = .190$, $p = .055$), while there was a negative correlation with the amount of time participants reported playing video games as children ($r = -.334$, $p < .005$). The amount of time participants reported reading as children also correlated positively with the amount of time participants reported reading as adults ($r = .450$, $p < .0001$), as did the frequency participants reported being read to as children ($r = .298$, $p < .01$). All four self-report measures of childhood environment correlated significantly with SES: amount participants reported reading ($r = .378$, $p < .005$), frequency participants reported being read to ($r = .538$, $p < .0001$), watching television ($r = -.265$, $p < .05$), and playing video games as children ($r = -.319$, $p < .005$).

While proficiency did not correlate with the amount of time participants reported reading as adults, there was a significant negative correlation between proficiency and the amount of time participants reported watching television as adults ($r = -.429$, $p < .0001$). In addition, a self-rating measure in which participants were asked to rate their language skills compared to other adult native speakers on a five-point scale correlated significantly with both SES ($r = .317$, $p < .005$) and proficiency ($r = .437$, $p < .0001$).

ERP Results

Overall, results from the correlational analysis supported the findings from the between-group analysis and provided converging evidence from a complementary analytical approach for effects of proficiency on neural organization for syntactic processing. This analysis revealed strongest effects of proficiency in later time windows over both anterior and posterior electrode sites. Importantly, these effects of proficiency were found to be independent of other confounding variables, as partial correlations were used to control for the effects of SES, working memory span, and education level. In addition to proficiency effects, this analysis also revealed an effect of SES on the amplitude of the early left anterior negativity.

Anterior negativity

100-300 ms TW. While no zero-order correlations reached significance in this time window, there was a near-significant partial correlation with proficiency and average difference amplitude over right anterior medial sites ($r = .194$, $p = .052$). Consistent with the results from the between-groups analysis, this analysis revealed that lower proficiency participants showed an increased negative response over these sites.

300-700 ms TW. Significant zero-order correlations were found between proficiency and average difference amplitude over both left anterior ($r = .365$, $p < .005$) and right anterior ($r = .334$, $p < .005$) sites (Figure 2.4). Partial correlations across these sites were also significant (left anterior: $r = .406$, $p < .0001$; right anterior: $r = .276$, $p < .05$), as were partial correlations across left anterior lateral ($r = .337$, $p < .005$), left

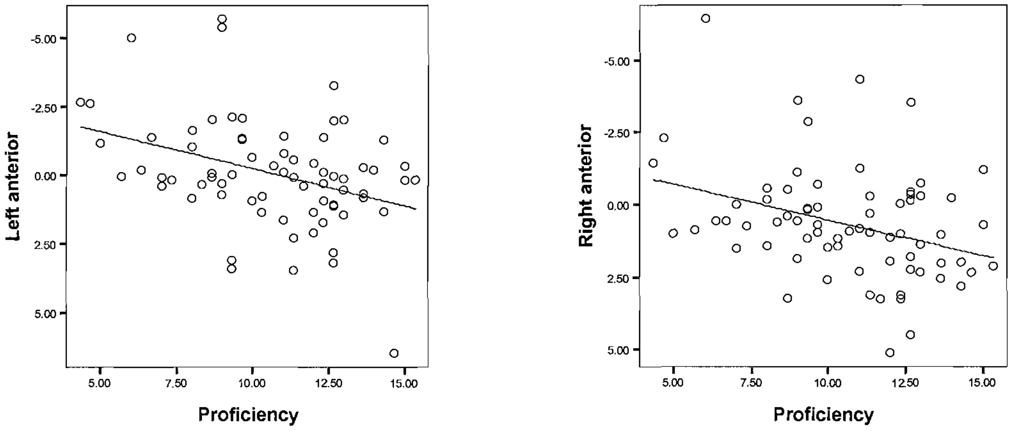

Figure 2.4 Correlation between average difference amplitude (violation – canonical, in µV) over left anterior and right anterior sites and proficiency in the 300-700 ms time window.

anterior medial ($r = .430$, $p < .0001$), and right anterior medial ($r = .325$, $p < .005$) sites. The relationship was weakest across right anterior lateral sites, where the partial correlation tended toward significance ($r = .184$, $p = .065$). These correlations revealed that lower proficiency participants showed a more negative response while higher proficiency participants showed a more positive response across this time window, consistent with the results from the between-groups analysis.

700-1200 ms TW. Significant zero-order correlations were found between proficiency and average difference amplitude over both left anterior ($r = .203$, $p < .05$) and right anterior ($r = .230$, $p < .05$) sites, revealing that lower proficiency participants showed a more negative response across this time window. Partial correlations across these sites only approached significance (left anterior: $r = .193$, $p = .057$; right anterior: $r = .177$, $p = .076$).

Posterior positivity (P600)

As shown in Figure 2.5, a significant zero-order correlation was found in the 300-1000 ms TW across posterior sites ($r = .279$, $p < .01$). A significant partial correlation was also observed across these sites ($r = .274$, $p < .05$). Consistent with the results from the between-groups analysis, these correlations revealed that higher proficiency participants showed a larger P600 response. Additional analyses revealed a relationship between the size of the P600 across posterior sites and the presence of a positivity across anterior sites in the 300-700 ms time window: there were significant positive zero-order correlations between the posterior P600 and average difference amplitude between 300-700 ms across both left (r = .448, p < .0001) and right (r = .420, p < .0001) anterior sites. This relationship was stronger over medial sites in both left (medial: r = .505, p < .0001; lateral: r = .334, p < .001) and right (medial: r = .506, p < .0001; lateral: r = .263, p < .05) hemispheres.

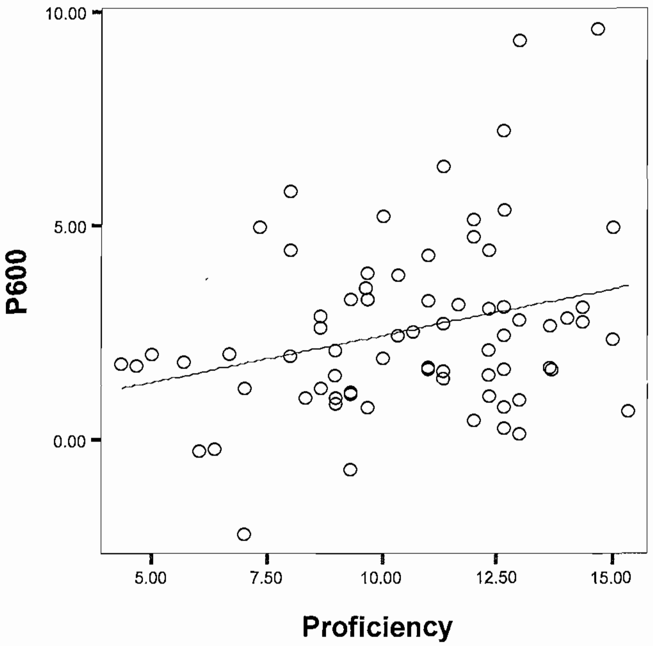

Figure 2.5 Correlation between average difference amplitude (violation – canonical, in μV) over posterior sites and proficiency in the 300-1000 ms time window (P600).

Socioeconomic status

In addition to effects of proficiency, exploratory analyses using the correlational approach revealed significant relationships between SES and neural organization for syntactic processing, specific to left anterior sites. While a zero-order correlation across left anterior sites in the 100-300 ms time window only approached significance (r = -.176, p = .069), a partial correlation across these sites controlling for proficiency, WM, and education level was significant ($r = -.218$, $p < .05$), revealing that participants from higher SES backgrounds showed a larger amplitude negativity to syntactic violations over left anterior sites. This relationship was slightly stronger over left anterior lateral sites (partial correlation: $r = -.223$, $p < .05$) than over left anterior medial sites (partial correlation: $r = -.197$, $p = .052$). This relationship also held over the 300-700 ms time window, where there was a significant partial correlation between left anterior average difference amplitude and SES ($r = -.232$, $p < .05$).

In order to investigate the contributions of factors related to self-reported childhood experience, the relationship between left anterior average difference amplitude and SES was examined while controlling for the amount participants reported reading, being read to, watching television, and playing video games as children. These factors were found to moderate the relationship between the neural response to syntactic violations and SES, as the partial correlation between average difference amplitude over left anterior sites and SES was reduced over both the 100-300 ms ($r = -.081$, NS) and 300-700 ms ($r = -.021$, NS) time windows. None of these factors were found to moderate any of the correlations with proficiency described above.

Discussion

In this study event-related potentials elicited by phrase structure violations were examined as native speakers of English listened to simple sentences in English. Participants were recruited from a wide spectrum of society and given standardized measures of English language proficiency, and two analyses using complementary approaches were performed. In the between groups analysis, participants were divided based on standardized proficiency scores into Lower Proficiency (LP) and Higher Proficiency (HP) groups. Analyses revealed differences in brain organization between the two proficiency groups, with HP participants showing a more restricted and focal early anterior negativity both spatially and temporally and a larger and more widely distributed positivity to violations in English. In the correlational analysis, we explored the relationship between proficiency and the neural organization for syntactic processing across a wide spectrum of proficiency scores by examining the degree to which individual proficiency scores correlated with individual neural responses to syntactic violations in regions and time windows identified in the between-group analysis. This approach also employed partial correlation analyses to control for possible confounding variables. This correlational analysis provided converging evidence for the effects of proficiency discovered in the between-groups analysis, confirming that differences in proficiency affect neural indices of syntactic processing reflected in both anterior negativity and posterior positivity components. Additionally, this analysis revealed effects of socioeconomic status specific to left anterior sites. Below we discuss possible interpretations of these results and their implications for theories of sentence processing, discuss future directions for research, and comment on the potential of research into proficiency differences for enriching our knowledge about language processing.

Anterior Negativity

While the component known as the left anterior negativity is so named because it most often has been reported to display a distribution which is maximal over left anterior electrode sites (e.g., Coulson, King, & Kutas, 1998b; Gunter et al., 1999; Hahne &

Friederici, 1999; Münte et al., 1993; Neville et al., 1991) this is not always the case. Several studies have reported an anterior negativity which is more bilateral in distribution (e.g., Friederici & Frisch, 2000; Friederici & Meyer, 2004; Friederici et al., 1993; Frisch, Hahne, & Friederici, 2004; Hagoort et al., 2003; Hahne, 2001; Hahne & Friederici, 1999, 2002; Hahne & Jescheniak, 2001; Münte et al., 1997; Rossi et al., 2006; Yamada & Neville, 2007; Ye, Luo, Friederici, & Zhou, 2006). To date no theory of language processing has sought to address the functional significance of these differences in distribution, though the question has been identified as an important one for future research (Hahne & Friederici, 2002).

While the differences in distribution of the anterior negativity effect have sometimes been attributed to subtle differences in the stimuli used (Hagoort et al., 2003), in other cases a bilateral negativity has been found using the same stimuli and experimental methods as in other studies which did find a left lateralized anterior negativity (Hahne & Friederici, 2002). This raises the hypothesis that proficiency differences in the participants tested may have at least contributed to the observed differences in distribution. The results of the current study support this hypothesis. In the between-groups analysis, participants who scored higher on standardized tests of English proficiency showed a more focal, left-lateralized early anterior negativity to straightforward phrase structure violations in English, while participants who scored lower showed a more widespread distribution of this effect both spatially and temporally. This between-groups spatial difference was reflected in an increased negativity over right anterior medial sites in the 100-300 ms time window in lower proficiency participants, a finding which was supported by a near-significant correlation between proficiency and average difference amplitude over right anterior medial sites in this time window in the correlational analysis.

The anterior negativity found in this study began early, around 100 ms, and was elicited by insertion phrase structure violations. Such early components elicited by word category violations have been interpreted by some researchers to reflect early and automatic processes in which a word is integrated into the phrase structure of the preceding sentence fragment (Friederici, 2002). While other theories dispute the automaticity of these processes with regard to the influence of contextual information (van den Brink & Hagoort, 2004), both theories are consistent in their view that early anterior negative components reflect processes which make immediate use of incoming input to guide online parsing. Given these interpretations, our results suggest that such early and immediate sentence parsing processes may operate differently, or be used differently, in adult monolingual native speakers who differ in their linguistic proficiency when processing their native language.

A preliminary functional explanation for these differences is that LP participants recruited additional resources related to early, automatic processing in order to parse straightforward phrase structure violations in simple sentences in their native language. Given the similarity of the effect reported here to those previously reported for monolinguals and the spatial and temporal differences between groups, it seems likely that these differences reflect the recruitment of additional resources in similar systems. While the early effect is larger over right anterior medial sites in the LP group, there is still a small negative deflection in the HP group. Thus it appears that these differences reflect the less efficient use in LP participants of neural systems similar to those used by HP participants, which are highly focal and short duration systems that make immediate use of incoming input to guide syntactic parsing. This interpretation is consistent with some ERP evidence from bilinguals. This evidence suggests that when these resources are recruited in late bilinguals, the distribution is related to proficiency, as the anterior negativity to phrase structure violations has been found to be more bilateral and widespread in distribution with increases in age of immersion and decreases in English proficiency (Weber-Fox & Neville, 1996). Evidence from neuroimaging studies of sentence processing also supports this interpretation. Activation in perisylvian language areas of the left hemisphere (e.g., Caplan, Alpert, & Waters, 1999; Caplan et al., 2002; Stromswold, Caplan, Alpert, & Rauch, 1996) and bilaterally (Just, Carpenter, Keller, Eddy, & Thulborn, 1996) has been found to vary as a function of syntactic complexity and, presumably, the amount of resources necessary to process more complex syntactic structures. Another study found increased activation in right hemisphere perisylvian areas to syntactic violations when participants were asked to perform an on-line repair task in addition to a grammaticality judgment task, leading the authors to speculate that the right hemisphere may provide additional processing resources "whenever the linguistic capabilities of the left hemisphere are exhausted" (Meyer, Friederici, & von Cramon, 2000).

The between-group analysis also revealed that the anterior negativity effect was more focal temporally in HP participants, while the effect was temporally more extended in LP participants. This was supported by the correlational analysis, which revealed that lower proficiency correlated with increased negativity in both the 300-700 ms and 700-1200 ms time windows. ERP studies of language development have reported a pattern in which language-related ERP effects become more focal spatially and temporally with increases in age and/or language ability (e.g., Adamson-Harris et al., 2000; Hahne, Eckstein, & Friederici, 2004; Mills et al., 1993). While caution is necessary when comparing studies of children and adults, this raises the hypothesis that individual differences in the development of neural systems important for some aspects of language processing may endure into adulthood. This hypothesis will be discussed more below with relation to the correlational results with socioeconomic status.

The finding that the anterior negativity effect extended to the 700-1200 ms time window in the LP group was somewhat unexpected. Previous studies have reported an N400-like "wrap-up" effect which has been observed to the final word in sentences judged to be unacceptable due to either a semantic or syntactic violation (e.g., Hagoort et al., 1993; Hagoort & Brown, 1999; Osterhout & Holcomb, 1992, 1993). The late negativity observed in this study could reflect similar processes engaged when participants encountered the final word in the sentence. While the distribution of this "wrap-up" effect is usually more widespread and central than the distribution of the late negativity observed here, the relatively late position of the violation creates a temporal and spatial overlap with the posterior positivity which makes a definitive interpretation of this effect difficult based solely on this evidence. However, the ERP component analysis in Chapter IV allows for a degree of clarification regarding the interpretation of this component. That analysis provides evidence that one of the neural generators of this component is anatomically close to the neural generator of the anterior negativity in the 100-300 ms time window, suggesting that the negativity over anterior sites in the later time window indexes to some degree similar processes as the negativity in the earlier time window.

Posterior Positivity (P600)

We found a typical biphasic response in which the anterior negativity was followed by a later, posterior positivity which is consistent in latency and distribution with the component typically referred to as the P600. The P600 has been interpreted as an index of more controlled processes related to syntactic repair and revision in the face of a violation (Friederici, 2002) or to the cost of syntactic integration (Kaan et al., 2000), and more recently as an index of the amount of competition between alternative options as the parser attempts to unify linguistic elements in the comprehension of an utterance (Hagoort, 2003). As with the anterior negativity, the between-group analysis revealed differences in the P600 effect between groups: the P600 was larger in amplitude in the HP group compared to the LP group and was more widespread in distribution, extending to anterior medial sites. These findings were confirmed by the correlational analysis, in which proficiency positively correlated with average difference amplitude over anterior sites in the 300-700 ms time window and over posterior sites in the 300-1000 ms time window.

A more frontally distributed P600 has been hypothesized to reflect processing difficulties associated with revision when the parser encounters grammatical but non-preferred continuations in syntactically complex and/or ambiguous sentences, while a P600 with a more posterior distribution has been hypothesized to reflect a parsing failure and/or resulting repair processes when the parser encounters a grammatical violation (Friederici et al., 2002; Hagoort & Brown, 2000). Given these past findings concerning the distribution of the P600, it is unclear why straightforward, unambiguous violations would elicit a more frontally distributed P600 in the HP group. However, the correlational analysis revealed strong correlations between the positivity across anterior sites and the positivity across posterior sites across all 72 participants, suggesting that the frontally distributed P600 reflects part of a more widespread effect reflecting similar processes as opposed to separate processes reflected in different distributions. While both groups showed a posterior P600 to phrase structure violations, this effect was larger in HP participants and positively correlated with proficiency across all participants. The size of the P600 has been shown to be reduced when participants are not performing a grammaticality judgment task (Hahne & Friederici, 2002), which suggests that this difference in amplitude may reflect greater engagement of processes related to revision and repair in the context of the grammaticality judgment task on the part of the HP participants. However, as there was no task manipulation which explicitly required repair processes this interpretation is necessarily tentative and calls for more research.

Overall, the strength of the correlations between average difference amplitude and proficiency reveal that the strongest effects of proficiency were found in the 300-700 ms time window over anterior sites and in the 300-1000 ms time window over posterior sites. While lower proficiency is associated with an extended negativity or weak positivity over anterior sites and a smaller P600 across posterior sites, higher proficiency is associated with a robust and widespread P600 extending to anterior sites. While the functional interpretation of the P600 is still being clarified, it is clear that the process or processes indexed by this component are more engaged in participants with higher proficiency. Be they related to repair and/or reanalysis in the face of a violation, syntactic integration in general, or competition between alternatives in the unification of linguistic elements for comprehension, activation of processes which become engaged when the parser encounters difficulty is likely to be associated with better performance across a variety of tasks involving syntactic processing, and the results from this study show that this is indeed the case.

Optimal Neural Organization for Syntactic Processing

Overall, the results presented here present a profile of neural organization for syntactic processing which is associated with higher proficiency. Reflected in this organization is an interaction between processes considered to be more automatic and those hypothesized to be more controlled. It is reasonable to propose that the response associated with higher proficiency represents the most efficient allocation of these processes: a more focal early anterior negativity, which indexes more efficient detection of word category violations, "frees up" more controlled resources involved with repair and reanalysis reflected in the widespread P600, and it is this allocation which represents an optimal neural organization for syntactic processing in monolinguals. While it is not possible to draw a definitive causal link between these processes, the relative timing makes it more likely that more efficient earlier processes would free up resources reflected in later processes and not the other way around. A different picture emerges with lower proficiency: less efficient automatic processes involved in the detection of word category violations, reflected in more widespread distribution spatially and temporally, are followed by reduced recruitment of more controlled processes. Here, again given the relative timing it is likely that the less efficient nature of these early processes does not allow for the recruitment of later processes in lower proficiency individuals to the same degree as in higher proficiency individuals. As discussed above, it is possible that these differences reflect the recruitment by lower proficiency individuals of additional resources in similar systems. However, the fMRI analysis in Chapter IV sheds light on the nature of these resources, and the evidence from that analysis suggests that they reflect similar, but less efficient, processes.

Other Possible Contributing Factors

While the group differences in syntactic processing found in this study have been discussed in terms of English language proficiency, and the correlational analysis allowed for the control for other possible mediating factors. Still, it is possible, and even likely in some cases, that other factors contributed to the results.

While in theory one possibility is that the pattern of results is due to differences in dialect, this is unlikely to explain the differences found. The experimental materials used were chosen to minimize any effects of dialect differences: the sentences used in the ERP paradigm were all simple, single-clause sentences created for a paradigm that was also used to investigate syntactic processing in 36 month-olds and the violations used were insertion phrase structure violations which are syntactic violations in any known dialect of English. All of the participants were native speakers of American English who came from the Eugene, Oregon area.

Another possibility is that individual resource limitations not explicitly controlled for are contributing to results found. One possibility is general intelligence. Due to our desire to more completely characterize language proficiency while gathering all data in a single session, we were unable to include a direct assessment of intelligence. However, there is considerable evidence that WM correlates with intelligence (e.g., Conway, Cowan, Bunting, Therriault, & Minkoff, 2002), and the correlational analysis revealed that the results with regard to proficiency were not significantly affected by WM. Still, it is possible that differences in general intelligence contributed to our findings, and the relationship between general intelligence and brain organization for language is an important consideration in future research. Another factor which may have affected our results is attention. While no attempts were made to control for individual differences in the types of attention, such as sustained endogenous attention, which may influence performance in experimental paradigms such as ours, it is likely that attention had little or no effect on our results. The behavioral measures were given in a small, enclosed room one-on-one with the lead author, a setting specifically designed to minimize differences in attention, and all participants performed the tasks in a similar time frame. In the between-groups analysis, all participants attended to the stimuli well enough to answer more than 84% of the probe questions accurately and score above 84% on the grammaticality judgment task, and only correct responses were used in the ERP analyses. As discussed above, the pattern of ERP results and modulation of ERP components reported are consistent with results from other populations (e.g., bilinguals). This pattern of results suggests that domain-general differences in attention are unlikely to have produced the specific pattern of results observed. More research is certainly needed into the interplay between WM, attention, intelligence, and language proficiency. Still, our results suggest that there exist proficiency differences in on-line syntactic processing which are independent of certain resource limitations, a finding which calls for further study.

Socioeconomic Status

This study also examined the relationship between linguistic proficiency and neural organization for syntactic processing in adults and the socioeconomic status environment in which they were raised. In both cases, significant relationships were found which raise important hypotheses for future research.

In the correlational analysis of 72 participants, self-reported childhood SES correlated significantly with adult linguistic proficiency as assessed by standardized measures. This raises the hypothesis that differences related to childhood SES environment which can affect language development may lead to differences in language proficiency which endure into adulthood. While this analysis is only correlational and therefore can not make any causal inferences or rule out genetic factors, additional evidence supports this hypothesis. Several self-reported measures of childhood environment - amount of time spent reading, being read to, watching television, and playing video games - correlated significantly with childhood SES, and there was a significant or near-significant relationship between proficiency and all of these measures but one. Of particular relevance is that the two measures of childhood reading showed the strongest correlations with SES, and both showed a positive relationship with adult proficiency. This is consistent with evidence that time spent reading or reading with an adult can have a positive effect on language development (Payne & et al., 1994; Scarborough & Dobrich, 1994). Other evidence suggests that there are differences in the speech mothers use when reading with their children, such as using more utterances per unit of time, utterances with greater structural complexity, and a larger vocabulary, and that these speech differences can affect language development (Hoff, 2006; Hoff-Ginsberg, 1991). Additionally, there is evidence that interventions which specifically seek to promote parent-child reading, such as Reach Out and Read, can positively affect vocabulary development (Mendelsohn et al., 2001; Sharif, Reiber, & Ozuah, 2002). While caution is necessary due to the correlational nature of this analysis, evidence for some specificity in the relationship between childhood environmental factors and adult proficiency strengthens the tentative hypothesis that some effects of childhood environment related to SES may have enduring effects on language proficiency. Future research which specifically addresses causal relationships with the use of targeted interventions, and which specifically addresses the role of genetic factors in the relationship between childhood SES and language development, will provide important evidence bearing on this hypothesis.

The correlational analysis also revealed a correlation between childhood SES and the neural response to syntactic violations, such that participants from higher SES backgrounds showed a larger negative response to violations than participants from lower

SES backgrounds. This effect was specific to left anterior sites in both the 100-300 ms and 300-700 ms time windows, and the results of the partial correlation analysis revealed that this effect was independent of proficiency, as well as working memory and education level. However, given the results discussed above with regard to SES and proficiency, the interpretation that the relationship between SES and left anterior negativity amplitude is independent of proficiency should be treated with caution. It is possible that this relationship is moderated to some degree by aspects of linguistic proficiency which were not reflected by the proficiency measures used, though further clarification is beyond the scope of this study. Still, these results raise the additional hypothesis that differences related to childhood SES environment which can affect language development may also have effects on neural organization for language which endure into adulthood. An alternate hypothesis is that these differences in the neural response of left anterior sites are the result of genetic differences which covary with our measurement of childhood SES. However, this relationship disappeared when childhood environmental factors - amount of time spent reading, being read to, watching television, and playing video games – were controlled for. This provides evidence that our measure of childhood SES is a mediating variable for specific aspects of childhood environment and strengthens the hypothesis that experiential factors may have effects on neural organization for syntactic processing which endure into adulthood. One recent piece of evidence supports this tentative hypothesis, as the degree of left hemispheric specialization in left inferior frontal gyrus in a rhyming task in five-year olds was found to correlate significantly with SES, even after controlling for behavioral performance (Raizada, Richards, Meltzoff, &

Kuhl, 2008). While much caution is necessary in comparing an adult ERP study of syntactic processing with an fMRI study of rhyming in children, these results suggest that environmental effects may be manifested in functional neural organization. While necessarily preliminary and cautious, the hypothesis that environmental effects of SES which impact language development may also have a lasting impact on neural organization for syntactic processing provides an intriguing direction for future research.

The results relating to SES discussed above were the result of a correlational analysis utilizing data collected from 72 adults from a wide spectrum of society and a wide range of childhood SES backgrounds. Reviews of results from studies of the effects of SES on language development in children suggest that the magnitude of differences related to SES depends on the range of SES in the sample studied (e.g., Hoff, 2006). Overall, this suggests that in order to get a more complete picture of neural organization for syntactic processing, or of neural organization for any aspect of cognition, it will be fruitful to study samples from a wider and more diverse spectrum of society.

Implications and Future Directions

Results from the present study have implications for the study of language processing and cognition in general. In both cases, our results underscore the importance of expanding research programs to include participants who better represent the wide range of human society. By making theoretical assumptions based on studies of participants drawn from the relatively homogenous participant pool that is the university setting, researchers may be missing an important opportunity for a veridical understanding of neural organization for language processing. This is problematic in the field of cognitive neuroscience as a whole where a majority of the studies which seek to characterize the neural organization of language processing use university students as participants. While this is understandable on practical grounds, the results presented here suggest that it will be fruitful to branch out and include participants from many segments of society and to better characterize participants in terms of behavioral performance. Such research can provide a more complete picture of the neural systems important in language processing.

The results from the present study provide several lines of research for the future, two of which will be addressed in the following chapters. First, the characterization of the relationship between proficiency and syntactic processing in monolingual adults has the potential to contribute to issues in second language acquisition research, including the relationship between age of acquisition and proficiency by directly comparing late learners of English who are matched for proficiency, as characterized by the measures used in the current study, with monolingual native speakers. This is the focus of Chapter III. Second, ERPs lack the spatial resolution necessary to characterize differences in the recruitment of specific neuroanatomical regions for language processing. The use of an identical syntactic processing paradigm in fMRI, with its excellent spatial resolution, will shed important light on this question. Also, given the modulations in ERP components reported here, this line of research also has the potential to address questions concerning the neuroanatomical sources of ERP components which index language processing. This is the focus of Chapter IV. Finally, an important future line of research will be to determine the factors in development which are important in producing the differences in adults reported here. Current research in our laboratory is characterizing the developmental timecourse of ERP components which index language processing to systematically explore biological and experiential factors which may effect language proficiency.

CHAPTER III

SYNTACTIC PROCESSING IN ADULT MONOLINGUALS AND PROFICIENCY-MATCHED BILINGUALS INDEXED BY EVENT-RELATED POTENTIALS

An enduring question in the study of second language acquisition concerns the relative contributions of age of acquisition (AOA) and ultimate linguistic proficiency to neural organization for second language processing. Several event-related potential (ERP) and neuroimaging studies of second language learners have found that, while subsystems implicated in online semantic processing are relatively invulnerable to delays in second language acquisition, neural organization for syntactic processing is altered by delays in acquisition as short as four years (Dehaene et al., 1997; Hahne, 2001; Hahne & Friederici, 2001; Kim et al., 1997; Wartenburger et al., 2003; Weber-Fox & Neville, 1996). However, such delays in second language acquisition are typically associated with lower language proficiency (Johnson & Newport, 1989), rendering it difficult to assess whether differences in AOA or proficiency lead to these effects. One approach to this problem is to study participants of different proficiency levels matched for AOA. In Chapter II we used ERPs to examine the relationship between AOA and proficiency by studying online syntactic processing in English-speaking adults who, as monolingual native speakers, had the same AOA but varied in their native language proficiency as assessed by standardized measures of English proficiency. Results from this study revealed large effects of proficiency on neural organization for syntactic processing. Another approach to this problem is to study participants who differ in AOA but who are matched on proficiency level on the same language. Here we take this approach and test the hypothesis that AOA will also have effects on neural organization for syntactic processing independent of proficiency. To this end, we compare online syntactic processing in a group of late learners of English matched for grammatical proficiency with the Lower Proficiency monolingual participants from Chapter II. We used the same standardized measures to assess proficiency and the same ERP paradigm, which allowed for a more direct assessment and comparison of the differential effects of AOA and proficiency. Specifically, we compared the ERP response to auditory phrase structure violations in both groups to test the hypothesis that non-native speakers of English who learned English late recruit different neural systems to achieve a level of proficiency comparable to that of some native speakers.

ERP studies of language processing

ERPs provide an on-line, multidimensional index of cognitive processes with a temporal resolution of milliseconds and thus have emerged as one of the more widely used methodologies used in examining on-line language processing. Consistent with other methodologies, ERP studies have demonstrated that separate linguistic subsystems are mediated by non-identical neural mechanisms. Numerous studies in both the visual and auditory modalities have found that semantically unexpected words elicit a negative-going potential peaking around 400 ms (N400) compared to contextually appropriate words (Friederici et al., 1993; Holcomb & Neville, 1991; Kutas & Hillyard, 1980), leading to the hypothesis that the N400 component indexes semantic processes of lexical integration.

While the N400 has consistently been related to aspects of semantic processing, at least two components hypothesized to index syntactic processing have been identified. The first of these is a negative-going wave, typically larger over left anterior electrode sites between 100-500 ms, known as the left anterior negativity (LAN). The LAN has been elicited by a variety of syntactic violation types, such as phrase structure violations (e.g., Friederici et al., 1993; Gunter et al., 1999; Hahne & Friederici, 1999; Neville et al., 1991) and morphosyntactic violations (e.g., Coulson et al., 1998b; Friederici et al., 1993; Münte et al., 1993). The LAN typically occurs in one or both of two time windows (100-300 ms and 300-500 ms), which has led some researchers to propose the existence of two distinct, separate components, with the second, termed the early left anterior negativity (ELAN), indexing processes different from those indexed by the LAN (Friederici, 1995; Friederici & Mecklinger, 1996; Hahne & Jescheniak, 2001). Two recently proposed theories of online sentence processing account for these components in different ways. Friederici (2002) proposes that the ELAN is functionally distinct from both the LAN and N400 components and that it reflects early and automatic processing of word category violations in a first phase of sentence processing which is autonomous and independent of contextual or semantic influences. In this model, the LAN and N400 index activation in a second, later phase in which lexical-semantic and verb argument structure are processed, and in which contextual and semantic information can influence the parser. Hagoort and colleagues (Hagoort, 2003; Hagoort, 2005; van den Brink & Hagoort, 2004) propose a different model in which semantic and syntactic information are processed in parallel as soon as they are available and posit that the timing differences reported between LAN and ELAN effects are a result of differences in the online availability of morphosyntactic and word category information.

The second component which has been observed in ERP studies of syntactic processing is a large positive-going wave usually maximal over bilateral posterior regions and peaking at 500-1000 ms., known as the P600 (Osterhout & Holcomb, 1993). The P600 is consistently elicited by syntactic violations (Hagoort et al., 1993; Hagoort & Brown, 2000; Hahne & Friederici, 1999; Osterhout & Holcomb, 1992; Osterhout & Mobley, 1995) as well as by violations of preferred syntactic structure (Osterhout & Holcomb, 1993; Osterhout et al., 1995) or in well-formed sentences of higher syntactic complexity (Kaan et al., 2000; Kaan & Swaab, 2003a, b). While the distribution of the P600 is usually posterior, several studies have found a late positivity with a more frontal distribution to grammatically correct but non-preferred structures (Friederici et al., 2002; Kaan & Swaab, 2003a, b; Osterhout & Holcomb, 1992). This has led to the proposal that the frontally distributed P600 reflects processing difficulties related to revision in the face of non-preferred structures, while the posteriorally distributed P600 reflects processes related to the failure of a parse and related processes of repair and meaning rescue (Friederici et al., 2002; Hagoort & Brown, 2000) or to syntactic integration difficulty (Kaan et al., 2000).

Second language processing

Based on evidence from the development of sensory and motor systems, Lenneberg (Lenneberg, 1967) proposed that similar maturational processes might constrain language development such that there may be sensitive periods during which the effects of language experience are maximal on ultimate linguistic proficiency and neural organization for language. This hypothesis is supported by behavioral data from both first and second language acquisition which suggest that proficiency decreases with delays in language immersion (Johnson & Newport, 1989; Mayberry, 1993; Mayberry & Eichen, 1991; Mayberry, Lock, & Kazmi, 2002; Newport, 1990). This evidence also suggests that different subsystems are differentially affected by delays in language experience, as syntactic processing appears to be more profoundly affected while semantic processing appears to be relatively invulnerable to such delays. Other evidence suggests that a small number of non-native speakers who acquire a second language after the end of a hypothesized sensitive period, around the onset of puberty, can attain a level of proficiency in syntactic processing which is similar to that of native speakers (Birdsong, 1992; White & Genesee, 1996), though the question of whether such individuals recruit the same neural mechanisms as native speakers to achieve such a level of proficiency is an open one.

Several ERP studies of bilinguals that have replicated behavioral findings of reduced grammatical proficiency with delays in second language exposure have provided evidence bearing on differences in neural organization for second language processing which might underlie the effects of proficiency. In a study of Chinese-English bilinguals, Weber-Fox and Neville (1996) found that systems involved in lexical-semantic processing, as reflected by the N400 response to semantic violations, were not affected by delays in exposure as long as eleven years. In contrast, systems involved in syntactic processing were found to be sensitive to delays of even four years: while syntactic violations elicited a biphasic response in all groups consisting of an anterior negativity between 300-500 ms followed by a P600, the anterior negativity was left-lateralized only in groups with earlier ages of first exposure to English, bilateral in groups whose first exposure to English was later, and right-lateralized in participants whose first exposure was after age 16. Two subsequent studies of late bilinguals did not find an anterior negativity to syntactic violations. ERP studies of Japanese-German (Hahne & Friederici, 2001) and Russian-German (Hahne, 2001) late bilinguals reported that, while semantic violations elicited an N400 in both groups of late learners, syntactic violations failed to elicit an anterior negativity response in either group, though such violations did elicit a P600 in the Russian-German group. Recently, two studies have reported more native-like ERP effects to syntactic violations in second language learners. In a study of Japanese-English bilinguals of different second language proficiency levels, Ojima and colleagues (Ojima et al., 2005) report that, while semantic violations elicited an N400 in both late learner proficiency groups, syntactic violations elicited a left-lateralized negativity between 350-550 ms only in the native speaker and high proficiency late bilingual groups. Rossi and colleagues (Rossi et al., 2006) report that both low- and high-proficiency late learners of German and Italian processing their respective second languages showed an extended bilateral anterior negativity beginning around 100 ms and a P600 to phrase structure violations and high-proficiency learners of both languages showed a biphasic LAN-P600 response to verb agreement violations.

Overall, these results illustrate that anterior negativity effects can be elicited in late bilinguals under certain experimental conditions and that these effects seem to be related to the level of second language proficiency. However, these present a disparate pattern of results which makes interpretation difficult. While it is possible that differences in second language proficiency are the primary factor driving these differences, differences in quantification of proficiency across studies, as well as the fact that different languages were investigated, limit this interpretation. Another factor which limits the degree to which interpretation across studies is possible is methodological differences. For example, the Ojima et al. study featured visual presentation of short, simple, active sentences, which made the violations very predictable, and stimuli sentences were presented with no filler sentences. Also, ERPs were averaged to all sentences, as there was no online measure of grammaticality judgment. In contrast, the Rossi et al. study used auditory presentation, included filler sentences (although with no different violation types), and averaged only to correct responses. Overall, this limited and disparate set of results underscores the need for more ERP research on second language acquisition, and raises the possibility that a greater degree of collaboration between laboratories in an effort to make proficiency measures and stimulus materials more comparable would lead to more interpretable results.

While several positron emission tomography and functional magnetic resonance imaging studies have examined the neural indices of second language processing, most have focused on the semantic subsystem using word generation, single word semantic judgment, or picture naming tasks. Studies which have investigated the syntactic subsystem have primarily used paradigms in which participants listened to sentences or stories in both native and second languages; while the use of such paradigms engage syntactic processes to some degree, because syntactic processing is not separately assessed, the degree to which the focus is limited to syntactic processes is limited. While differences in tasks and paradigms across studies limit the generalizability of the results, overall the findings are consistent with the behavioral and electrophysiological results in that less variability between first and second language processing is found in temporal lobe areas, which are typically implicated in semantic processing. However, more variability is found, in patterns of results in different studies, in frontal areas which have been implicated in nonlexical compositional processes such as syntactic processing (for a recent review, see Indefrey, 2006), comparable to the disparate pattern of ERP results from studies of second language syntactic processing discussed above. Neuroimaging studies which have specifically examined the role of experience and proficiency have found evidence for a role for both age of exposure and ultimate second language proficiency in the determination of neural organization for a second language. Some studies have found more variable neural organization with delays in second language exposure (Dehaene et al., 1997; Kim et al., 1997), though these studies employed story listening and silent speech generation paradigms which limit the degree to which syntactic processes were in focus. Studies which have directly compared experience and proficiency have reported mixed results. One study reported that, while no differences in neural organization for first and second languages were found for early acquisition high proficiency bilinguals, late acquisition (after age six) bilinguals recruited additional resources in inferior frontal and parietal regions for grammatical processing in their second language (Wartenburger et al., 2003). Another study found no differences in neural activation between two groups of highly proficient bilinguals who differed in age of acquisition while participants listened to stories in their second language (Perani et al., 1998), though again the use of a story listening paradigm limited the degree of focus on syntactic processes.

Data from two ERP experiments suggest that significant differences in proficiency exist in monolingual adults and are linked to altered neural organization as indexed by ERPs. In a visual sentence processing paradigm, Weber-Fox, Davis, and Cuadrado (Weber-Fox et al., 2003) compared the brain response to visually presented semantic violations in participants who scored either exceptionally high or in the normal range on four subtests of the Test of Adult and Adolescent Language-3 (TOAL-3), a standardized assessment of English language proficiency. While no differences were found in early ERP components indexing perceptual processing, high proficiency participants had an earlier N280 to closed-class words only over left anterior regions, suggesting more rapid lexical access of grammatical words specifically in these participants. In Chapter II we reported results from a study in which we examined differences in the neural response to auditory phrase structure violations in English sentences in two groups of monolingual native speakers of English who were classified as higher or lower proficiency based on their scores on the TOAL-3. Violations elicited a typical biphasic response in both groups, but there were differences in this response between groups. The anterior negativity effect was spatially and temporally more focal in the left hemisphere in the higher proficiency group but more widely distributed and prolonged in the lower proficiency group. The P600 effect was larger in amplitude and more broadly distributed in higher proficiency participants compared to lower proficiency participants. These effects of proficiency on neural organization for syntactic processing were confirmed by a correlational analysis across a wide range of proficiency scores.

The present study

Because numerous lines of evidence suggest that the syntactic subsystem is more vulnerable to differences in language experience, here we focus on this subsystem. In Chapter II we studied the effect of proficiency on neural organization for syntactic processing by studying a group of monolingual native speakers, who had the same age of acquisition, who differed on standardized measures of English proficiency. Here we continue this systematic exploration of the relative contributions of age of acquisition and proficiency to neural organization for syntactic processing by comparing two groups of participants who were matched on English proficiency but who had different ages of acquisition. We recruited native speakers of German who had acquired English late but who had achieved a level of grammatical proficiency, based on a standardized measure of English grammatical proficiency, equal to that of the Lower Proficiency monolingual group from Chapter II. Both groups were run in the same auditory ERP paradigm featuring phrase structure violations in simple, single-clause sentences in English. We hypothesized that the neural response to syntactic violations would be affected by differences in age of acquisition, and that early and late components of this response would be differentially affected. Specifically, we predicted that differences related to age of acquisition would be most strongly reflected in differences in the early anterior negativity, a component hypothesized to reflect early and automatic processing. In contrast, we hypothesized that the P600, a late component thought to reflect more controlled processes, would be more similar in late learners and native speakers.

Method

Participants

Thirty-six right-handed adults with normal hearing participated in the study. Nineteen participants (the Non-Native Speaker group; NNS) were native speakers of German who began learning English between the ages of 10-12 and had reached a high enough level of proficiency in English to function as undergraduate students, graduate students, or professors at the University of Oregon. Any participant with a score more than two standard deviations above the mean on any behavioral or ERP measure was removed from the analysis as an outlier; this resulted in the removal of one NNS participant. Seventeen participants (the Native Speaker group; NS) were monolingual native speakers of English recruited from both the university and general population. These were the same participants who formed the Lower Proficiency group discussed in Chapter II; as such, they had lower proficiency scores that matched those of the late learners.

Behavioral Language Inventories

The groups were matched for proficiency based on their scores on the Speaking/Grammar subtest of the Test of Adolescent and Adult Language-3 (TOAL-3; Hammil, Brown, Larsen, & Wiederholt, 1994). The TOAL-3 Speaking/Grammar subtest requires participants to repeat exactly sentences said by the examiner as the sentences increase in syntactic difficulty. In order to receive a correct score, the participant must repeat the item without any changes in syntax or morphology. Several factors motivated the choice of this test. First, the Speaking/Grammar test uses a sentence repetition task, which is hypothesized to be a good index of grammatical proficiency because participants revert to their preexisting knowledge of syntax when sentences exceed short term memory limits (Dale, 1976). Measures such as the Speaking/Grammar subtest which use elicited imitation under time pressure have been claimed to be good measures of implicit language knowledge in second language learners because they are reconstructive in nature, requiring participants to process the stimulus in a manner which assimilates it into an internal grammar (Erlam, 2006; Munnich, Flynn, & Martohardjono, 1994). Second, the Speaking/Grammar subtest was chosen because it provides a measure of English grammatical proficiency which is relatively independent of working memory demands. This was desirable because of the high working memory performance of the late learners recruited compared to the native speakers (see below). Two additional tests were administered to assess linguistic proficiency: the Listening/Grammar subtest of the TOAL-3, and the Saffran and Schwartz Grammaticality Judgment Test (Linebarger et al., 1983). The TOAL-3 Listening/Grammar subtest requires participants to determine, out of three sentences presented auditorily, which two sentences have similar meaning. The Saffran and Schwartz Grammaticality Judgment Test is a 78-item assessment in which participants must recognize a variety of syntactic violations, adapted for purposes of this study into the auditory modality. In order to assess WM capacity, participants were also given the Carpenter Span Reading Test (Daneman & Carpenter, 1980), a widely-used assessment in which participants must recall the final word of two or more sentences after reading them consecutively. Participants also filled out a questionnaire which gathered information on education level and socioeconomic status of origin (SES) as measured by the Hollingshead Four Factor Index of Social Status (Hollingshead, 1975).

Bilingual Questionnaire

In order to explore the role of different aspects of language experience in second language acquisition, NNS participants were given an additional questionnaire. This questionnaire included questions about participants' amount of English exposure throughout their lives; sources of this exposure; first exposure to English instruction and amount of time spent studying English; amount of time spent living in an English-speaking country; relative helpfulness of different activities in learning English; relative frequency of English use throughout their lives in school, home, and other environments; and self-ratings of German and English proficiency in spoken, written, and overall language.

Stimuli

In the ERP paradigm, participants heard both English sentences and Jabberwocky sentences, in which open-class words were replaced with pronounceable nonwords to greatly reduce the semantic context; only the results for the English stimuli are presented here. The English stimuli were sentences which were canonical (50%) or which contained an insertion phrase structure violation in which an additional closed-class word was inserted in a sentence-final prepositional phrase. In all cases, the phrase structure violation clearly occurred at the onset of either a demonstrative (50%) or possessive (50%) pronoun directly following the inserted pronoun. The ERPs to the onset of the target word (underlined below) in the canonical and violation (*) sentences were compared:

English: Timmy can ride the horse at his farm.

*Timmy can ride the horse at my his farm.

A number of measures were undertaken in order to provide prosodic variability as well as to insure that subjects listened fully to the sentences and did not focus only on the location of the critical violation. In 5% of the experimental sentences an additional prepositional phrase was added to the beginning of the sentences, and in 20% of the experimental sentences an adjective was placed directly after the target word so that the target word was not invariably in the penultimate position in the sentence. In addition, filler sentences and probe questions were constructed. Filler sentences contained a permutation phrase structure violation in which a main verb and the determiner of the object noun phrase were reversed. Probe questions took the form "Did you hear the word (blank)?" Participants heard 62 sentences of each condition. Twenty-eight filler sentences (10% of total) were pseudo-randomly interspersed between the experimental sentences, as were 16 probe questions, such that filler sentences and probe questions occurred equally across quarter stimulus blocks and were always separated by at least two experimental sentences.

All sentences were recorded using SoundEdit 16 Version 2 with 16-bit resolution and a 16 Khz sampling rate then transferred to a PC for presentation. The sentences were spoken by a female with natural tempo and prosody and critical word onsets were identified and coded by three trained coders using both auditory cues and visual inspection of sound spectrographs for increased accuracy. Any sentences in which codes differed by more than 20 milliseconds between coders were re-coded by all three coders together until a consensus was reached by all three to ensure reliability.

Procedure

Most participants were tested in one three-hour session, with the standardized tests of language administered immediately before ERP testing. A subset of participants in both the NS group (N = 5) and the NNS group (N = 7) were given the behavioral measures and ERP testing in separate sessions. In each ERP session a 32-channel electrode cap (Electro-Cap International) was applied while the participant completed an information sheet which included questions about education, socioeconomic status, handedness, neurological history, and language habits. NNS participants also completed the questionnaire assessing their acquisition and current usage of English. In the third part of each session subjects were seated in a comfortable chair in an electrically shielded, sound-attenuating booth. Sentences were presented via a speaker placed centrally on a monitor 70 in. from the participant. Participants were given auditory instructions including examples of both sentence types and emphasizing the need to judge the sentences based on grammatical, and not semantic, correctness. On each trial, participants pushed one of two response buttons to play a sentence. While the sentences were playing, participants were asked to refrain from blinking or moving their eyes as a box with a central fixation cue ('*') was displayed. After each sentence, participants were cued to make a judgment with a display of "Yes or No?" on the screen. The judgment was made with a button press with either the left or right hand, counterbalanced across participants. Participants proceeded at their own pace and were given two regularly scheduled breaks and additional breaks as requested.

EEG Equipment and Analysis

The EEG was recorded using tin electrodes mounted in an appropriately sized elastic cap (Electro-Cap International) over 29 scalp sites based on Standard International 10-20 electrode locations: F7/F8, F3/F4, FT7/FT8, FC5/FC6, T3/T4, C5/C6, CT5/CT6, C3/C4, T5/T6, P3/P4, TO1/TO2, O1/O2, FP1/FP2, Fz, Cz, and Pz. Scalp electrode impedances were kept below 3 KOhms. Data from all scalp electrodes were referenced on-line to the EEG from an electrode placed over the right mastoid and later referenced off-line to the mathematical average of the left and right mastoids. Horizontal eye movements were monitored using electrodes placed at the outer canthus of each eye and referenced to each other, while vertical eye movements were monitored using an electrode placed beneath the right eye and referenced to the right mastoid. The raw EEG signal was collected at a sampling rate of 250 Hz and was amplified using Grass Amplifiers with high- and low-pass filter settings of 0.01 Hz and 100 Hz, respectively.

Only trials on which subjects responded correctly were included in the ERP analyses. The EEG data for each participant were examined for eye movements, muscle artifact, and amplifier saturation and drift, and any trials contaminated by these artifacts were excluded from final data analyses. ERPs were computed for 1200 ms after the onset of the target word relative to a 100 ms prestimulus baseline. ERP waveforms were measured within time windows determined by visual inspection of individual and group averages; specific time windows are described in the Results section. Based on *a priori* hypotheses from previous results and on visual inspection of the effects, the anterior negativity effect was characterized by analyzing the 12 anterior electrode sites and the P600 by analyzing the 12 posterior electrode sites. Mean voltage amplitude was measured within each time window and analyzed using ANOVAs with repeated measures, including, 2 levels of condition (C: canonical, violation), 2 levels of hemisphere (H: left, right), 3 levels of anterior-posterior (A: frontal, fronto-temporal, temporal (anterior sites); central, parietal, and occipital (posterior sites)), and 2 levels of lateral-medial (L: lateral, medial), as well as a between-subjects factor, age of acquisition, with two levels (N: Native Speakers, Non-Native Speakers). Following omnibus ANOVAs, additional analyses were performed in step-down fashion such that follow-up analyses were performed to isolate any significant interactions, collapsing across factors with which an interaction was not found. When significant between-group interactions were found, separate ANOVAs were performed for each group to better characterize group differences. Greenhouse-Geisser corrections were applied for all ANOVAs with greater than one degree of freedom.

Results

Behavioral Results

Behavioral results for all measures of proficiency and working memory are summarized in Table 3.1. Non-Native Speaker (NNS) and Native Speaker (NS) groups were matched on the Speaking/Grammar subtest of the TOAL-3. The resulting mean average scores for the NS ($M = 15.47$, $SD = 4.26$) and NNS ($M = 17.11$, $SD = 3.46$) groups were not statistically independent ($t(33) = 1.566$, NS). NNS participants scored higher than NS participants on the TOAL-3 Listening/Grammar subtest ($t(33) = 3.373$, $p < .001$). Although this result seems surprising, a likely explanation involves group differences in working memory span, as this particular subtest likely induces a high working memory load. The NNS group did have a significantly higher working memory span than the NS group ($t(33) = 2.669$, $p < .05$). The NS group scored higher on the Saffran and Schwartz Grammaticality Judgment Test ($t(33) = 2.525$, $p < .05$). In the ERP grammaticality judgment task, there was a trend for a higher percentage of correct responses by the NNS group ($M = 97.41$, $SD = 1.93$) compared to the NS group ($M = 94.96$, $SD = 9.94$) which did not reach significance ($t(33) = 1.723$, $p = .094$). The NNS group also had a higher level of education ($t(33) = 5.948$, $p < .005$) and SES ($t(33) = 3.12$, $p < .005$) than the NS group.

Bilingual Questionnaire

Results from the Bilingual Questionnaire revealed that all NNS participants began learning English in a school setting at around the same age ($M = 11.05$ years, $SD = 1.10$, range 10-14). Only one NNS participant had parents who spoke English in the home, and only 2-3 times per month. Participants had spent on average 27.7 months total living in an English-speaking country, although after the removal of four outliers the mean time spent living in an English-speaking country went down to 8.6 months. In order to access the effect of these outliers on the behavioral measures used, group analyses of all measures were run with and without the outliers; because no significant differences were found for any of the measures, all of the analyses reported here include all 18 NNS participants. When asked to rate their language skills on a four-point scale for both English and German, participants rated themselves significantly better in German for listening, reading, writing, and speaking. Participants reported that on average they rarely heard English before age 11, and the most common source for those who did have such exposure was the radio. When asked to rate activities in terms of helpfulness in learning English, formal instruction was rated most helpful and socializing second most helpful, with reading rated next most helpful and watching TV scoring much lower. Participants reported almost exclusive use of German throughout primary and secondary school, with use of English increasing only in adulthood, and then most often in a university or work setting.

ERP results

The ERP data to the critical word in English sentences over all electrode sites are shown for the NS group in Figure 3.1 and for the NNS group and Figure 3.2. Visual inspection of the waveforms revealed clear patterns and clear differences between groups. The NS group showed a biphasic response to phrase structure violations in English: an

Table 3.1

Behavioral results

Group	TOAL-3 S-G	TOAL-3 L-G**	Saffran and Schwartz*	Carpenter Span*
Native Speakers				
(n = 17, 7 F)				
M	17.06	19.00	74.29	2.79
(SD)	(3.36)	(7.98)	(3.08)	(.53)
Range	9-22	7-32	67-78	2-4
Percentile	16	25	N/A	N/A
Non-native Speakers				
(n = 18, 8 F)				
M	15.11	28.17	70.61	3.22
(SD)	(4.07)	(4.20)	(5.22)	(.52)
Range	5-20	21-34	57-77	2-4
Percentile	N/A	N/A	N/A	N/A

* = $p < .05$, ** = $p < .01$

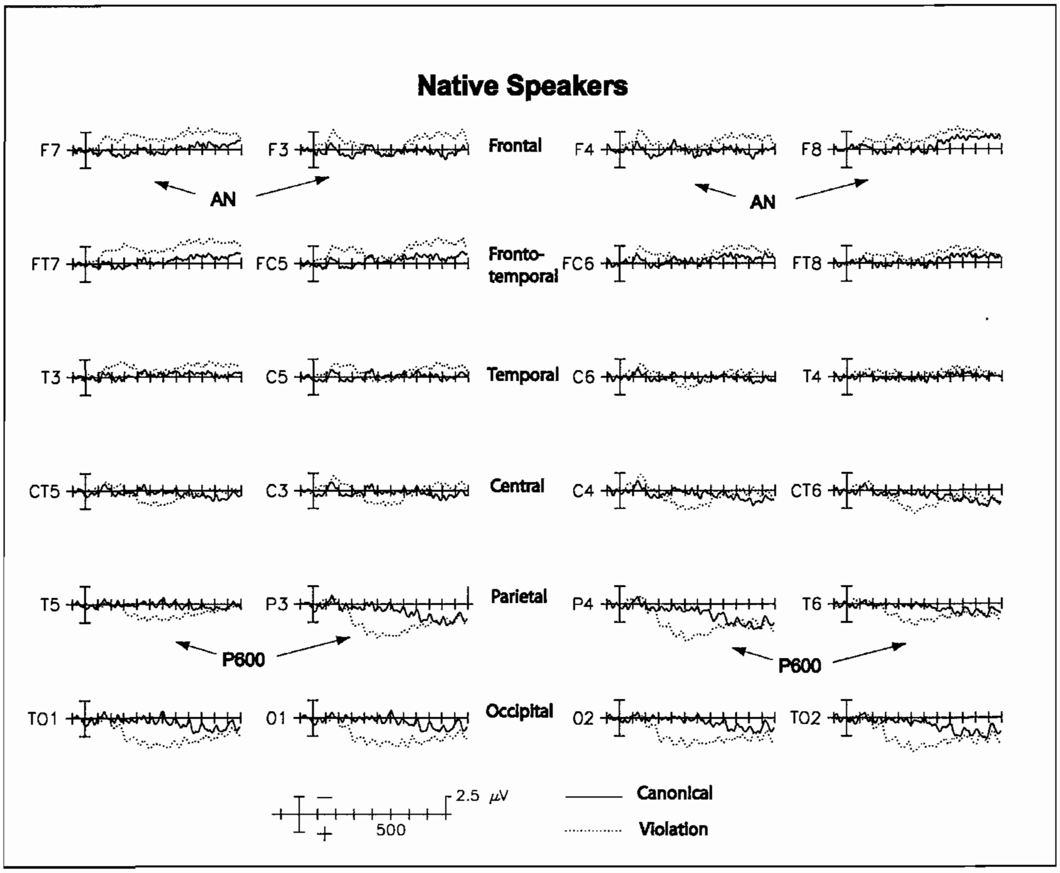

Figure 3.1. ERPs to English phrase structure violations for the NS group.

extended, bilateral anterior negativity with onset around 100 ms and a posterior positivity peaking around 600 ms. A different pattern was observed in the NNS group, who showed no anterior negativity but a robust P600 over posterior sites extending to anterior sites.

Early (100-300 ms) anterior negativity

In the NS group, analyses across anterior electrode sites in the 100-300 ms time window revealed a significant main effect (C: F(1, 16) = 14.94, p < .001) which was largest over anteriormost sites (C x A: F(2, 32) = 10.41, $p < .005$). While this effect showed a greater degree of left lateralization over lateral sites (C x H x L: F(1, 16) = 4.65, $p < .05$), overall it was bilateral (C x H: F(1, 16) = 1.81, NS) and evenly distributed across lateral and medial sites (C x L: F(1, 16) = 0.53, NS).

In the NNS group, analyses across anterior electrode sites in the 100-300 ms time window in the NNS group revealed no main effect (C: F(1, 17) = .69, NS) and no significant interactions with condition. A group interaction supported the observation that the negativity was larger in the NS group in this time window (C x N: F(1, 33) = 4.67, $p < .05$).

Later anterior negativity

300-700 ms. In the NS group, analyses across anterior sites in the 300-700 ms time window revealed a significant negativity largest over anteriormost (C x A: F(2, 32) = 12.79, $p < .0001$) and lateral (C x L: F(1, 16) = 12.28, $p < .005$) sites.

In the NNS group, analyses in this time window over anterior sites revealed a significant positivity largest over fronto-temporal and temporal (C x A: F(2, 32) = 12.04, $p < .005$) and medial sites (C x L: F(1, 16) = 19.56, $p < .0001$). An interaction supported this difference in effects between groups (C x N: F(1, 34) = 6.15, $p < .05$).

700-1200 ms. In the NS group, analyses across anterior sites in the 700-1200 ms time window revealed a significant main effect (C: F(1, 16) = 5.39, $p < .05$), a negativity which was largest over anteriormost sites (C x A: F(2, 32) = 5.07, $p < .05$).

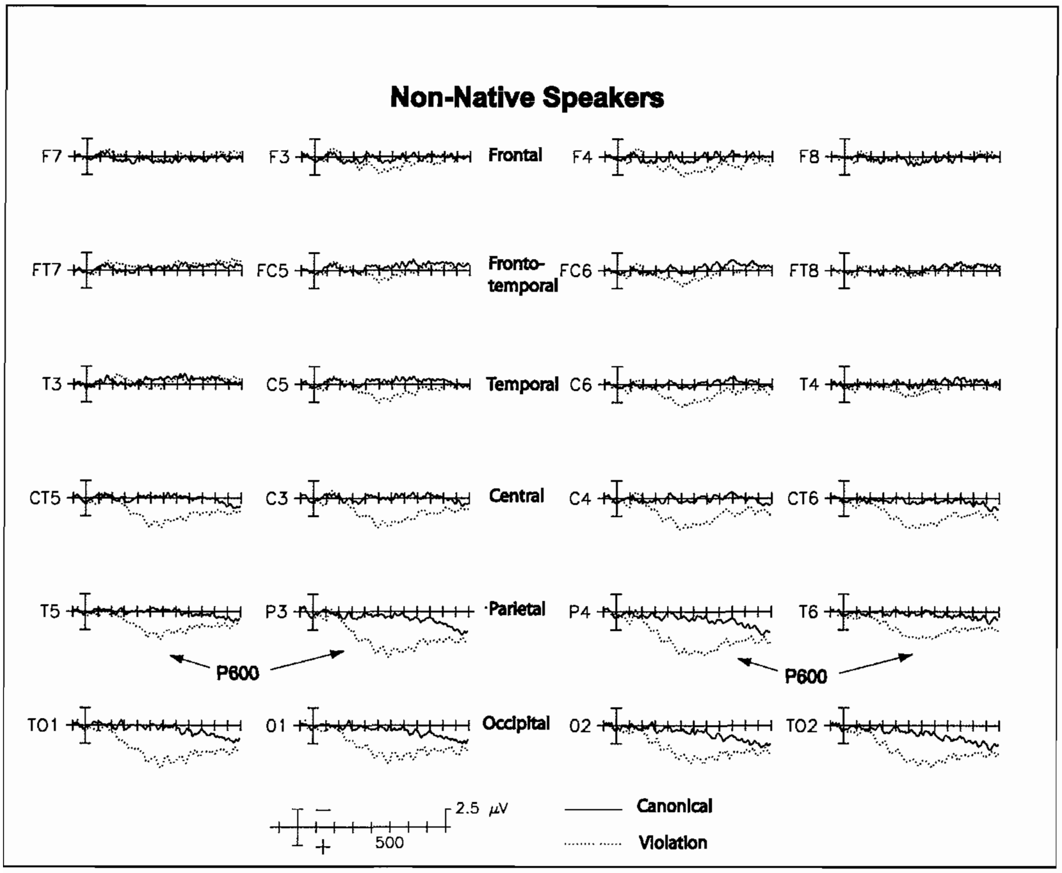

Figure 2.2. ERPs to English phrase structure violations for the NNS group.

In the NNS group, analyses in this time window over anterior sites revealed a significant positivity largest over temporal (C x A: F(2, 32) = 3.72, p < .05) and medial (C x L: F(1, 16) = 16.47, p < .005) sites. A significant group interaction supported this difference in effects between groups (C x N: F(1, 34) =6.08, p < .05).

Posterior positivity (P600)

In the NS group, analyses over the three posterior rows of electrodes in the 300-1000 ms time window revealed a main effect of condition (C: F(1, 16) = 15.55, p <

.005), a positivity which was largest over posteriormost sites (C x A: $\underline{F}(2, 32) = 11.80$, $\underline{p} < .0001$).

In the NNS group, analyses in this time window over posterior sites revealed a main effect of condition (C: $\underline{F}(1, 17) = 26.65$, $\underline{p} < .0001$). A near-significant group interaction revealed a trend for the P600 to be larger in the NNS group than in the NS group (C x N: $\underline{F}(1, 33) = 3.14$, $\underline{p} = .084$).

As visual inspection suggested that the P600 was longer in duration in the NNS group, an analysis was conducted in the 1000-1200 ms time window. A significant group interaction revealed that the P600 was larger in the NNS in this time window, with the difference maximal over central and parietal rows (C x A x N: $\underline{F}(2, 68) = 4.33$, $\underline{p} < .05$).

Discussion

In this study event-related potentials elicited by phrase structure violations were examined as two groups of English speakers listened to simple sentences in English. Groups consisting of either native speakers of English (NS) or non-native speakers who did not begin acquiring English until around age 11 (NNS) were matched on a standardized measure of English grammatical proficiency. Analyses revealed differences in neural organization for syntactic processing between the two groups. In the NS group, consistent with their lower proficiency status violations elicited a large, bilateral, and prolonged anterior negativity followed by a P600. In contrast, in the NNS group violations elicited only a P600 which was more widespread spatially, extending to more anterior sites, and temporally, extending to 1200 ms, compared to the NS group. The P600 in the NNS group also tended to be larger than in the NS group. Below we discuss possible functional interpretations of these results and their implications for theories of second language acquisition, and discuss future directions for research into the relative contributions of age of acquisition and proficiency in determining neural organization for language.

Proficiency Matching

Groups were matched for English proficiency using the Speaking/Grammar subtest of the TOAL-3. This measure was chosen because in part because it requires elicited imitation under time pressure, and tests which use elicited imitation are considered to be good measures of implicit language knowledge (Dale, 1976; Erlam, 2006; Munnich et al., 1994). This measure was also chosen because it is relatively independent of working memory demands, which was desirable because the NNS participants had a higher working memory span than the NS participants. While efforts were made to match the groups on working memory span, this proved to be difficult for several reasons. As discussed in Chapter II, in the group of English native speakers working memory correlated with proficiency, though the correlational analyses in Chapter II showed that proficiency effects on neural organization for language were independent of working memory differences. The NNS participants were recruited from the University of Oregon population; as individuals who were able to work or study at a foreign university using primarily their second language, they had achieved a high enough level of proficiency to match lower proficiency native speakers. However, the use of participants from the university community, including graduate students and professors from higher SES backgrounds, made it difficult to match this group on working memory span with a group of lower proficiency native speakers. This underscores the difficulty of conducting such research in a small university community in the United States. In future studies seeking to replicate the present results it will be fruitful to recruit participants from larger communities with a wider range of individuals with good second language proficiency, though the use of larger communities also presents potential problems, such as increased likelihood of differences in early second language exposure. Still, it is unlikely that group differences in working memory affected the results, as the ERP paradigm minimized working memory demands by using phrase structure violations in simple, single-clause sentences.

Another important point with regard to proficiency matching is that the NS group was significantly higher on the Saffran and Schwartz Grammaticality Judgment task. While having groups which were matched on this measure as well would have been ideal, it is also unlikely that this had a profound effect on the results. First, while the average score on this measure for the NNS group was lower than that for the NS group, NNS participants still scored an average of 90% correct. This, combined with the high performance of the NNS participants on the grammaticality judgment task in the ERP paradigm (97%), suggests that this group difference did not reflect a profound difference in proficiency which would potentially confound the results. Additionally, the NNS group actually outperformed the NS group on one measure of proficiency, the TOAL-3 Listening/Grammar subtest, though as noted above this test induces a higher working memory load than the other proficiency measures used. Taken together, the behavioral results show that with one exception the NNS participants in this study scored at comparable or slightly higher levels on the proficiency measures used than did NS participants, adding a degree of confidence that the measures used accurately reflected a group of late learners of English closely matched for proficiency with the English native speakers.

Anterior Negativity

Phrase structure violations in English elicited an anterior negativity in the NS group which began around 100 ms and was robust and widespread, extending to 1200 ms over anterior sites bilaterally. In contrast, the NNS group differed markedly, even though this group performed the online grammaticality judgment task with a slightly higher degree of accuracy than the NS group. In the NNS group, violations did not elicit a significant negative effect over anterior sites, suggesting differences in the degree to which resources reflected in the early anterior negativity were recruited by NNS participants. The early anterior negativity to word category violations has been hypothesized to reflect early and automatic processes in which a word is integrated into the phrase structure of the preceding sentence fragment (Friederici, 2002). These results suggest that individuals who acquire a language later in life rely primarily on different, more controlled, neural mechanisms to achieve a level of proficiency comparable to that of some native speakers. This also suggests that the development of early and automatic processes hypothesized to be indexed by the early anterior negativity may be governed by maturational constraints consistent with a sensitive period.

Results from previous ERP studies of syntactic processing in second language learners support this interpretation, as syntactic violations in the non-native language of late learners either failed to elicit an anterior negativity (Hahne, 2001; Hahne & Friederici, 2001) or elicited a negative effect in a later time window (Ojima et al., 2005; Weber-Fox & Neville, 1996). While Weber-Fox and Neville did find an early response to phrase structure violations over anterior sites, this response was restricted to right hemisphere sites in the latest learning (i.e., 11-13 and older than 16 years age of exposure) bilingual groups and was interpreted as a delayed response to the preceding word in the sentence. One study has reported robust early anterior negativity effects to word category violations in this time window in non-native speakers, even in those of lower proficiency (Rossi et al., 2006).

Posterior Positivity

Phrase structure violations elicited a robust posterior positivity in the NS group, part of a biphasic response which is consistent with much previous ERP research examining the neural response to syntactic violations in native speakers. Violations also elicited a robust posterior positivity in the NNS group. This is consistent with previous research examining syntactic processing in late second language learners, as several studies have reported a P600 to syntactic violations in such groups (Hahne, 2001; Rossi et al., 2006; Weber-Fox & Neville, 1996), and suggests that processes reflected in the P600 may be less sensitive to maturational constraints than those reflected in the early anterior negativity. However, two ERP studies of syntactic processing in late learners do not report a P600 to syntactic violations (Hahne & Friederici, 2001; Ojima et al., 2005). One study which did not report a P600 (Hahne & Friederici, 2001) attributed the finding to differences in second language proficiency: while participants in that study had an error rate of around 20% in an online grammaticality judgment task, participants in the study using similar stimuli in which a P600 was found for late learners (Hahne, 2001) had an error rate of 8%. Proficiency differences also likely played a role in the other study which did not report a P600 in late learners (Ojima et al., 2005), as the groups of high and low proficiency late learners had error rates of 13 % and 33 %, respectively, in an offline acceptability judgment task on stimuli consisting of three-word sentences featuring straightforward subject-verb agreement violations.

While violations elicited a P600 in both groups, the P600 in the NNS group was more widespread spatially, extending across anterior sites, and also tended to be larger compared to the NS group. The P600 has been hypothesized to reflect more controlled processes involved with a failure to parse and related processes of repair (Friederici et al., 2002; Hagoort & Brown, 2000) or difficulty in syntactic integration (Kaan et al., 2000). Thus the present results suggest that late learners may rely more on these controlled processes to achieve a level of proficiency comparable to some native speakers.

The P600 in the English condition was more focal temporally in the NS group, while it extended to 1200 ms in the NNS group independent of differences in proficiency. This result suggests subtle differences in the use of the resources reflected in the P600. It is possible that this might reflect the more efficient use of resources important for syntactic integration and reanalysis in the NS group as a result of more experience with English, though this hypothesis is necessarily preliminary and requires further research.

Implications and Future Directions

An important question in the study of second language acquisition is the degree to which age of acquisition and proficiency affect neural organization for syntactic processing in a second language. While these factors are confounded in many studies, efforts to systematically examine the relative contributions of these factors are increasing. Here we report results from the second in a series of experiments specifically designed to address this question. By examining native speakers with a wide range of scores on standardized tests of English proficiency in the Chapter II, we were able to form a group which matched a group of late learners of English on a standardized measure of English grammatical proficiency. This then allowed us to more directly examine the effects of age of acquisition on neural organization for syntactic processing by comparing the neural response to auditory syntactic violations in the same paradigm in groups which differed on this factor. Our results support the hypothesis that non-native speakers of English who learned English late recruit different neural systems to achieve a level of proficiency comparable to that of some native speakers and provide evidence that processes indexed by the early anterior negativity effect may be governed by maturational constraints consistent with a sensitive period. These results further raise the hypothesis that late learners may rely more on controlled processes which are less sensitive to maturational constraints in the face of reduced availability of resources which are more governed by maturational constraints.

While the results discussed above shed light on the role of age of acquisition in the determination of neural organization for syntactic processing, there remains much work to be done. Methodological differences between laboratories, both specific to the ERP paradigms used as well as with regard to measures of proficiency, make between-studies interpretation and comparison difficult. Of particular importance will be the development and use of better measures of proficiency. Here a higher degree of cooperation between laboratories would greatly help the field overall in this regard, as many of the laboratories actively pursuing this line of research are in different countries with researchers who are speakers of different native languages, using paradigms for which extensive data on native speakers already exist. This is an obvious opportunity for cooperation between laboratories, either at the level of collaborative studies or at a lower level of cooperation featuring the exchange of proficiency and stimulus materials, which is rarely pursued. Such cooperation using paradigms in different languages also raises the tantalizing possibility of directly comparing ERPs from the same participants while processing their native and their second language. The field would also benefit from the establishment of guidelines with respect to the characterization of participants, in particular a more comprehensive characterization of second language proficiency, which could be used across laboratories. Taking such factors into consideration as the field moves forward can only lead to stronger results and a better understanding of the role of age of acquisition and proficiency in neural organization for second language processing.

These results also provide several directions for future research. First, it will be important to further explore the degree to which second language proficiency can impact neural organization for syntactic processing in late learners. While the results presented here provide further evidence that certain processes important for syntactic processing are sensitive to maturational constraints, the group of late learners studied here were on average of relatively low proficiency compared to native speakers. The expansion of this study to include late learners of higher proficiency would shed more valuable light on this question. As discussed above, a data set including a wide range of late second language learners of varying proficiency levels could allow for a correlational analysis similar to that performed in Chapter II, which would in turn allow for a more comprehensive investigation of the factors which affect neural organization for syntactic processing in second language learners. Another important future direction is the use of fMRI in conjunction with ERPs to more fully characterize the effects of both age of acquisition and proficiency on the recruitment of specific neuroanatomical regions in syntactic processing. This is another current line of research in our laboratory, and the use of fMRI in conjunction with ERPs to shed further light on the effects of proficiency on neural organization for syntactic processing, as well as to address questions regarding the neuroanatomical sources of ERP components related to syntactic processing, is the focus of Chapter IV. Finally, for a more complete investigation of maturational constraints on the recruitment of processes involved in syntactic processing, it will also be important to characterize the interaction between age of acquisition and proficiency in bilinguals at different stages of development.

CHAPTER IV

PROFICIENCY DIFFERENCES IN SYNTACTIC PROCESSING OF NATIVE SPEAKERS AS INDEXED BY FMRI

The advent of modern neuroimaging techniques such as positron emission tomography (PET) and functional magnetic resonance imaging (fMRI), combined with a rich literature linking brain lesions in specific areas to specific deficits, has led to a greater understanding of neural organization for syntactic processing. While in early studies methodological constraints inherent in the use of block designs limited the degree to which the focus was put specifically on syntactic processes, the advent of event-related designs which allow for the presentation of randomly intermixed stimulus trials has made it possible to conduct studies with a more constrained focus on syntactic processing and which more closely approximate designs used in event-related potential (ERP) studies. Although much progress has been made, there still exists a great deal of variability in results from neuroimaging studies of syntactic processing. While one source of this variability is likely a result of methodological differences between studies, another possible explanation for at least some of this variability, and one which has not been explored in the literature, is that differences in proficiency between participants may have contributed to this variability. The results from Chapter II provided evidence, from converging methodological approaches, that proficiency differences affect neural organization for syntactic processing as indexed by ERPs. However, the question of how these differences in neural organization are reflected in a measures of brain activation with better spatial resolution is an open one. Most neuroimaging studies which have examined groups that differ in language processing, like most ERP studies, have examined groups which differ on working memory capacity and present manipulations of syntactic complexity in the visual modality with written sentences (Caplan, Waters, & Alpert, 2003; Fiebach, Vos, Friederici, & Fiebach, 2004; Waters, Caplan, Alpert, & Stanczak, 2003). In Chapter II, we reported differences in neural organization for online syntactic processing between two groups of monolingual native speakers of English who were classified as higher or lower proficiency based on their scores on standardized tests of English, using a paradigm which employed auditorily presented phrase structure violations in simple, single-clause sentences which incurred low demands on working memory resources. These effects of proficiency between groups on neural organization for syntactic processing were confirmed by a correlational analysis across a wide range of proficiency scores. The results from Chapter II raise the hypothesis that proficiency differences indexed by modulations of ERP components which index syntactic processing will also be reflected in modulations of activation in an fMRI study using a similar paradigm. This also raises the hypothesis that individual modulations of ERP components can be used as covariates in an analysis of fMRI data from the same participants and thereby provide further insight into the neural generators of these components related to syntactic processing. Here we seek to explore these hypotheses and expand our findings from a methodology with excellent temporal resolution, ERPs, to a complementary methodology with excellent spatial resolution, fMRI. To this end, the present experiment employed the same auditorily presented phrase structure violations from our previous study in an event-related fMRI design. Participants were prescreened using the same behavioral measures used in Chapter II, and data from those with proficiency scores falling into the upper or lower quartile on standardized tests were gathered in both ERP and fMRI paradigms.

Neuroimaging studies of syntactic processing

Findings from neuroimaging studies of syntactic processing reveal a general degree of overall agreement but also a great deal of heterogeneity across studies. Generally the results provide support for the role in language processing of left perisylvian regions first identified with the advent of research on the relationship between brain and language in the middle of the 19th century. It was then that Paul Broca and Karl Wernicke linked brain lesions in specific areas to specific language deficits known collectively as aphasia (Goodglass, 1993). Deficits in speech production characterized by a lack of closed-class words and grammatical morphemes were linked to lesions in the left inferior frontal gyrus (LIFG), known as "Broca's area", while deficits in comprehension characterized by the production of fluent, grammatical speech lacking semantic content were associated with lesions in the left posterior superior temporal gyrus (STG) at the tempo-parietal junction, known as "Wernicke's area". This dissociation led to the assignment of a primary role for syntactic processing to Broca's area, and for semantic processing to Wernicke's area. However, subsequent aphasia research suggested that this model was inadequate and insufficient to account for the range of deficits and lesions identified by advances in language pathology research (for a review, see Dronkers & Larsen, 2001). Neuroimaging studies of language processing have provided further evidence that such a model is inadequate, and neuroimaging studies of syntactic processing specifically have reinforced the idea that the neural substrates underlying syntactic processing are not limited to the LIFG. Overall, the data suggest that syntactic processing is distributed over a number of neural areas largely across classical left perisylvian regions but also including a wider range of frontal, temporal, and parietal regions as well as right hemisphere regions.

Several different types of paradigm have been used in neuroimaging studies of syntactic processing. One of the first such paradigms involved a comparison between word lists or consonant strings which do not have syntactic structure and sentences. The most consistent result from these studies is increased activation for the processing of sentences in superior and/or middle temporal areas both posteriorally and anteriorally, with some studies reporting left-lateralized activation (Bavelier et al., 1997; Humphries, Binder, Medler, & Liebenthal, 2006; Mazoyer, Tzourio, Frak, Syrota, & et al., 1993; Neville et al., 1998; Stowe et al., 1998; Stowe et al., 1999) and others reporting left-lateralized posterior temporal activation and bilateral anterior temporal activation (Friederici, Meyer, & von Cramon, 2000; Mazoyer et al., 1993) or increased right hemisphere activation when deaf native signers were processing sentences in American Sign Language (Neville et al., 1998). Additionally, while some studies reported increased activation in left inferior frontal areas for the processing of sentences (Bavelier et al., 1997; Neville et al., 1998), others did not (Friederici, Meyer et al., 2000; Humphries et al., 2006; Mazoyer et al., 1993; Stowe et al., 1998; Stowe et al., 1999).

Another design which has been used to examine syntactic processing using neuroimaging techniques is the comparison of the processing of normal sentences with Jabberwocky sentences, which have intact syntactic structure with pronounceable pseudowords, or syntactic prose sentences, which have intact syntactic structure but no coherent semantic context. By disrupting sentence-level semantic processing, or in the case of Jabberwocky, word-level semantic processing, such paradigms are thought to provide a more pure manipulation of syntactic processing. Additionally, with the reduction in semantic cues which might aid in syntactic processing in normal circumstances, such paradigms might engage neural areas underlying syntactic processing to a greater extent. The most consistent result from studies using this manipulation is increased activation to Jabberwocky sentences in anterior temporal regions bilaterally (Friederici, Meyer et al., 2000; Mazoyer et al., 1993; Meyer et al., 2000). Less consistency was found across studies for other areas, as some studies reported increased activation for Jabberwocky in LIFG (Friederici, Meyer et al., 2000) or in the bilateral deep frontal operculum (Meyer et al., 2000), and one study reported activation in LIFG and superior and middle temporal areas that was greater for normal language (German) than for Jabberwocky sentences (Röder, Stock, Neville, Bien, & Rösler, 2002).

Other neuroimaging studies have used a manipulation to increase the focus on syntactic processing which involves the comparison of syntactically more simple sentences compared to sentences of higher syntactic complexity. The logic is that the processing sentences of higher syntactic complexity involves additional syntactic operations, and therefore areas which show increased activation to these complex sentences should be areas which mediate syntactic processing. Such paradigms also often involve a confound with working memory, as processing syntactically more complex constructions such as those used in such paradigms (e.g., object relative clauses compared to subject relative clauses) also involves a higher working memory load. Many studies which have used such a manipulation have reported increased activation with increases in syntactic complexity in LIFG (Ben-Shachar, Hendler, Kahn, Ben-Bashat, & Grodzinsky, 2003; Ben-Shachar, Palti, & Grodzinsky, 2004; Caplan, Alpert, & Waters, 1998; Caplan, Alpert, Waters, & Olivieri, 2000; Caplan & Waters, 1999; Constable et al., 2004; Keller, Carpenter, & Just, 2001; Michael, Keller, Carpenter, & Just, 2001; Röder et al., 2002; Stowe et al., 1998; Stromswold et al., 1996) or bilateral IFG (Fiebach, Schlesewsky, Lohmann, von Cramon, & Friederici, 2005; Just et al., 1996). Several of these studies also reported increased activation in left posterior superior and middle temporal regions (Constable et al., 2004; Keller et al., 2001; Michael et al., 2001; Röder et al., 2002; Stowe et al., 1998) or bilateral superior and middle temporal regions (Ben-Shachar et al., 2003; Ben-Shachar et al., 2004; Fiebach et al., 2005; Just et al., 1996).

With the recent development of paradigms for use in PET and fMRI studies which feature randomly intermixed trials, the use of violation paradigms such as those commonly used in ERP studies of language processing has become more prevalent. The more traditional blocked design does not lend itself to the study of syntactic violations, as processing a series of violations presented in a block renders them predictable and thus likely engages different processes than those necessary to processes unpredictable violations in an event-related design. Overall, results from studies using syntactic violation paradigms are more heterogeneous than results from other neuroimaging studies using different paradigms, likely to some degree due to greater overall inconsistency across studies, in particular with respect to the use of different violation types. Early studies of syntactic violations using block designs reported increased activation for violations in bilateral IFG, left superior temporal areas, and left angular gyrus and supramarginal gyrus (Embick, Marantz, Miyashita, O'Neil, & Sakai, 2000), left inferior temporal regions to syntactic as well as semantic and pragmatic violations (Kuperberg et al., 2000), and bilateral IFG to phrase structure and morphosyntactic violations, with unique activation for phrase structure violations in the insula and basal ganglia of the left hemisphere (Moro et al., 2001). Studies using event-related designs have reported increased activation for violations in bilateral IFG and superior and middle temporal regions (Ni et al., 2000); left posterior STG (Meyer et al., 2000), and bilateral superior frontal cortex, left insula, and right anterior STG (Newman, Pancheva, Ozawa, Neville, & Ullman, 2001); left middle frontal gyrus (for the processing of Jabberwocky violations) (Indefrey, Hagoort, Herzog, Seitz, & Brown, 2001); LIFG (Suzuki & Sakai, 2003); left posterior and anterior STG, left basal ganglia, and left frontal operculum (Friederici et al., 2003); and bilateral parietal regions (Kuperberg et al., 2003). A recent study by Friederici and colleagues (Friederici, Fiebach, Schlesewsky, Bornkessel, & von Cramon, 2006) provided evidence for a dissociation of activation within inferior frontal areas by directly comparing the neural response to sentences of varying complexity with the response to syntactic violations. A core region of LIFG, the pars opercularis, was found to be activated parametrically with increases in complexity while syntactic violations elicited activity in a more posterior inferior frontal area, the left deep posterior frontal operculum. Violations also elicited increased activity in the right intraparietal sulcus, consistent with other evidence that parietal regions may play a role in the processing of syntactic violations (Embick et al., 2000; Kuperberg et al., 2003).

ERP studies of syntactic processing using violations typically report a biphasic response in which an earlier negativity, often maximal over left anterior sites, is followed by a later positivity usually maximal over posterior sites (P600) (for a review, see Friederici, 2002). Research concerning the neural generators of these components has focused on studies which use the same stimulus materials previously shown to elicit these ERP effects, using either dipole modeling of data from magnetoencephalography (MEG) or ERP studies of patients with focalized brain lesions (for a review, see Friederici & Kotz, 2003) Results from a MEG study using dipole modeling of the magnetic equivalent of the early anterior negativity suggest that activation in the frontal operculum, adjacent to IFG, and anterior STG in fMRI studies bilaterally, but larger in the left hemisphere, may reflect the neural generators of this component (Friederici, Wang, Herrmann, Maess, & Oertel, 2000). Studies of patients with lesions in the anterior temporal lobe and the basal ganglia (e.g., Kotz, Frisch, von Cramon, & Friederici, 2003) support this interpretation and further suggest that the basal ganglia may modulate syntactic processes indexed by the P600. Based on results from the fMRI study discussed above using the same stimulus materials (Friederici et al., 2003), a recent model also hypothesizes that posterior STG supports processes of syntactic integration which the P600 is hypothesized at least in part to reflect (Grodzinsky & Friederici, 2006). While differences in temporal resolution limit the degree to which fMRI results can address the question of the neural origins of ERP components related to syntactic processing, gathering ERP and fMRI data from the same participants in a similar paradigm raises a possibility which has yet to be explored. With ERP and fMRI data from the same participants, individual modulations in these components, quantified by average difference amplitude across different electrode sites and time windows, can be used as covariates in the analysis of fMRI data from the same participants to shed further light on the neural underpinnings of these components. In this experiment we explored this possibility by gathering ERP and fMRI data from participants with extreme scores on measures of proficiency which were shown in Chapter II to modulate the ERP response to syntactic violations.

Neuroimaging studies of individual differences

Only three published studies have examined individual differences using neuroimaging paradigms, and all have used manipulations of complexity. Two PET studies from the same laboratory (Caplan et al., 2003; Waters et al., 2003) compared the processing of less complex subject relative clause sentences and more complex object relative sentences and compared groups which either differed in working memory span but were matched for speed of syntactic processing, as measured by a timed behavioral grammaticality judgment task, or were matched on working memory span but differed on speed of processing. No differences were found for groups differing on working memory span, as greater complexity resulted in increased activation in bilateral inferior frontal areas for both groups. However, differences were found with respect to speed of processing. While fast-performing participants showed a similar increase in activation in bilateral inferior frontal areas with increases in complexity, slow-performing participants showed an additional increase in activation in left superior temporal areas. The authors interpret these findings as evidence that regions involved in the processing of syntactic complexity may be differentially recruited by participants who differ on rate of syntactic processing, though more research is clearly needed in this area. Fiebach and colleagues (Fiebach et al., 2004) used fMRI to examine the processing of sentences with either short or long regions of temporary syntactic ambiguity in two groups of participants who varied in working memory span. Consistent with previous results, increases in working memory and syntactic processing demands with the processing of long regions of ambiguity resulted in increased activation in LIFG, as well as in intraparietal sulcus. An interaction with working memory span was found in LIFG, as only low span participants showed increased activation with greater complexity in this region, suggesting that this area is also sensitive to differences in syntactic processing difficulty which may be the result of individual differences in available working memory capacity. While it is interesting to note that two studies found no interaction with complexity and working memory span and one did, it would be premature to draw strong conclusions solely on the basis of three published studies.

The only neuroimaging studies to directly assess proficiency have examined differences in second language proficiency, and with mixed results: studies which have directly compared age of acquisition and proficiency have found evidence in favor of a stronger role for both age of acquisition (Wartenburger et al., 2003) and ultimate proficiency (Perani et al., 1998) in the neural organization of second language processing, though these studies did not use paradigms which specifically assessed syntactic processing.

Individual differences and effects of experience

Several studies of both monolingual native speakers and of bilinguals suggest that language experience may affect linguistic proficiency and related neural systems. Behavioral studies of language development in native speakers of English report that parents who talk more to their children tend to have children with larger vocabularies (Hart & Risley, 1995) and tend to have children who score higher on tests of syntactic comprehension(Huttenlocher et al., 2002). While these effects could be the result of genetic differences, some evidence suggests effects specific to language experience: teachers who use more complex speech in preschool classrooms tend to have students who score higher on tests of syntactic comprehension (Huttenlocher et al., 2002). ERP studies of monolingual children suggest that brain organization is predicted by language knowledge: children with larger vocabularies (Mills et al., 1993) and children who score higher on tests of language comprehension (Adamson-Harris et al., 2000) show more mature patterns of brain organization for language, including greater focalization, as compared with children with smaller vocabularies or those who score lower on comprehension tests. ERP studies of deaf adults suggest that early effects of language experience can endure into adulthood, as individuals exposed to American Sign Language (ASL) from an early age recruit right hemisphere areas in addition to left hemisphere language areas when processing ASL, but those not exposed to ASL at an early age do not show this bilateral response to ASL and score lower on tests of ASL grammar (Neville, Coffey, Lawson, Fischer, & et al., 1997; Newman et al., 2002; Newport, 1990). ERP studies of bilinguals suggest that linguistic subsystems are differentially sensitive to effects of age of acquisition, with the syntactic subsystem displaying less focal neural organization with delays in second language exposure as short as 4-6 years, while the semantic subsystem appears to be affected by delays in second language exposure only after 11-13 years of age (Weber-Fox & Neville, 1996). Similar results have been observed for native and late learners of ASL (Capek et al., 2002).

Data from two ERP experiments suggest that significant differences in proficiency exist in monolingual adults and are linked to altered neural organization as indexed by ERPs. In a visual sentence processing paradigm, Weber-Fox, Davis, and Cuadrado (Weber-Fox et al., 2003) compared the brain response to visually presented semantic violations in participants who scored either exceptionally high or in the normal range on four subtests of the Test of Adult and Adolescent Language-3 (TOAL-3), a standardized assessment of English language proficiency. While no differences were found to early components indexing perceptual processing or to open-class words, high proficiency participants had an earlier N280 to closed-class words over left anterior regions, suggesting more rapid lexical access to words carrying grammatical information in these participants.

In Chapter II we reported results from a study in which we examined differences in the neural response to auditory phrase structure violations in English sentences in two groups of monolingual native speakers of English who were classified as higher or lower proficiency based on their scores on the TOAL-3. Violations elicited a typical biphasic response in both groups, but there were differences in this response between groups. In English this effect was spatially and temporally more focal in the left hemisphere in the higher proficiency group but more widely distributed in the lower proficiency group, and the P600 effect was larger in amplitude and more broadly distributed in higher proficiency participants compared to lower proficiency participants. These effects of proficiency on neural organization for syntactic processing were confirmed by a correlational analysis across a wide range of proficiency scores.

The present study

Here we further explore the relationship between proficiency and neural organization for language in monolingual native speakers by expanding the ERP research presented in Chapter II to the fMRI methodology, making use of the complimentary spatial and temporal resolution of these techniques. Here, as in Chapter II, we maximized proficiency differences by recruiting participants from a wide spectrum of society and selected participants with scores which were similar to those from Chapter II; i.e., at or near the upper and lower quartiles on standardized tests of English proficiency. These participants formed Higher Proficiency (HP) and Lower Proficiency

(LP) groups, and both ERP and fMRI data were collected from participants in both groups. We minimized the effects of other potential cognitive resource limitations such as WM by using a paradigm which examined the neural response to phrase structure violations in simple, single-clause sentences presented auditorily. In order to make the paradigm as comparable as possible across the two methodologies, we employed an event-related design featuring the same stimulus presentation parameters used in our previous ERP study. We assessed the effects of proficiency on the BOLD response to syntactic violations using two complementary approaches. In the first approach, we conducted an analysis with a direct group comparison to identify regions of differential activation in processing violations in the HP group compared to the LP group, and vice versa. In the second, we included individual proficiency scores as covariates to identify regions which correlated with individual differences in proficiency. We also utilized data collected from the same participants in both ERP and fMRI paradigms to investigate the neural generators of ERP indices of syntactic processing. This was examined by taking advantage of proficiency-related modulations in the ERP response to syntactic violations, as discussed in Chapter II. By including individual average difference amplitude measures across different areas and time windows as covariates in group-level fMRI analyses, we identified brain regions which likely contribute to different and specific electrophysiological responses to syntactic violations.

The fMRI results from previous studies discussed above, along with results from Chapter II, raised specific hypotheses for the current study. We predicted that violations would elicit a distributed pattern of activation in left perisylvian areas, and possibly additional frontal, parietal, and right hemisphere areas as well. We also predicted that the ERP modulations of neural activity related to proficiency discussed in Chapter II would also be reflected in differences in the BOLD response to syntactic violations. A characteristic difference between proficiency groups in Chapter II was an extended bilateral anterior negativity in lower proficiency participants. Therefore we hypothesized that differences between groups in the neural response to syntactic violations in the fMRI paradigm would be observed over right hemisphere and/or anterior medial regions. Another prediction related to the results presented in Chapter II is that higher proficiency participants would show increased neural activity relative to lower proficiency participants over posterior regions likely to be involved in the generation of the P600 component. While, as discussed above, evidence on the neural generators of ERP indices of syntactic processing is scant, based on the evidence which exists we predicted that individual modulations in the early anterior negativity would be reflected in inferior frontal and anterior superior temporal areas, including frontal operculum, anterior STG, and possibly IFG. Previous evidence suggests that P600 modulations may correlate with activation in both anterior and posterior temporal lobe and parietal areas as well as the basal ganglia, though here again the evidence is scant. In general, the neural regions which underlie ERP indices of syntactic processing are not well known, and our approach will provide convergent evidence bearing on this issue.

Method

Participants

Right-handed, normal hearing, native, monolingual speakers of English without known neurological disorders, recruited from both the university and non-university populations, participated in the study. Participants were paid for their time. A total of 67 participants were run in the behavioral testing paradigm described below, which employed the same measures as in Chapter II. From these participants, 24 were selected based on behavioral performance to form Lower Proficiency (LP; N = 12) and Higher Proficiency (HP; N = 12) groups. An average standardized score for the three subtests of the Test of Adolescent and Adult Language-3 (TOAL-3) (Hammil et al., 1994) was calculated for all participants, and only participants whose average standardized score fell above or below a benchmark average score calculated from scores from our previous experiment (roughly below the 25th percentile on average for the LP group, above the 75th percentile on average for the HP group) were retained for the full experiment. With the exception of one participant from the Lower Proficiency group whose ERP data were excluded due to excessive artifact, all participants in this study were a subset of those included in the correlational analyses described in Chapter II.

Behavioral Language Inventories

Three behavioral tests were administered to assess linguistic proficiency: two grammar subtests of the TOAL-3 and the Saffran and Schwartz Grammaticality Judgment Test (Linebarger et al., 1983). The TOAL-3 Listening/Grammar subtest requires participants to determine, out of three sentences presented auditorily, which two sentences have similar meaning. The TOAL-3 Speaking/Grammar subtest requires participants to repeat exactly sentences said by the examiner. The sentences gradually increase in syntactic difficulty. The Saffran and Schwartz Grammaticality Judgment Test is a 78-item assessment in which participants are asked to judge the grammaticality of sentences containing a variety of syntactic violations, adapted for purposes of this study into the auditory modality. To assess working memory capacity, participants were also given the Carpenter Reading Span Test (Daneman & Carpenter, 1980), a widely-used assessment in which participants must recall the final word of two or more sentences after reading them consecutively.

Stimuli

In both the ERP and fMRI paradigms, participants heard both English sentences and Jabberwocky sentences, in which open-class words were replaced with pronounceable nonwords to greatly reduce the semantic context; only the results for the English stimuli are presented here. The English stimuli were sentences which were canonical (50%) or which contained an insertion phrase structure violation (50%) in which an additional closed-class word was inserted in a sentence-final prepositional phrase. In all cases, the phrase structure violation clearly occurred at the onset of either a demonstrative (50%) or possessive (50%) pronoun directly following the inserted pronoun. The blood oxygen-level-dependent (BOLD) response to the onset of the target word (underlined below) in the canonical and violation (*) sentences were compared:

Timmy can ride the horse at his farm.
*Timmy can ride the horse at my his farm.

All sentences were recorded using SoundEdit 16 Version 2 with 16-bit resolution and a 16 Khz sampling rate then transferred to a PC for presentation. The sentences were spoken by a female with natural tempo and prosody and critical word onsets were identified and coded by three trained coders using both auditory cues and visual inspection of sound spectrographs for increased accuracy. Any sentences in which codes differed by more than 20 milliseconds between coders were re-coded by all three coders together until a consensus was reached by all three to ensure reliability.

Procedure

Standardized tests of language were administered in a separate session to determine eligibility for the full experiment. In addition to the fMRI paradigm, participants were also run in the same ERP paradigm; details of the procedure and acquisition parameters for the ERP paradigm are as described in Chapter II. Eligible participants then returned for three separate sessions on separate days, with no more than a month elapsing between the first and last session. One session consisted of ERP data acquisition; in this session participants also completed an information sheet which included questions about education, socioeconomic status, handedness, neurological history, and language habits. fMRI data were gathered in two separate sessions on separate days to minimize participant fatigue, necessary because an additional language paradigm was also used. Results from this paradigm, which employs semantic and syntactic violations in a narrative context, will be discussed elsewhere. fMRI sessions were always consecutive (i.e., both before or both after the ERP session), and the order of initial session was counterbalanced across participants. Three blocks of stimuli sentences were created so that no sentences were repeated across sessions.

In each fMRI session participants were first given instructions outside of the magnet. These instructions included hearing examples of both sentence types and emphasized the need to judge the sentences based on grammatical, and not semantic, correctness, as well as instructions emphasizing the need to restrict head movement were also given. Participants were then placed comfortably in the magnet, with head movement restricted using a vacuum pillow and side cushioning. Sentences were presented via etymotic earphones inserted directly into the ear canal, with magnet noise suppressed by a headphone-like hearing protection device placed over the ears. On each trial, participants pushed one of two buttons on a response box in the right hand to play a sentence. While the sentences were playing a box with a central fixation cue ('*') was displayed on a projected image viewed through a mirror attached to the MRI head coil. After each sentence, participants were cued to make a judgment with a display of "Yes or No?" on the projector screen. The judgment was made by button press with either the index or middle finger, counterbalanced across participants and kept constant across sessions for each participant. After each judgment participants were cued with a display of "Ready" to play the next sentence; participants were instructed to play the next sentence as soon as they were ready. The use of a self-paced paradigm allowed for a closer approximation of the conditions of ERP acquisition, as well as providing variable jitter in the response timing. This also meant that critical trials were temporally overlapping to various degrees. Based on the work of Miezin and colleagues (Miezin, Maccotta, Ollinger, Petersen, & Buckner, 2000) showing that an increase in the number of trials can provide more statistical power despite small decreases in the hemodynamic due to temporally overlapping trials, we used a paradigm with temporal overlap. Based on power analyses by that group we calculated that 80 trials per condition would provide sufficient power with the variable degree of temporal overlap in our paradigm.

Each fMRI session consisted of seven functional blocks: four blocks of the auditory sentence paradigm described above and three blocks of the additional narrative context paradigm. Each auditory sentence block consisted of 46 sentences (including filler sentences and probe questions) and was preceded and followed by 30-second periods during which the central fixation cue was presented with no stimuli to provide hemodynamic baseline data; participants were instructed to relax, remain still, and maintain fixation on the cue during these periods.

fMRI Acquisition and Analysis

MRI data were acquired at the University of Oregon Lewis Center for Neuroimaging. Imaging was carried out on a Siemens Allegra 3-Tesla magnetic resonance imaging system (Siemens Medical Systems, Erlangen, Germany) using a transmit/receive volume head coil with a field of view covering the entire neocortex. A typical scanning session began with an auto-alignment scan followed by a T2-weighted three-plane multi-slice anatomical localizer. Blood oxygen level dependent (BOLD) images were acquired with a gradient-echoplanar imaging sequence (32 slices, interleaved acquisition, 3 mm^2 in-plane resolution, 4 mm thickness, no inter-slice gap, TR = 2000 ms, TE = 30 ms). Slices were oriented in the transverse plane roughly parallel with the base of the brain, including the cerebellum. Functional scans were variable in length, as the task was participant-paced, with a maximum length of 390 seconds (195 acquisitions). Each scanning session consisted of four independent functional runs for this paradigm, interleaved with three functional runs for the narrative context paradigm (average length approximately 500 seconds/250 acquisitions) and one high-resolution anatomical scan (first session; T1-weighted gradient echo, TR = 1570 ms, TE = 3 ms, 1 mm slice thickness) or diffusion tensor imaging scan (second session). On each visit, participants typically spent 60-75 minutes in the scanner. A total of five functional runs were excluded from this analysis: one due to excessive participant head motion , one due to a technical problem with acquisition, and three because one participant requested to leave the scanner before the end of the experimental session.

Data analysis was carried out using FEAT (FMRI Expert Analysis Tool) Version 5.63, part of FSL (FMRIB's Software Library, www.fmrib.ox.ac.uk/fsl). The following pre-statistics processing was applied; motion correction using MCFLIRT (Jenkinson, Bannister, Brady, & Smith, 2002); non-brain removal using BET (Smith, 2002) spatial smoothing using a Gaussian kernel of FWHM 5mm; mean-based intensity normalization of all volumes by the same factor; highpass temporal filtering (Gaussian-weighted least-squares straight line fitting, with sigma = 30.0s). Time-series statistical analysis was carried out using FILM with local autocorrelation correction (Woolrich, Ripley, Brady, & Smith, 2001). Z statistic images were thresholded using clusters determined by $z > 2.3$ and a (corrected) cluster significance threshold of $p = .05$ (Worsley, Evans, Marrett, & Neelin, 1992). Registration to high resolution images was carried out using FLIRT

(Jenkinson et al., 2002; Jenkinson & Smith, 2001). Second-level analysis was carried out using a fixed effects model, by forcing the random effects variance to zero in FLAME (FMRIB's Local Analysis of Mixed Effects) (Beckmann, 2003; Woolrich, Behrens, Beckmann, Jenkinson, & Smith, 2004). Higher-level analysis was carried out using FLAME (FMRIB's Local Analysis of Mixed Effects) stage 1 only (i.e., without the final MCMC-based stage) (Beckmann, 2003; Woolrich et al., 2004). Results from the general linear model analysis were interpreted by inspecting event-related averages of significant clusters using the Perl Event-related Average Timecourse Extraction program (http://www.jonaskaplan.com/peate/index.html).

Three types of analysis are reported here. First, we conducted a whole-brain analysis in all participants employing a direct comparison of phrase structure violation effects (violation > canonical), using clusters determined by $z > 2.58$ ($p < .005$, uncorrected), with a minimum cluster size of 20 voxels to guard against Type I error. Second, we analyzed proficiency effects by directly assessing group differences. We compared areas in which activation to violations was greater in HP participants than in LP participants to areas in which activation to violations was greater in LP participants than in HP participants. Third, we used a correlational approach in which the demeaned proficiency score (composite standardized score from three measures of the TOAL-3) was used as a covariate in the general linear model, as well as the modeled (expected ideal) hemodynamic response from the stimuli time course. The statistic derived is based on how well the behavioral measure correlates with each subjects average estimated response (beta value) to the condition of interest. If participant fMRI responses are correlated with their behavioral measure, the behavioral covariate will explain some fraction of the total variance of the fMRI signal. The statistical maps show for which voxels the covariate explained a significant fraction of the response. While the same threshold was used for this analysis, a more liberal minimum cluster size of 10 voxels was employed. An additional analysis using this correlational approach explored possible neural generators of ERP components related to syntactic processing by using as covariates individual average ERP difference amplitude (violation – canonical), calculated over several regions and time windows motivated by the ERP results from Chapter II: anterior sites over both hemispheres in the 100-300, 300-700, and 700-1200 ms time windows, and posterior sites in the 300-1000 ms time window. For this exploratory ERP component analysis, a more liberal threshold of $z > 1.96$ ($\underline{p} < .025$) was used. This correlational approach yielded statistical maps which showed whether any given voxel covaried with the individual average difference amplitude. Anatomical regions for significant clusters were defined using the Harvard-Oxford cortical structural atlas (Harvard Center for Morphometric Analysis, http://www.cma.mgh.harvard.edu/) and the Tailarach Demon application (Research Imaging Center, University of Texas Health Science Center at San Antonio (http://ric.uthscsa.edu/td_applet/), using peak statistic voxel coordinates.

Results

Behavioral Results

Lower Proficiency (LP) and Higher Proficiency (HP) groups were determined by standardized scores on the three TOAL-3 subtests used as described in the methods section. The mean average standardized scores for the resulting LP (M = 8.46, SD = 1.45) and HP (M = 13.63, SD = 0.95) groups were statistically independent ($t(22) = 10.33$, $p < .0001$). The mean scores for each behavioral measure are displayed in Table 4.1. While all participants were within normal limits for native speakers, the groups were distinct in terms of TOAL-3 standardized scores: the mean scores for the LP group were at or below the 37th percentile on each subtest while the mean scores for the HP group were at or above the 84th percentile for each subtest. The LP and HP groups in this study were also not statistically different on any of these variables from the LP and HP groups in Chapter II.

In the grammaticality judgment task performed during fMRI acquisition, there was no difference in performance between groups ($t(22) = 1.529$, NS). Scores on measures used to insure that participants were listening to the entire sentence indicated that this was indeed the case. The HP group answered 98.96% of the English probe questions correctly and the LP group answered 95.68% of the questions correctly ($t(22) = 1.541$, NS).

Relationships between proficiency and other factors were observed. Proficiency scores correlated with working memory span ($r = .522$, $p < .005$) and socioeconomic status of the family in which participants were raised until 18 years of age as calculated using the Hollingshead Four Factor Index of Social Status (Hollingshead, 1975) ($r = .435$, $p < .05$). The correlation between proficiency and education level was not significant.

Table 4.1

Mean scores on behavioral measures of proficiency and working memory.

Group	TOAL-3 L-V***	TOAL-3 L-G***	TOAL-3 S-G**	Saffran and Schwartz+	Carpenter Span*
HP					
(n = 12, 7 F)					
M	30.50	33.08	23.42	75.83	3.33
(SD)	(2.54)	(2.27)	(1.50)	(1.19)	(.86)
Range	26-35	28-35	21-25	74-78	2-5
Percentile	84	84	91	N/A	N/A
LP					
(n = 12, 5 F)					
M	23.33	17.92	18.08	74.75	2.66
(SD)	(5.10)	(4.10)	(4.76)	(1.96)	(.39)
Range	14-29	11-24	8-23	71-78	2-3
Percentile	37	25	25	N/A	N/A

* = $p < .05$, ** = $p < .01$, *** = $p < .0001$, + = $p = .116$

ERP and fMRI results: Effects of Proficiency

The main focus of this chapter is on the results from the fMRI analysis in relation to proficiency. In addition, a preliminary analysis is presented employing the ERP data from these participants to investigate links between proficiency-related variability in separate ERP components and activations in fMRI.

ERP results

The ERP results from these participants are generally consistent with those reported for all 72 participants in Chapter II, suggesting similar relationships in this data

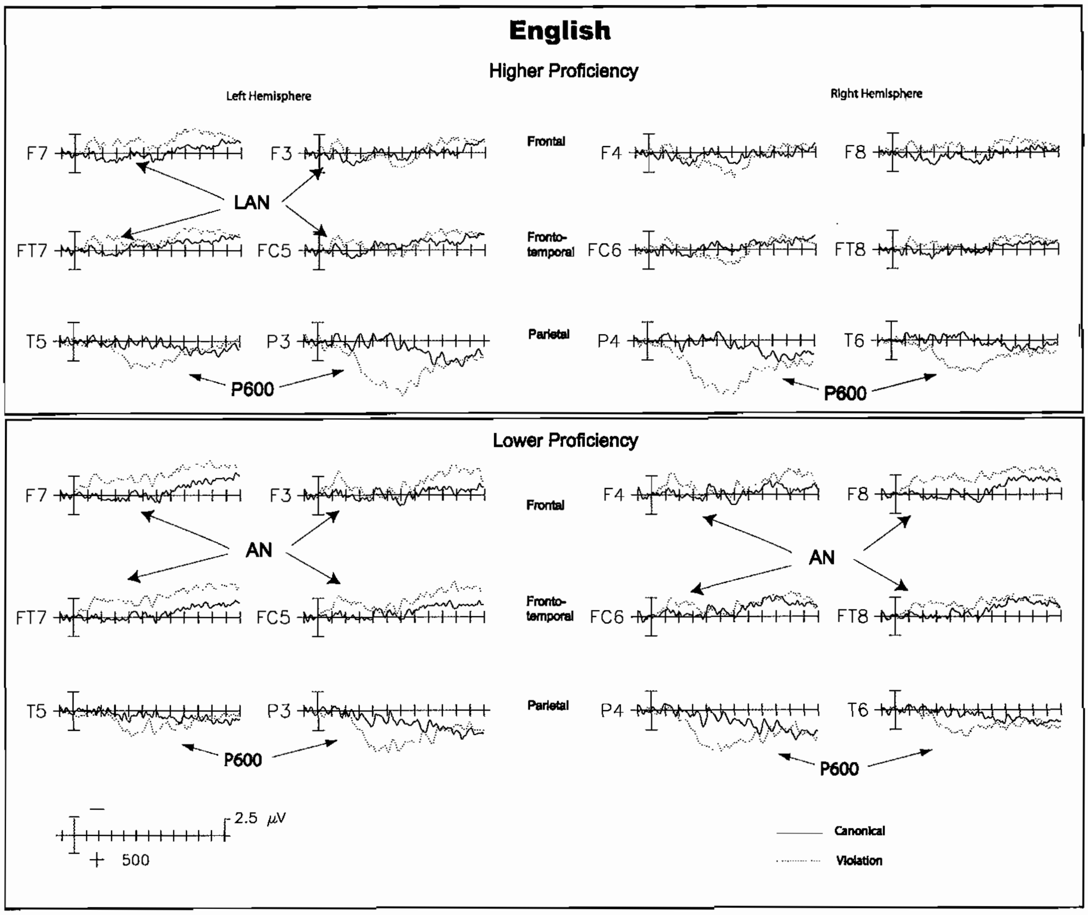

Figure 4.1. ERPs to English phrase structure violations for HP (N = 12) and LP (N = 11) groups in the fMRI analysis, showing representative electrode rows illustrating the anterior negativity (frontal and fronto-temporal) and P600 (parietal) effects.

set (Fig. 4.1). However, as the number of participants is only one third that of Chapter II, the results are statistically weaker. In the 100-300 ms time window, the relationship between proficiency and average difference amplitude over right anterior medial sites did not reach significance. Since this relationship was not as statistically strong as the other relationships with proficiency discussed in Chapter II, this suggests that this relationship is only apparent with larger numbers of participants and more variability in proficiency. However, a partial correlation controlling for proficiency, working memory span, and education level revealed a similar but weaker relationship between SES and left anterior average difference amplitude between 100-300 ms (r = -.300, p = .099), with higher SES participants tending to show a larger negativity in this time window over left anterior sites, as observed in Chapter II. In the 300-700 ms time window, near significant partial correlations were observed between proficiency and average difference amplitude over left (r = .357, p = .069) and right (r = .375, p = .052) anterior sites, revealing that violations tended to elicit a positivity over anterior sites in this time window in the HP group but a negativity in the LP group as in Chapter II. In the 700-1200 ms time window, a near significant partial correlation was observed between proficiency and average difference amplitude over left anterior sites (r = .349, p = .066), reflecting the tendency for the negativity to be prolonged over this time window in LP participants, again consistent with the results from Chapter II; however, this relationship did not approach significance over right anterior sites. In the 300-1000 ms time window over posterior sites, there was a near significant partial correlation between proficiency and average difference amplitude ($r = .326$, $p = .074$), reflecting a trend for violations to elicit a larger P600 in HP participants as found in Chapter II.

fMRI Results

All participants

Results from the whole-brain analysis of all participants are displayed in Figure 4.2 and Table 4.2 (all clusters $p < .005$, uncorrected). Consistent with previous neuroimaging studies of syntactic processing, violations elicited a distributed pattern of activation with peak activation in left perisylvian and parietal areas, with less activation also found in homologous right hemisphere areas. The largest clusters of activation were

English violation > canonical (N = 24)

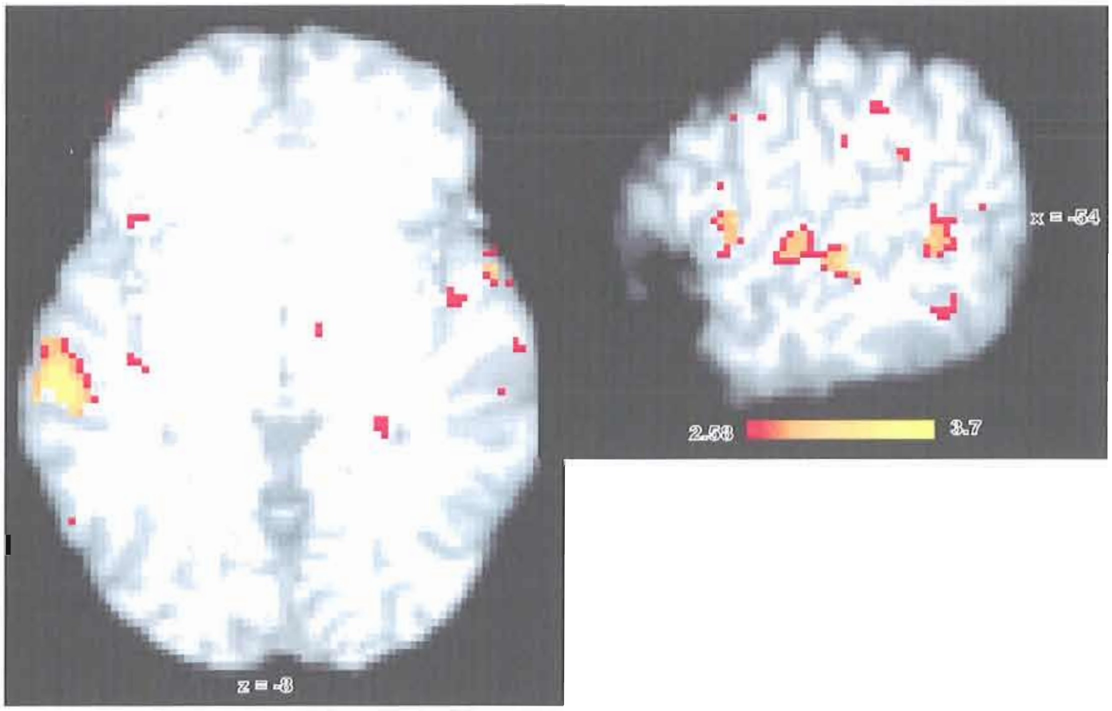

Figure 4.2 Representative axial and left hemisphere sagittal slices showing areas of significant activation for English phrase structure violations.

Table 4.2
Significantly activated clusters from whole-brain analysis for all participants (violation > canonical, p < .005 uncorrected), by region with left hemisphere activations listed first.

				MNI coordinates		
Cortical region*	BA*	Cluster Size	Z-max	x	y	z
Frontal						
L precentral gyrus/MFG	6	57	3.08	-44	-2	60
L precentral gyrus	9	46	3.39	-60	8	22
L IFG (pars orbitalis)	47	40	3.14	-42	20	-10
L frontal pole/MFG	47	37	2.96	-52	44	-12
L precentral gyrus / IFG (pars opercularis)	44	31	3.54	-54	6	8
R frontal pole/MFG	10	44	3.13	52	42	-2
Supplementary motor cortex	6	171	3.62	-8	-2	62
R SFG	6	130	3.65	16	-6	68
	6	44	3.21	-8	-4	50
Temporal						
L posterior STG/MTG	22	511	4.93	-62	-26	-6
L posterior MTG	22	191	3.59	-52	-52	2
L temporal pole / IFG (pars orbitalis)	38/47	98	3.2	-46	16	-10
L planum polare / anterior STG	22	28	2.87	-42	-16	-12
R posterior MTG/STG		125	3.51	56	-34	0
R posterior STG	22	44	3.49	64	-14	0
R planum polare / anterior STG	22	22	2.96	48	0	-10

Table 4.2 con't

Parietal/occiptial						
L superior parietal lobe/ posterior SMG	40	546	3.58	-38	-44	48
L posterior SMG	40	88	4.06	-60	-44	26
L anterior SMG/ postcentral gyrus	40/2	62	3.53	-50	-26	34
L precuneous	31	33	2.90	-12	-64	18
R superior LOC	7	74	2.95	34	-66	60
R postcentral gyrus/ anterior SMG	2/40	49	3.22	38	-32	42
R anterior SMG		20	3.30	56	-28	36
Posterior cingulate	23	34	3.01	-2	-26	26

* Abbreviations: BA: Brodmann area; IFG: inferior frontal gyrus; SFG: superior frontal gyrus; MFG: middle frontal gyrus; STG: superior temporal gyrus; MTG: middle temporal gyrus; SMG: supramaginal gyrus; AG: angular gyrus; LOC: lateral occipital cortex.

in left superior parietal lobe/posterior supramarginal gyrus (SMG; Brodmann area (BA) 40) and left posterior middle temporal gyrus (MTG)/superior temporal gyrus (STG) (BA 21/22). Activations were also observed in left frontal regions including two subregions of left inferior frontal gyrus (LIFG), pars triangularis and pars opercularis (BA 45/44), as well as in adjacent precentral gyrus and middle frontal gyrus (BA 47). Homologous right hemisphere activations included right MTG/STG, SMG, and frontal pole. More central superior activation was also observed in supplementary motor cortex and adjacent right superior frontal gyrus (BA 6).

fMRI differences by proficiency group

Differences in activation related to group differences in proficiency were directly assessed in a group-level analysis comparing areas in which there were significant differences in activation between HP and LP groups. These results are presented in Figure 4.3 and Table 4.3. Differential activation to syntactic violations in the HP > LP comparison was observed in an area encompassing left temporal pole and left IFG pars orbitalis ($\underline{p} < .0008$, uncorrected) while differential activation in the LP > HP comparison was found in right superior frontal gyrus (SFG) ($\underline{p} < .0008$, uncorrected). Inspection of the BOLD response revealed that, while the HP > LP differences reflected greater group activation in the HP group, the LP > HP differences reflected a pattern of differential deactivation such that HP participants showed reduced activation in superior frontal gyrus to violations compared to HP participants. Deactivation in right SFG also correlated significantly with activation in left temporal pole/IFG ($\underline{r} = -.435$, $\underline{p} < .05$).

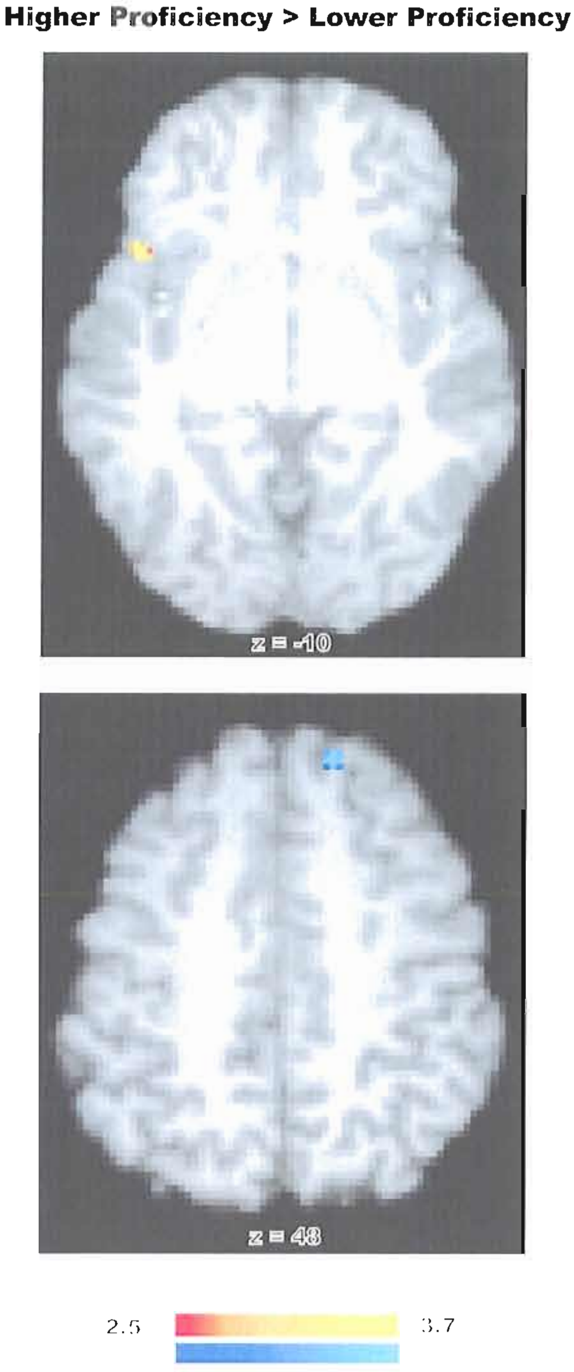

Figure 4.3 Representative slices showing areas of differential activation (violation > canonical; in orange/red) and deactivation (violation > canonical; in blue) in a direct comparison of proficiency groups.

Table 4.3
Significantly activated clusters from the group comparison.

Higher Proficiency > Lower Proficiency

Cortical region	BA	Cluster Size	Z-max	MNI coordinates x	y	z
L temporal pole/ IFG (pars orbitalis)	38/47	20	3.17	-48	16	-10

Lower Proficiency > Higher Proficiency

Cortical region		Cluster Size	Z-max	MNI coordinates x	y	z
R SFG	8	21	3.18	16	46	48

* Abbreviations: BA: Brodmann area; IFG: inferior frontal gyrus; SFG: superior frontal gyrus.

fMRI proficiency differences: Correlational analysis

Differences in neural activation related to proficiency were also examined in a complementary approach in which individual proficiency scores were included as covariates in a group-level analysis. Results from this analysis are presented in Figure 4.4 and Table 4.4. Activation in two left hemisphere regions correlated with individual proficiency scores: left temporal pole/IFG pars orbitalis (BA 38/47) and left posterior MTG (BA 37). Consistent with the results from the group comparison, the correlation in left IFG pars orbitalis/temporal pole was positive ($r = .377$, $p < .05$), as was the correlation with left posterior MTG ($r = .406$, $p < .05$) , showing that HP participants recruited these areas to a greater degree than LP participants. Partial correlations

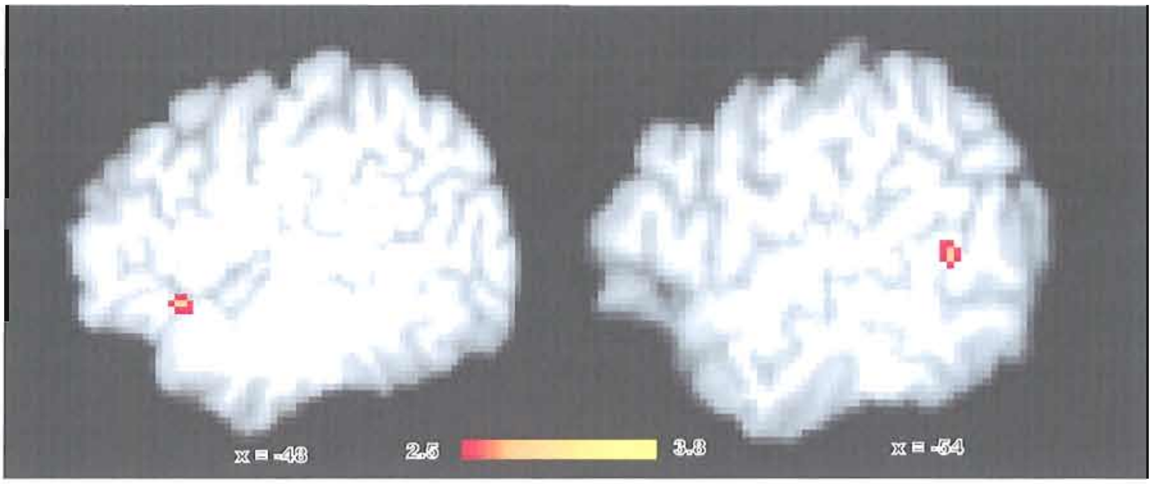

Figure 4.4 Representative slices showing activation correlating with individual proficiency scores.

Table 4.4

Clusters in which activation correlates with individual proficiency scores.

Cortical region*	BA	Cluster Size	Z-max	MNI coordinates x	y	z
L temporal pole/ IFG (pars orbitalis)	38/47	18	3.16	-48	16	-10
L posterior MTG	37	10	3.23	-56	-54	6

* Abbreviations: BA: Brodmann area; IFG: inferior frontal gyrus; MTG: middle temporal gyrus

controlling for the effects of SES, working memory span, and education revealed moderate effects of these variables, though correlations with proficiency still neared significance for both left temporal pole/ IFG pars orbitalis (BA 38/47) ($\underline{r} = .318$, $\underline{p} = .086$) and left posterior MTG ($\underline{r} = .337$, $\underline{p} = .067$). A significant correlation was also observed between activation in these two areas ($\underline{r} = .526$, $\underline{p} < .01$).

ERP components correlational analysis

Given that data were collected from the same participants in both ERP and fMRI paradigms, we conducted preliminary analyses investigating the hypothesis that proficiency-related variation in the ERP response could be linked to particular activations on fMRI, and thereby raise hypotheses regarding the neural generators of ERP indices of syntactic processing. This was done by performing a correlational analysis in which ERP individual difference amplitudes (violation – canonical) were included as covariates in a group-level analysis of fMRI modulations (violation – canonical). The logic of this approach is that modulation (violation – canonical) in areas which contribute to the generation of a given ERP component should covary with that component. The analysis reported here includes all participants. All analyses were conducted at two different threshold levels, a more conservative threshold of $z > 2.33$ ($p < .01$) and a more liberal threshold of $z > 1.96$ ($p < .025$). As expected, results using the more liberal threshold produced a more widespread pattern of activity; as this pattern was interpretable based on a priori hypotheses, results from the analysis using the more liberal threshold are presented here. As shown in Figure 4.5 and Table 4.5, this analysis yielded many significant correlations between fMRI activations and ERP components.

100-300 ms anterior electrodes. The ERP response to violations in the 100-300 ms time window correlated with activation in left IFG pars triangularis/opercularis. This activation was specific to left hemisphere sites, for ERP responses over both left and right anterior sites. Additional clusters of activation were observed in the left temporal pole, suggesting that multiple neural regions contribute to the anterior negativity.

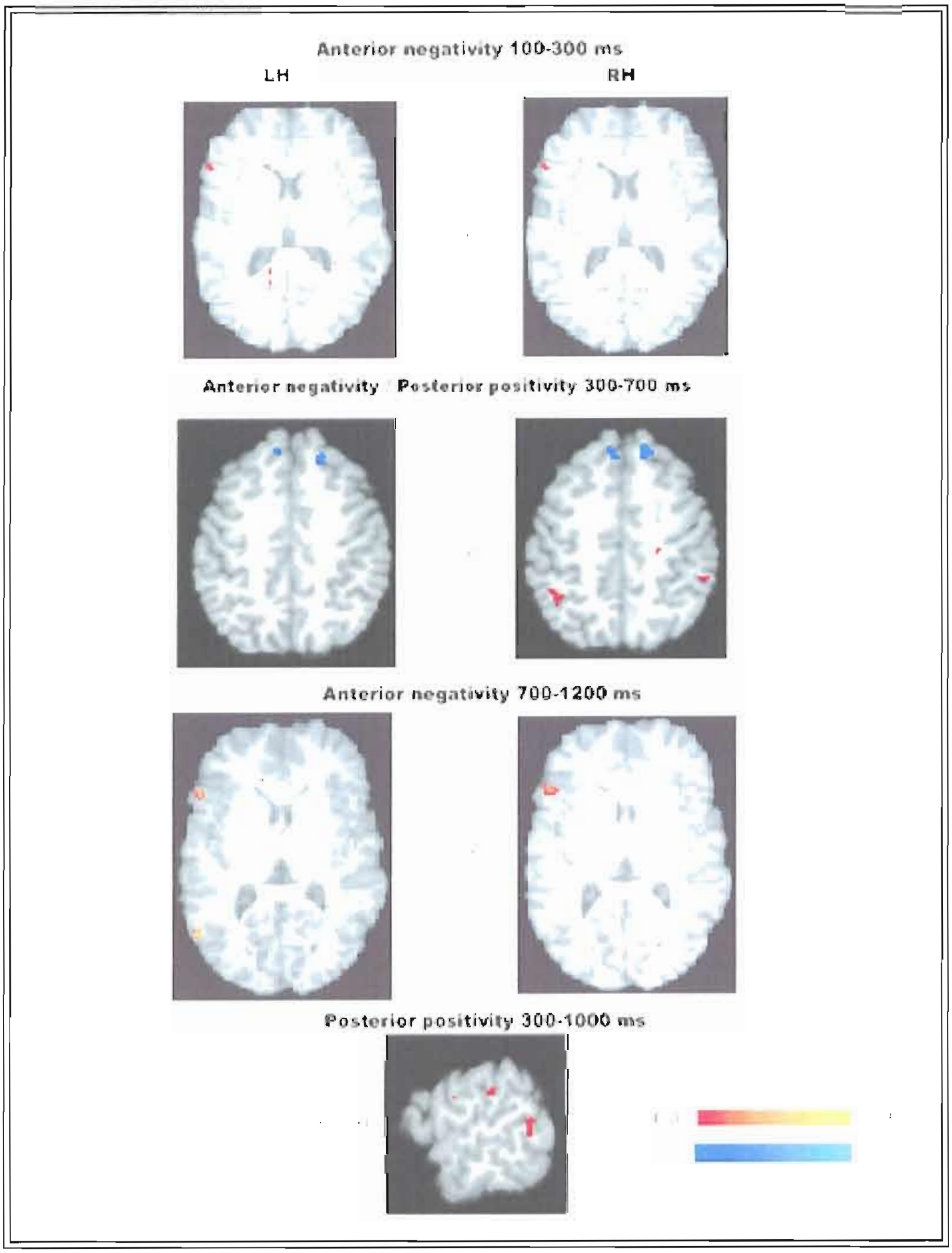

Figure 4.5 Representative slices showing fMRI modulation that correlated with average individual difference amplitude of ERP effects (violation – canonical) over anterior sites in the three time windows analyzed and over posterior sites in the 300-1000 ms time window. Areas showing deactivation (canonical > violation) are in blue.

Table 4.5
Clusters in which activation correlates with ERP average difference amplitude, by hemisphere and time window.

				MNI coordinates		
Cortical region*	BA*	Cluster Size	Z-max	x	y	z
Left anterior ERP – 100-300 ms						
L IFG (pars triangularis/ opercularis)	45/44	37	2.57	-56	24	8
L temporal pole	38	22	2.64	-36	16	-28
	38	21	2.28	-40	16	-40
Right anterior ERP – 100-300 ms						
L IFG	45/44	37	2.46	-56	26	2
Left anterior ERP – 300-700 ms						
R frontal pole/SFG	8	57	2.67	20	40	44
L posterior MTG/ITG	20	54	2.70	-60	-20	-26
R anterior MTG/ITG	20	116	2.72	58	-4	-34
Right anterior – 300-700 ms						
L SFG	8	169	3.18	-6	42	44
L insula	13	69	3.01	-38	12	-12
R SFG	8	106	2.82	16	42	50
R frontal pole/MFG	11	72	2.58	38	44	-16
R anterior MTG/ITG	21	28	2.48	56	0	-36
L posterior SMG/AG	40	212	3.04	-54	-46	38
L superior LOC	7	48	2.47	-20	-70	40
L AG	39	37	2.22	-38	-54	44
R posterior SMG/AG	40	198	2.92	60	-46	32
R superior LOC/AG	7/39	47	2.39	58	-60	34

Table 4.5 con't

R posterior SMG	40	31	2.60	58	-40	52
Posterior cingulate	31	55	2.7	-4	-36	38
Left anterior – 700-1200 ms						
L IFG (pars triangularis/opercularis)	45/44	44	2.47	-54	22	4
Right anterior – 700-1200 ms						
L IFG (pars triangularis/ (pars triangularis/opercularis)	45/44	44	2.76	-52	24	2
L frontal orbital cortex	47	21	2.38	-46	36	-8
P600 – 300-1000 ms						
L posterior MTG	37	48	2.50	-56	-56	6

* Abbreviations: BA: Brodmann area; IFG: inferior frontal gyrus; SFG: superior frontal gyrus; MFG: middle frontal gyrus; STG: superior temporal gyrus; MTG: middle temporal gyrus; ITG: inferior temporal gyrus; SMG: supramaginal gyrus; AG: angular gyrus; LOC: lateral occipital cortex.

300-700 ms anterior electrodes. Activation correlating with the ERP response in the 300-700 ms time window showed a more widespread pattern over frontal, temporal, and parietal areas; as shown in blue in Figure 4.5, SFG bilaterally was deactivated to violations compared to canonical critical words. This widespread pattern was especially evident for activations correlating with activity over right anterior sites, consistent with the pattern of results from Chapter II, in which the distribution of negative and positive

ERP responses was shown to vary in this time window as a function of proficiency, and suggests multiple generators contributing to ERP effects in this time window. As discussed below in relation to the putative generator of the posterior P600, several regions in this time window, including left supramarginal gyrus, left angular gyrus, and posterior cingulate, were identified as likely contributing to the P600 effect over anterior sites. While no correlation with LIFG pars triangularis/opercularis was observed at the $z > 1.96$ ($p < .025$, uncorrected) threshold, a correlation with this region was observed at a lower threshold ($z > 1.64$, $p < .05$, uncorrected). To address specific hypotheses raised by the results from Chapter II, we conducted additional analyses in this time window.

As reported in Chapter II, an extended negativity in this time window is typical of LP participants. We hypothesized that this more widespread distribution might reflect less efficient, but similar, resources to those indexed by the anterior negativity in the 100-300 ms time window. To explore this, we included the clusters which correlated with the early ERP response (100-300 ms time window) in an additional analysis of the ERP response in the 300-700 ms time window. This analysis revealed a strong relationship in the LP group between the ERP response over left anterior sites in the 300-700 ms time window and the LIFG cluster which correlated with the ERP response in the 100-300 ms time window ($r = .843$, $p < .005$); this correlation, while weaker, tended toward significance for HP participants ($r = .437$, $p = .103$). These results suggest that the same, or similar, LIFG areas which at least in part generate the anterior negativity in the 100-300 ms time window also generate the anterior negativity extending over the 300-700 ms time window.

700-1200 ms anterior electrodes. Activation correlating with the ERP response in the 700-1200 ms time window was observed in similar left IFG regions found to correlate with activity in the 100-300 ms time window, as well as in left frontal orbital cortex. These results, taken with those discussed above, suggest similar neural generators for the extended negativity over 100-300, 300-700, and 700-1200 ms time windows across hemispheres.

300-1000 ms posterior electrodes. Activation correlating with the ERP response in the 300-1000 ms time window was observed in left posterior MTG, the same region found to correlate positively with proficiency. This result is also consistent with the results in Chapter II that a larger P600 response is associated with higher proficiency and suggests a role for this region in the generation of the P600. The results discussed above for the 300-700 ms time window, as well as the results from Chapter II, suggest multiple generators of the more widespread P600 characteristic of HP participants in this time window. Therefore additional analyses were conducted comparing activation in the left posterior MTG and other regions found to correlate with the ERP response in the 300-700 ms time window. Three regions correlated with left posterior MTG in HP participants, suggesting a role for these areas in the generation of the more widespread positivity: left supramarginal gyrus ($r = .743$, $p < .01$), posterior cingulate ($r = .771$, $p < .01$), and left angular gyrus ($r = .708$, $p < .01$). While positive correlations were also observed between left posterior MTG and these areas in LP participants, none reached significance. This likely reflects the reduced overall positivity characteristic of LP participants.

Discussion

In this study we expanded on the results reported in Chapter II by further exploring the relationship between proficiency and neural organization for language in monolingual native speakers by examining the BOLD response to phrase structure violations in auditorily presented sentences. Proficiency differences were maximized by recruiting participants from a wide spectrum of society and prescreening to select participants with scores at or near the upper and lower quartiles on standardized tests of English proficiency. Also, in order to make the paradigm as comparable as possible across the two methodologies, we employed an event-related design employing the same stimulus presentation parameters used in the ERP study discussed in Chapter II. As in Chapter II, we assessed the effects of proficiency on the response to syntactic violations using two complementary approaches. Results from these analyses provide additional and consistent evidence from a complementary methodology and provide a more comprehensive account of the effects of proficiency on neural organization for language.

Effects of Syntactic Violations: All Participants

Consistent with previous studies of syntactic processing, results from the whole-brain analysis of all participants revealed that the processing of auditorily presented phrase structure violations elicited activation across classical left perisylvian regions including IFG, superior temporal gyrus, and supramarginal gyrus, and to a lesser degree right hemisphere homologues. These results are in line with an increasing body of literature suggesting that neural substrates underlying syntactic processing are not limited to the LIFG but are distributed over a number of neural areas largely across classical left perisylvian regions but also including a wider range of frontal, temporal, and parietal regions as well as right hemisphere regions.

The largest regions of activation elicited by violations in this study were left posterior superior temporal gyrus (STG) and middle gyrus (MTG) and the left superior parietal lobe encompassing supramarginal gyrus (SMG). Activity related to syntactic processing in posterior STG/MTG has been reported in several studies of syntactic processing (Cooke et al., 2006; Embick et al., 2000; Friederici et al., 2003; Meyer et al., 2000; Ni et al., 2000), and, this region has been found to be consistently activated in a wide range of language processing studies (for a recent review, see Vigneau et al., 2006). Based in part on evidence from the above studies for a role for posterior STG in syntactic processes, as well as the finding that patients with lesions in posterior STG demonstrate a selective absence of the P600 (Friederici & Kotz, 2003), a recent hypothesis proposes that processes of syntactic integration are subserved by left posterior STG (Grodzinsky & Friederici, 2006). This is consistent with our results, as this region showed large and robust activation to phrase structure violations. While no activation in this area correlated with individual difference amplitudes in the ERP component analysis, this is not inconsistent with an interpretation for the posterior STG as a partial generator of the P600. While strong differences in the amplitude of the P600 relating to proficiency were found in Chapter II, this was only in relation to the amplitude, and not the presence, of the effect, and the P600 effect was consistent across proficiency groups and is a consistent finding in the literature on syntactic processing. Based on this evidence, it appears that syntactic integration processes hypothesized to be subserved in part by the posterior STG and reflected in the P600 are likely less affected by proficiency differences than other processes reflected in the P600.

Activation in studies of syntactic processing has also been reported in parietal regions including SMG as well as angular gyrus (Embick et al., 2000; Friederici et al., 2006; Kuperberg et al., 2003). Kuperberg and colleagues found that morphosyntactic violations which elicited a P600 in the same participants in the same paradigm elicited increased activation in bilateral inferior parietal lobule, intraparietal sulcus, and parieto-occipital sulcus, suggesting that these regions may at least in part be neural generators of the P600 effect. These results are consistent with the results from the ERP component analysis, as bilateral SMG activation correlated positively with amplitude differences over right anterior sites, suggesting a role for SMG in the generation of the P600 effect extending over anterior sites. Additional analyses also suggested that left SMG, as well as left angular gyrus and posterior cingulate, may in part generate the more widespread P600 characteristic of HP participants.

Phrase structure violations also elicited activation in left inferior frontal areas including a region encompassing LIFG pars opercularis and pars triangularis, an area in which activation has also been reported by a number of neuroimaging studies of syntactic processing (e.g., Cooke et al., 2006; Embick et al., 2000; Moro et al., 2001; Ni et al., 2000; Suzuki & Sakai, 2003). While, as discussed above, there is some degree of variability in the results from previous studies concerning the role of this region in syntactic processing, the most consistent finding has been an increase in activation with increases in difficulty usually related to manipulations of syntactic complexity. While our paradigm did not involve manipulations of syntactic complexity, and in fact specifically sought to avoid confounds with working memory and complexity by examining the processing of violations in simple, single-clause sentences, there are other potentially important differences in the paradigm used here and most paradigms used in previous neuroimaging studies of syntactic processing. Namely, our paradigm featured participant-paced presentation of stimuli which is more rapid than the presentation typically employed in previous studies, in which stimuli were typically presented with intervals of several seconds or more. While in our paradigm participants did proceed at their own pace, all participants moved rather rapidly through the paradigm. It is thus possible that this more rapid presentation engendered enough of an increase in processing demands for simple sentences to activate areas which were previously found to respond to increases in processing demands brought about by other experimental manipulations. This hypothesis is necessarily speculative and requires more research.

Activation in these areas of LIFG is also consistent with Hagoort's model of unification (Hagoort, 2005). Hagoort posits the LIFG to be the neuroanatomical component crucial for unification processes, which he defines as the integration of lexically retrieved information into a representation of multi-word utterances. He is careful to point out that the LIFG consists of related but anatomically distinct areas. He hypothesizes that these areas form a "unification gradient" in LIFG from more anterior and ventral areas, hypothesized to have greater involvement in semantic processing, to more posterior and dorsal areas, hypothesized to be more involved in phonological processing. The more central LIFG area in between these sides of the gradient is posited to play a crucial role in the syntactic aspect of unification, an interpretation which is compatible with the results reported here. However, as discussed above it is also possible that methodological differences are a factor, and more research is needed to clarify this issue, using paradigms which more closely approximate the rapid pace of everyday language use.

We also found activation to phrase structure violations in an area encompassing temporal pole in anterior STG and LIFG pars orbitalis. Several studies of syntactic processing have reported activation in anterior STG/temporal pole, in both the left (Meyer, Alter, & Friederici, 2003; Meyer et al., 2000) and right (Newman et al., 2001) hemisphere. While we also observed right hemisphere activation, we found a larger extent of activation in this region in the left hemisphere. Left hemisphere activation in anterior STG has been associated with syntactic repair (Meyer et al., 2000) as well as the processing of phrase structure violations (Friederici et al., 2003), and dipole modeling of the magnetic equivalent of the early anterior negativity suggests that activation in the frontal operculum, adjacent to IFG, and anterior STG in fMRI studies bilaterally, but larger in the left hemisphere, may reflect the neural generators of this component (Friederici, Wang et al., 2000). A proposal by Friederici (Friederici, 2004; Grodzinsky & Friederici, 2006) hypothesizes that the frontal operculum is involved in the computation of phrase structures. While the activation reported here did not extend to frontal operculum, the extent of activation in adjacent LIFG pars orbitalis nearly reached this area. Our pattern of activation is consistent with a role for this neural region in the processing of local syntactic violations, and results from our ERP component analysis support the hypothesis that this area also has a role in the generation of the anterior negativity. As discussed below, more precise localization of these potential neural generators of ERP components using anatomically defined regions-of-interest (ROIs) will likely clarify these discrepancies between studies.

Proficiency Differences

In Chapter II, we reported differences in neural organization for syntactic processing as indexed by ERPs in monolingual native speakers of English. In higher proficiency participants, syntactic violations elicited a more focal early response over anterior sites followed by a larger and more widespread P600, while violations elicited a different response in lower proficiency participants characterized by an extended negativity over anterior sites and a reduced P600. Here we expanded this line of research by gathering both ERP and fMRI data from the same group of participants using a similar paradigm. As a subset of the participants examined in the correlational analysis in Chapter II, they had similar profiles in their ERP response to syntactic violations. This allowed us to examine the hypothesis that proficiency differences reflected by modulations of ERP components which index syntactic processing would be reflected in modulations of activation in fMRI. We predicted that a similar pattern of differences in neural organization for syntactic processing would also be reflected in the fMRI results, and that the use of modulations of ERP components would clarify the interpretation of this pattern in light of the results from Chapter II.

One goal of the study presented in this chapter was to assess the hypothesis that proficiency differences would be reflected in modulations of activation in fMRI.

Employing two complementary analyses, we found focal, significant areas in which neural activity was modulated by proficiency differences. These differences were relatively independent, though not entirely, of the effects of SES, working memory span, and education. A direct group comparison revealed greater activation for Higher Proficiency (HP) participants in an area encompassing left temporal pole and left inferior gyrus (IFG) pars orbitalis, while the other between-group difference was characterized by differential deactivation for HP participants compared to Lower Proficiency (LP) participants in right superior frontal gyrus. This was supported by a correlational analysis which found that proficiency positively correlated with activity in both left temporal pole/IFG and in left posterior middle temporal gyrus (MTG). These results provide converging evidence from complementary methodologies for the findings from Chapter II that differences in proficiency in monolingual native speakers are reflected in differential neural organization for syntactic processing.

A second goal of the study presented here was to use individual modulations in the ERP data gathered from the same participants to link proficiency differences in fMRI activation to the proficiency differences in the ERP response to syntactic violations discussed in Chapter II. By inspecting fMRI correlates of ERP activity, we were able to link areas found to be modulated by proficiency differences in the fMRI analysis to the ERP results from Chapter II. The ERP component analysis identified as a possible neural generator of the early left anterior negativity two areas in left temporal pole, adjacent to the cluster of activation correlating with proficiency in left temporal pole/IFG pars orbitalis. The ERP component analysis also identified as a possible neural generator of the P600 the same region of posterior MTG found to correlate with proficiency. These results are consistent with those from Chapter II suggesting that differences in processes indexed by both the early left anterior negativity and the P600 underlie differences in neural organization related to proficiency. The ERP component analysis also identified bilateral areas of deactivation in SFG as possible neural generators of the ERP response in the 300-700 ms time window, suggesting a role for the differential deactivation in right SFG in proficiency differences in the ERP response in that time window.

The results from Chapter II suggested that neural organization for syntactic processing associated with higher proficiency represents an interaction between processes hypothesized to be more automatic, as reflected in the early anterior negativity, and those considered to be more controlled, as reflected in the P600. We hypothesized that this interaction represented differential allocation of these resources associated with higher proficiency, with the relative timing suggesting that more efficient earlier processes are followed by greater engagement of more controlled processes related to repair and reanalysis. The fMRI results are consistent with this interpretation and provide evidence concerning the possible neuroanatomical generators of the ERP components reflected in this differential allocation of resources.

Early anterior negativity

Greater activation was observed for HP participants in left temporal pole/IFG pars orbitalis, a region which also correlated with modulations of the early left anterior negativity in the ERP component analysis. Activation in left temporal pole was specific to the 100-300 ms time window over left anterior sites, suggesting that proficiency differences in the fMRI response in this region may be related specifically to this early ERP effect. This is also consistent with the results from Chapter II, in which the more focal early left anterior negativity was hypothesized to interact with the recruitment of resources indexed by the P600. The early anterior negativity has been hypothesized to reflect early and automatic processing of word category violations (Friederici, 2002), and in Chapter II it was hypothesized that this more focal effect interacted with the increased recruitment of more controlled processes in HP participants. While the temporal resolution of fMRI limits inferences about the relative timing of processes, the relative specificity of certain results from the ERP component analysis permits a greater degree of inference. Specifically, activity in two clusters in left temporal pole was found to correlate uniquely with left anterior activation in the 100-300 ms time window. This raises the hypothesis that that this differential activation for HP participants in left temporal pole/IFG pars orbitalis reflects a greater engagement of processes which contribute to more efficient processing of word category violations. This interpretation is limited by the observation that, while differences related to SES were observed, no differences in the amplitude of the anterior negativity effect in the 100-300 ms time window were observed between proficiency groups in Chapter II. However, it is not expected that the fMRI results will be a direct reflection of processes indexed by ERPs, as even a direct coupling of EEG and fMRI is hypothesized to account for only a fraction of the variance of each measure (Herrmann & Debener, 2008).

While it is not immediately clear why increased activation in a neural region would reflect a more focal ERP effect, one possibility is supported by our results is that increased activation leads to the recruitment of resources indexed by the P600. This interpretation is supported by the finding that proficiency-modulated activation in left temporal pole/IFG pars orbitalis significantly correlated with proficiency-related modulation in posterior MTG, an area identified in the ERP component analysis as a potential neural generator of the P600. These results raise the hypothesis that increased functional connectivity between these regions might play a role in the neural organization for syntactic processing associated with higher proficiency, such that increased coordination between regions associated with the early left anterior negativity and the P600 leads to a more effectively functioning system. This is consistent with a recent study by Prat, Keller, and Just (2007) which reported differences in functional connectivity, as defined by the correlation of activity in one region with that in another, between low and high capacity readers. Consistent with the present results, they found greater synchronization, as quantified by correlation coefficients, between left inferior frontal and posterior temporal regions in high capacity readers compared to low capacity readers in a sentence processing task which varied syntactic complexity. As Prat and colleagues point out, while descriptions of correlation between neural regions do not provide evidence that one region causes activity in another region, or even that regions are directly communicating, such descriptions can still provide a useful characterization of brain activity at the network level. While more work is certainly necessary, the results reported here raise interesting hypotheses for future investigations of individual differences in language proficiency as well as potentially other cognitive functions. Diffusion tensor imaging data were also gathered from the participants in this study, allowing future analyses to examine the degree to which anatomical connectivity might interact with hypothesized differences in functional connectivity.

The results from Chapter II suggested a different picture with respect to the recruitment of processes hypothesized to reflect early and automatic processing of word category violations in LP participants. Phrase structure violations elicited an anterior negativity in the LP group with a similar early onset to that observed in the HP group, but which showed a more extended distribution. Although we hypothesized in Chapter II that this extended negativity might reflect the recruitment of additional resources by lower proficiency individuals, another possibility suggested by those results was that the extended negativity reflected the less efficient operation of similar automatic processes related to word category detection, and that the less efficient nature of these processes resulted in reduced recruitment of more controlled processes. This second hypothesis was supported and clarified by the fMRI results. The ERP component analysis in the 300-700 ms time window suggested that the negativity in this time window is generated by similar LIFG regions involved in the generation of the effect in the 100-300 ms and 700-1200 ms time window, providing support from a complementary methodology for our interpretation of the results from Chapter II. As discussed in Chapter II, differences in the distribution of the anterior negativity in the literature on syntactic processing have largely remained unexplained with regard to their functional relevance. Our results suggest that previous differences in the distribution of this effect may be related in part to the slower and less efficient operation of similar resources related to the processing of word category violations.

P600

In Chapter II, the increased recruitment of more controlled processes by HP participants was reflected in differences in the P600 effect, which is hypothesized to reflect more controlled processes related to repair, reanalysis, and syntactic integration (e.g., Friederici, 2002; Kaan et al., 2000). Results from the fMRI analysis are consistent with these findings and, as with the early anterior negativity, provide evidence regarding the neuroanatomical generators of these processes. Specifically, results from the ERP component analysis suggest that, in addition to the posterior MTG area associated with proficiency differences in the P600 effect, other regions which likely contribute to the P600 effect include left angular gyrus, left supramarginal gyrus, and posterior cingulate cortex.

A somewhat unexpected finding was differential deactivation in right SFG in HP participants. Deactivation specific to task demands (task-induced deactivation) reflects relative decreases in activation to an active task and is a common finding in neuroimaging studies (e.g., Binder et al., 1999; Mazoyer et al., 2001). While task-induced deactivation has also been found to vary as a function of task difficulty (McKiernan, Kaufman, Kucera-Thompson, & Binder, 2003), this seems an unlikely explanation for the differential deactivation observed in this study: HP participants performed at a high accuracy rate on both the grammaticality judgment and the probe question task, and there were no differences in online task performance between groups. An alternative explanation involves the hypothesis that task-induced deactivation reflects in part the reallocation of processing resources in regions remote from those involved in a task (Gusnard & Raichle, 2004). As discussed above, the ERP component analysis suggested that a number of distributed neural generators in frontal, medial temporal, and bilateral parietal areas contribute to the ERP effects in the 300-700 ms time window. This raises the hypothesis that the more anterior distribution of the P600 in HP participants represents in part deactivation reflecting the reallocation of processing resources to other neural regions. However, as interpretation of the relationship between deactivation in right SFG and possible neural generators of ERP components in the 300-700 ms time window proved difficult, further clarification of this hypothesis is beyond the scope of this study. It is unclear whether this deactivation is specifically related to syntactic processing, as the superior temporal gyrus is part of a network of regions which typically show task-induced deactivation, including middle and superior frontal gyri, posterior cingulate cortex, rostral anterior cingulate cortex, and angular gyrus (Binder et al., 1999; Mazoyer et al., 2001). Modulations in posterior cingulate and left angular gyrus were also observed in the ERP component analysis in the 300-700 ms time window, providing further evidence that the P600 effect may reflect both processes related to revision, repair, and syntactic integration as well as processes related to task-induced deactivation and reallocation of resources. A more in-depth analysis of modulations related to ERP components which includes anatomical ROI analyses, which is beyond the scope of this study, will provide further clarification of the processes reflected in the P600 as well as the neurophysiological indices of deactivation.

Reallocation of resources

The hypothesis that the increased activation in LIFG pars orbitalis/temporal pole reflects more efficient early and automatic processing of word category violations which interacts with the recruitment of more controlled processes is strengthened by the other fMRI results with regard to proficiency differences, as well as the ERP component analyses. Activation in left posterior middle temporal gyrus (MTG) correlated with proficiency, and this area was also identified as likely contributing to the generation of the P600 effect. Increased activation in left temporal pole/IFG correlated significantly with activity in both right SFG and left posterior MTG, supporting the hypothesis that increased activation in this region in HP participants is related to a differential allocation of resources in the processing of syntactic violations.

Thus the results from the fMRI analysis of proficiency differences provide additional support for the picture of optimal neural organization for syntactic processing which emerged from the results from Chapter II. More efficient processing of word category violations, reflected in increased activation in left temporal pole/IFG pars orbitalis in the fMRI results and a more focal early anterior negativity in the ERP results, interacts with the recruitment of more controlled processes, reflected in differential deactivation in right SFG and increased activation in posterior MTG in the fMRI results and a larger and more widespread P600 in the ERP results. This suggests that higher proficiency participants, when encountering a word category violation, engage more processes related to the early and automatic recognition of this violation in this early time window, and that the increased engagement of these processes then leads to the recruitment of more processes involved with reanalysis and repair of this violation. As discussed above, this suggests a degree of greater functional connectivity between these regions in HP participants. In contrast, when encountering a word category violation lower proficiency participants do not engage some processes related to early and automatic recognition of the violation to the same degree in this early time window, as suggested by decreased activation in left temporal pole/IFG pars orbitalis in these participants. The evidence suggests that this in turn results in slower processing of word category violations, as evidenced by an extended negativity over anterior sites, and reduced recruitment of more controlled processes involved with reanalysis and repair, indexed by reduced activation in posterior MTG and a reduced P600.

ERP Component Analysis

While ERPs provide excellent temporal resolution on the order of milliseconds, they measure synchronized electrical activity reflecting a blurred spatial mixture of underlying cortical activity which spreads quickly through neural tissue and tends to spread laterally due to the high resistance of the surrounding skull. For this reason, precise localization of the neural generators of ERP components remains difficult, and due to these physiological limitations a foolproof method for definitively localizing ERPs may never be discovered (Luck, 2005). Technological advances have made it feasible to acquire simultaneous ERP and fMRI data in the same experimental paradigm, and recent evidence suggests that this approach shows promise (for a recent review, see Debener, Ullsperger, Siegel, & Engel, 2006). Still, such setups are expensive and complicated technical environments with a high degree of sensitivity to potential artifact in both methodologies, and as such face practical limitations (Herrmann & Debener, 2008). Therefore, novel approaches to the integration of ERP and fMRI methodologies which circumvent the need for simultaneous EEG-fMRI recording are desirable. One approach which has shown promise is the application of parametric variations of a stimulus and correlate the influence of these variations on both the ERP and BOLD signal, an approach which has been applied with some degree of success (e.g., Horovitz, Skudlarski, & Gore, 2002). Here we took a similar approach by using proficiency-related modulations in the ERP response to syntactic processing in an exploratory analysis of the fMRI activations corresponding to these indices. As even a direct coupling of EEG and fMRI is thought to represent only a fraction of the variance of each measure (Herrmann & Debener, 2008), the degree to which this approach can precisely identify neural generators of these ERP components is limited. Still, the results from this approach were interpretable and fit a priori hypotheses based on the literature on syntactic processing reviewed above, thus suggesting that such an approach can provide valuable insight into questions regarding the interplay between ERP and fMRI data and the neural generators of ERP indices of syntactic processing.

We used individual modulations of the ERP response, as quantified by average difference amplitude across different electrode sites and time windows, as covariates in group-level fMRI analyses. Results were interpreted with the straightforward logic that modulations in the ERP response to violation critical words relative to canonical critical words, which is either a negative or positive reflection of the ERP waveform, would correlate with the BOLD response to the same comparison, which was quantified in most brain regions as an activation.

The most consistent result was that activation in LIFG pars opercularis/triangularis correlated with modulations of the anterior negativity effect, over both left and right hemispheres and in both the 100-300 and 700-1200 ms time windows, as well as in the 300-700 ms time window at a lower threshold. However, there was a degree of spatial variation between likely generators of components explored. This is consistent with a putative role for LIFG in syntactic processing, though as discussed above activation of LIFG to syntactic violations is not a consistent finding in the literature. The area of LIFG found to correlate with the anterior negativity encompassed both pars opercularis, which has been more associated with syntactic processing, and more anterior pars triangularis, which has been more associated with semantic processing (Hagoort, 2005), and is consistent with the central LIFG hypothesized by Hagoort to play a role in the syntactic unification of elements in a sentence. However, there was not an exact overlap with the regions of LIFG activated in the analysis including all participants, which is likely due in part to the normalization and spatial smoothing in the fMRI analysis. It is also possible that the different analytical approaches picked up on different aspects of neural activity in LIFG related to syntactic processing. Also, as discussed above, there is likely not a complete overlap in the amount of variance related to syntactic processing measured by ERPs and fMRI. This LIFG area was also more anterior than the frontal operculum, an area adjacent to IFG and hypothesized to play a specific role in the processing of phrase structure violations (Friederici et al., 2003) as well as in the generation of the anterior negativity (Friederici, Wang et al., 2000). Differences in methodology across studies may, as discussed above, contribute to these differences. It is also possible, and even likely, that multiple neural generators produce the anterior negativity. Our results, as well as those from Friederici and colleagues, support this hypothesis. Friederici and colleagues found evidence that anterior STG plays a part in the generation of this effect, and consistent with this our analysis also observed activation in left temporal pole which correlated with modulations of the left anterior negativity in the 100-300 ms time window.

While Friederici and colleagues also found evidence for generators of the anterior negativity in right anterior STG, in our analysis activation in LIFG correlated with modulations of the anterior negativity over both right and left hemispheres. This suggests that activation in LIFG generates modulations of the anterior negativity over both hemispheres, which is consistent with the rapid and lateral spread of electrical activity from ERP generators. This is also consistent with the observation that, while differences in the distribution of this effect are observed, it is most commonly left lateralized. Our results also suggested that the extended negativity observed across the 300-700 and 700-1200 ms time windows, which is more prominent in LP individuals as discussed in Chapter II, results from similar neural generators as the negativity observed in the 100-300 ms time window. Results from this analysis also provided evidence on the neural generators of the P600 component. Consistent with the hypothesis that the P600 reflects different and to some degree separable subprocesses hypothesized to be related to repair, reanalysis, or syntactic integration in general (Friederici, 2002; Kaan et al., 2000), our results suggest that a number of different neural generators, primarily in bilateral SMG, left AG, and posterior MTG, contribute to this effect.

Implications and Future Directions

In this chapter we illustrated the utility of a multifaceted approach to gain insight into the effects of proficiency on neural organization for syntactic processing. We gathered data from the same participants in both ERP and fMRI, and making use of ERP modulations related to proficiency characterized in Chapter II, we were able to provide converging evidence on several issues. As a compliment to the temporal information in Chapter II, we showed that differences in proficiency are reflected in differences in the activation, or deactivation, of specific neuroanatomical regions. We then were able to use the information from the fMRI results to provide functional clarification regarding effects reported in Chapter II. By gathering data from the same participants in both methodologies, we were also able to use the proficiency-related modulations of ERP components to shed light on the neural generators of those components.

While the approaches to fMRI analysis employed here are valuable, whole-brain and correlational analyses alone lack the high degree of neuroanatomical precision possible with fMRI due to the inherent spatial smearing which occurs when averaging across participants. To that end, one important future direction will be the use of region-of-interest (ROI) analyses in conjunction with the methods employed in this chapter. As we have demonstrated the potential for using modulations in ERP components related to behavioral differences as covariates in fMRI analysis to provide evidence on the neural generators of these components, a logical next step will be to combine this approach with anatomical ROI analyses. As we have shown above, it is likely that there are fine-grained differences in the precise anatomical generators of ERP components, and combining the approach employed in this chapter with an ROI approach will be a valuable future direction in both the investigation of possible neural generators of ERP components as well as the functional interpretation of the relationship between ERP and fMRI results.

CHAPTER V

CONCLUSION

The advent of modern neuroimaging techniques has made it possible to gain unprecedented understanding of many aspects of brain function, and the factors which affect their development and ultimate organization. Efforts to more fully characterize aspects of neural organization benefit from the systematic study of the effects of variables which may impact this organization. The experiments presented here represent the systematic study of the effects on neural organization for syntactic processing of two such variables, linguistic proficiency and age of second language acquisition. To this end, we used the same auditory phrase structure violation paradigm using complementary methodologies and complementary analytical approaches to constrain and strengthen interpretation of the results. In addition, we recruited participants from a wide spectrum of society in an effort to provide a more comprehensive picture of neural organization for syntactic processing in monolingual native speakers. Taken together, the results from these experiments constitute another step towards a more complete characterization of neural organization for syntactic processing while raising important hypotheses for future study concerning neural organization for language processing.

The experiments presented here used two complementary methodologies, each with a unique strength. Event-related potentials (ERPs) are measurements of continuous brain electrical activity time-locked to the presentation of a stimulus and provide an online, non-invasive index of cognitive processes with a temporal resolution of milliseconds. Complementing the unique temporal resolution of ERPs is functional magnetic resonance imaging (fMRI), with spatial resolution on the order of millimeters. In order to more directly compare results across methodologies, we used a paradigm with similar experimental parameters in each methodology. This paradigm examined the neural response to auditorily presented phrase structure violations in simple, declarative sentences in order to minimize possible confounds of literacy and working memory limitations.

In Chapter II we characterized the relationship between proficiency and syntactic processing using ERPs. As most ERP studies of syntactic processing use university students as participants, one goal of Chapter II was to go beyond the university community to sample participants from a wider spectrum of society. In addition to allowing for a more comprehensive characterization of neural organization for syntactic processing, this also allowed us to investigate the possibility that the well-documented effects related to socioeconomic status environment on various aspects of language development (e.g., Hart & Risley, 1995; Huttenlocher et al., 2002; Walker et al., 1994) may show some lasting effects into adulthood. In order to more fully characterize the effects of proficiency on neural organization for syntactic processing, two complementary approaches were employed. In the between groups analysis, participants were divided based on standardized proficiency scores into two groups based on their scores on standardized tests of English. Analyses revealed differences in brain organization between the two proficiency groups, with Higher Proficiency participants showing a more restricted and focal early anterior negativity spatially and temporally and a larger and more widely distributed positivity to violations in English. We also performed a correlational analysis in which we explored the relationship between proficiency and the neural organization for syntactic processing across a wide spectrum of proficiency scores by examining the degree to which individual proficiency scores correlated with individual neural responses to syntactic violations in regions and time windows identified in the between-group analysis. This approach also employed partial correlation analyses to control for possible confounding variables. This correlational analysis provided converging evidence for the effects of proficiency discovered in the between-groups analysis, confirming that differences in proficiency affect neural indices of syntactic processing reflected in both anterior negativity and posterior positivity components.

An additional and compelling result from the correlational analysis in Chapter II revealed a correlation between childhood socioeconomic status and the neural response to syntactic violations specific to left anterior sites. This relationship was not maintained when controlling for several childhood environmental factors, which provides some support for the hypothesis that factors related to specific aspects of the childhood environment may have enduring effects on neural organization for syntactic processing into adulthood.

The results of Chapter II, in addition to providing converging evidence from two analytical approaches for differences in neural organization related to proficiency, suggest that it would be fruitful for all subfields of cognitive neuroscience to strive to recruit participants from a wider spectrum of society. As the results from Chapter II suggest, such research would not only provide a more comprehensive picture of neural organization for cognition, but might also make discoveries which could lead to compelling hypotheses regarding the endurance of effects related to childhood experience.

The goal of Chapter III was to examine the effects of age of second language acquisition on neural organization for syntactic processing, independent of second language proficiency. The wide range of proficiency scores from the native speakers in Chapter II allowed us to match a group of non-native speakers of English who did not begin acquiring English until after the age of 11 with the Lower Proficiency group of native speakers from Chapter II. The results from Chapter III were consistent with previous evidence for maturational constraints on systems underlying aspects of syntactic reflected in the anterior negativity (e.g., Hahne, 2001; Hahne & Friederici, 2001; Weber-Fox & Neville, 1996), as non-native speaking late learners of English did not recruit processes reflected in the early anterior negativity despite being at the same level or better than the Lower Proficiency native speakers on all proficiency measures except one. However, the non-native speaking late learners did show a P600 to violations which tended to be larger than in the native speakers, suggesting that late learners may rely more on controlled processes to achieve a level of proficiency comparable to that of some native speakers. Overall, the results from Chapter III provided additional support for the hypothesis that the development of early, more automatic processes for syntactic processing reflected in the early anterior negativity may be governed by maturational constraints consistent with a sensitive period.

In Chapter IV, we revisited the question of proficiency differences in monolingual native speakers, with the focus on the mutually informative use of ERPs and fMRI. We gathered ERP and fMRI data from participants of varying proficiency using a syntactic processing paradigm with similar experimental parameters across methodologies. A whole-brain analysis of all participants found a distributed pattern of neural activation to syntactic violations maximally across left perisylvian regions, generally consistent with previous neuroimaging studies of syntactic processing. We then looked for neuroanatomical effects of proficiency using two methodological approaches and found greater activation in Higher Proficiency participants in two left hemisphere areas, left temporal pole/IFG pars orbitalis and left posterior MTG, as well as differential deactivation to violations in the Higher Proficiency group in right superior frontal gyrus. In Chapter IV we also used proficiency-related modulations in the ERP effects to find evidence for the neuroanatomical generators of ERP components indexing syntactic processing, and used these results to constrain the analysis of the fMRI results. This proved to be a fruitful approach, as we were able to find evidence that the extended negativity in the 300-700 ms time window characteristic of Lower Proficiency participants likely reflects the less efficient use of similar resources in the detection of word category violations, while the increased recruitment of left temporal pole/IFG pars orbitalis and left posterior MTG by higher proficiency participants likely represents a more efficient allocation of resources for the processing of syntactic violations, indexed electrophysiologically by a more focal early left anterior negativity and a larger and more widespread P600. In addition, this analysis identified potential generators of the anterior negativity across both hemispheres, and in both the 100-300 ms and 700-1200 ms time windows, primarily in anterior left IFG and temporal pole. Overall, the results from Chapter IV, in addition to shedding additional light on the question of proficiency effects on neural organization for language, suggest that the use of ERP modulations to constrain the interpretation of fMRI results can inform questions concerning the neural generators of ERP components.

In addition to providing evidence bearing on the role of proficiency and age of acquisition in neural organization for syntactic processing, the experiments presented here more generally suggest that a combination of mutually constraining methodological approaches, combined with the study of participants from a wider spectrum of society beyond the university community, can provide a more comprehensive picture of many key questions in cognitive neuroscience.

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