

Individual Differences in Grammatical Error Processing

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Abstract

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Psychology

Years of research using electrophysiology to study language processes have yielded important discoveries about language-specific event-related potentials. However, most of these studies examined grand averages and population differences and avoided looking at individual differences. More recently, a few studies have shown that variability exists between individuals in their ERP responses to grammatical errors and that this variability may be related to cognitive and linguistic abilities. The goal of this study was to replicate the variability found previously and to investigate its relationship with measures of memory and cognitive abilities. We tested Ullman's Procedural-Declarative model of language (Ullman 2001, 2004, 2005) by examining the relationship between procedural memory ability and the ERP response. We also investigated the possibility of gender differences in processing grammatical errors. Adult native English speakers read English sentences while event-related potentials (ERPs) were recorded. The relative magnitudes of the N400 and P600 to grammatical errors were compared to calculate a response dominance index (RDI) for each subject. We examined the correlation of the RDI with measures of declarative memory, procedural memory, verbal working memory, and processing

speed. We also investigated differences in the RDI between men and women and between those with a first-degree left handed relative (familial sinistrality, or FS+) and those without (FS-). We replicated the finding that individuals vary on their dominant response (P600 vs N400) to grammatical errors. We found no relationship between RDI and any of the predictor variables, but did find a difference between men and women in the size of the N400 effect to syntactic errors. This does not lend evidence to the Declarative-Procedural model of language, which may relate to its strong dependence on data from individuals with language disorder. We suggest that the gender difference indicates that men are more variable in their processing of grammatical anomalies and relate this back to the variation seen across studies of the P600 effect. These results also provide strong support for the feasibility of examining individual differences using ERP data, even in populations previously thought to be homogenous.

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Chapter 1. Introduction

Years of research using electrophysiology to study language processes have yielded important discoveries about language-specific event-related potentials. However, until recently, all of these studies examined grand averages and population differences and avoided looking at individual differences for fear of too little signal-to-noise ratio in the data. This study serves to not only demonstrate that individual differences research in language event-related potentials is viable, but that there exists systematic variation that can serve to inform our understanding of how sentences, particularly grammatical errors, are parsed.

1.1. Electroencephalography.

Electroencephalography (EEG) is a powerful way to examine linguistic processing, as it provides a millisecond-by-millisecond account of the brain's activity. Compared to functional magnetic resonance imaging, EEG provides data throughout language processing, rather than once every six seconds. Language processes occur very rapidly, and knowing what is going on during the process can be a more relevant question than where in the brain it occurs for some types of research. Event-related potentials (ERPs) reflect the summed postsynaptic activity of pyramidal cells in the cortex, time-locked to a stimulus of interest. When investigating sentence processing, the stimuli of interest are words embedded in a sentence and are averaged across a condition of interest to compare to other conditions.

1.2. Linguistic ERPs.

Historically, electrophysiological research into language processes has investigated the data as group means to increase the signal-to-noise ratio by way of averaging out random noise.

In addition, group means are useful in investigating how a population processes language. Much of the extant ERP and language literature has focused on two components, the N400 and the P600. The N400 component is a negative-going deflection that peaks at about 400ms after the onset of the eliciting stimulus. N400 amplitude is sensitive to a range of "lexico-semantic" variables, including lexicality (with pronounceable nonwords producing larger N400s than actual words), normative word frequency (with pronounceable pseudowords – letter strings with a frequency of zero -- eliciting the largest N400, and highly frequent words eliciting the smallest), and the "semantic fit" between a word and preceding context (with better-fitting words eliciting smaller N400s) (Kaan, Harris, Gibson, & Holcomb, 2000, Kutas & Federmeier, 2000, Kutas & Hillyard, 1980, 1984). N400s are seen in priming studies to the second word in a prime, whether it be semantic, orthographic, or phonetically primed, indicating that less processing is needed as a result of the priming (Coch et al., 2002, Grossi et al., 2001, Khateb et al., 2007, Kramer & Donchin, 1987, Rugg, 1984, Weber-Fox et al., 2003). The "N400 effect" has also been documented in research examining brain responses to conceptual anomalies in other domains. Research into arithmetic problems has shown that a larger N400 is elicited to incorrect answers to both symbolic and verbal math problems (Fisher, Bassok, & Osterhout, 2009, Fisher, Bassok, & Osterhout, 2010, Niedeggen & Rossler, 1999).

By contrast, syntactic anomalies typically elicit a positive-going wave that onsets at about 500 ms after the eliciting stimulus with a duration of several hundred ms (the *P600 effect*, Osterhout, Holcomb, & Swinney, 1994, Osterhout & Holcomb, 1992, Osterhout & Nicol, 1999). This effect generalizes well across different types of syntactic anomalies, such as violations of agreement (Hagoort, Brown, & Groothusen, 1993; Osterhout & Mobley, 1995; Vos, Gunter,

Kolk, & Mulder, 2001), verb inflection (Friederici, Pfeifer, & Hahne, 1993; Gunter, Stowe, & Mulder, 1997), case inflection (Münste, Heinze, Matzke, Wieringa, & Johannes, 1998), pronoun inflection (Coulson, King, & Kutas, 1998), phrase structure (Friederici et al., 1993; Hahne & Friederici, 1999; Neville, Nicol, Barss, Forster, & Garrett, 1991), case marking (Coulson et al., 1998; Friederici & Frisch, 2000; Frisch & Schlesewsky, 2001, 2005), and verb-argument structure (Friederici & Frisch, 2000; Frisch, Hahne, & Friederici, 2004; Osterhout, Holcomb, & Swinney, 1994). P600-like effects have been reported in studies in which non-English sentences were presented (e.g. English, French, Dutch, Italian, Japanese, etc.; Angrilli et al., 2002, Inoue et al., 2002).

P600 effects have also been reported to stimuli that are technically not syntactically anomalous but that are likely to be perceived to be anomalous, at least momentarily. A good example of such stimuli are the syntactically disambiguating words in "garden-path" sentences, that is, sentences in which (due to syntactic ambiguity) two possible syntactic interpretations are at least momentarily compatible with the input; the intended structure is indicated by subsequent disambiguating information in the sentence. Much evidence indicates that many speakers of a given language manifest a tendency to choose the same initial interpretation among the set of possibilities, only to have to reparse the sentence if the initial parse turns out to be incorrect. These types of sentences are therefore referred to as "garden-path" sentences. Although such sentences are not ungrammatical, they are momentarily perceived to be so, and typically elicit P600 effects (Friederici, Hahne, & Mecklinger, 1996; Frisch, Schlesewsky, Saddy, & Alpermann, 2002; Kaan & Swaab, 2003; Mecklinger, Schriefers, Steinhauer, & Friederici, 1995;

Osterhout & Holcomb, 1992; Osterhout & Holcomb, 1993, Hagoort, Brown, & Osterhout, 1999, Van Berkum, Brown, & Hagoort, 1999).

An important and long-lasting debate is whether these language-sensitive ERP effects are in any sense uniquely linguistic. A first-pass inspection of the available evidence might lead one to conclude that they are not. For example, unexpected events that are meaning-based but that are presented in a non-linguistic video format (in which specific, easily described events are depicted) elicit robust N400s (Reid & Striano, 2008, Sitnikova, Kuperberg, & Holcomb, 2003), and misspelled words can elicit P600-like positivities (Vissers, Chwilla, & Kolk, 2006, Kim & Osterhout, 2005). The question concerning the language-specificity of the P600 effect has been given its most contentious form in the debate about whether the P600 is another manifestation of the P300 component (for a review, see Donchin, 1981), which is a large-amplitude, posteriorly distributed positive wave elicited by a wide range of unexpected events, including many such events that are not in any sense linguistic. P300 amplitude is a function of the degree of deviance between what is expected and what actually occurs. For example, notes that deviate from expected musical forms elicit P300s, and P300 amplitude is a function of the degree of unexpectedness (Besson et al., 1998, Koelsch, 2005, Patel, 2003, Patel et al., 1998).

Perhaps the best evidence of whether the P600 is "just another" P300 comes from a study reported by Osterhout and Nicol (1999). Their study leaned heavily on Helmholtz's Rule of Superposition, which states that electrical fields summate where they intersect in both time and space. Osterhout and Nicol (1999) presented sentences containing an uppercase word (which were expected to elicit a P300 response), a syntactically anomalous word (which is expected to elicit a P600 response), or a word that was both in uppercase letters and syntactically anomalous.

Following Helmholtz's rule, the degree to which the brain response to the doubly anomalous word approximated the brain responses to the singly anomalous words added together would indicate the degree to which the two responses are elicited by independent neural sources. As expected, each anomaly elicited a large positive-going response. Most importantly, the ERP response to the doubly anomalous words was statistically indistinguishable from the sum of the responses to each of the two types of anomaly, when presented separately.

1.3. Individual Differences in Linguistic ERPs.

Although the P600 effect to syntactic errors has been widely replicated across many different languages and populations, recent research suggests that there is considerable variability in the ERP components elicited by syntactic errors when the ERP data is examined by individual (McLaughlin et al., 2010, Osterhout et al., 2004, Osterhout, 1997, Tanner, McLaughlin, Herschenson, & Osterhout, 2013, Tanner et al., 2014, Tanner & Van Hell, 2014, among others). While it is still true that the majority of individuals show P600s following syntactic errors, a non-insignificant minority show N400s (Osterhout et al., 2004, Osterhout, 1997, Tanner & Van Hell, 2014, among others). This variation in ERPs to linguistic stimuli is important in finding not only that this variation exists within populations previously thought to be homogeneous, but also that this variation is systematic and can be predicted by other subject factors and may predict language proficiency. This systematic variation can be used to investigate how ERPs and cognitive abilities are interrelated and how they relate to language proficiency. Tanner et al. (2014) developed a way to quantify the dominance of the ERP response, in a calculation of the relative P600 and N400 effect magnitudes called the Response Dominance Index (RDI). Individual measures of P600 and N400 magnitude, as well as their

combined interaction measured by the RDI have been examined as outcome variables in studies examining individual differences in ERP response (see below).

1.3.1. Second Language Learning.

Second language (L2) learners are a highly variable population in many ways, including motivation, aptitude, study techniques, etc. and some of this variability has been shown to manifest in their ERP responses to sentence comprehension in their second language. As classroom L2 learners progress through their studies, the ERP response to syntactic errors changes. Initially, these grammatical errors elicit N400s, but as proficiency increases, more and more of the sample show P600s (McLaughlin et al. 2010, Tanner et al., 2013). Both split-group (McLaughlin et al., 2010, Tanner et al., 2013) and correlational and regression studies (Tanner et al., 2014) have indicated that larger P600s to syntactic errors are correlated with increased proficiency. However, even in highly proficient populations, there are still some individuals who show N400s to grammatical errors, indicating that proficiency is not the only factor influencing RDI (Tanner et al., 2014).

1.3.2. First Language Variation.

The above finding that even highly proficient L2 individuals exhibit variation in the ERP response to syntactic errors helps explain why variation also exists within individuals in their first language (L1) (Osterhout et al., 2004, Osterhout, 1997, Tanner & Van Hell, 2014). While most L1 speakers can be thought of as highly proficient, there is still variability in proficiency, and this relates to the ERP response to grammatical errors. Pakulak and Neville (2010) found that higher L1 proficiency correlated with larger P600s to syntactic errors.

1.3.3. Predictors Beyond Proficiency.

Currently, only a few studies have attempted to identify which individual difference variables other than proficiency that might predict whether a person will show an N400 or P600 to grammatical errors, and there is currently no consensus. When examining ERPs in L2 learners, Tanner et al. (2014) found that motivation to learn the language predicted larger P600s to grammatical errors. When examining L1 processing, Tanner and van Hell (2014) found that having a first degree left-handed relative (familial sinistrality, or FS) correlated with an increased N400 to grammatical errors. Other studies found cognitive predictors such as verbal working memory and cognitive control related to the size of the P600 to grammatical errors (King & Just, 1991, Oines, 2012, Tanner, 2013, Ye & Zhou, 2008). Unpublished data from the Osterhout lab suggests that the ERP response differs by sex, with men more likely to show N400s to syntactic errors than women.

Evident from the range of predictors from the above studies, there is not yet consensus as to what predicts how an individual will respond to a grammatical error beyond general proficiency in the language. None of the prior studies replicated any of the others' findings, so the state of the literature is unconnected and unreplicated.

1.4. The Declarative-Procedural Model.

One predictor that may explain the variance in ERPs to syntactic errors is procedural memory skill. Ullman (2001, 2004, 2005) has proposed a Declarative-Procedural model of language that states that linguistic processes are underpinned by declarative memory and procedural memory. In his model, the declarative memory system is critical for linguistic

processes such as word learning, semantics, and lexical memory. However, the DP model also hypothesizes that declarative memory can also perform some grammatical functions too, and so can play a compensatory role if the procedural memory system is damaged or weak. This is possible because the declarative memory system is extremely flexible and therefore is able to learn, store, and process information in order to accomplish grammatical functions that are typically handled by the procedural memory system. It can do this in a number of ways, including chunking (i.e. storing “cooked” as one unit rather than the root plus the suffix ending denoting past tense) and learning explicit rules (Ullman, 2004).

1.4.1. Neurobiology of the Declarative-Procedural Model

The procedural memory system is based in the frontal/basal ganglia structures and the connections between these two areas (De Renzi, 1989, Squire et al., 1993). The basal ganglia and the supplemental motor area may play a particular role in the processing of sequences (Kandel, Schwartz, & Jessel, 2000, Willingham, 1998). The basal ganglia are highly connected with the frontal cortex (Alexander, Crutcher, & De Long, 1990, De Renzi, 1989, Squire et al., 1993). The many circuits connecting the basal ganglia with the frontal cortex are parallel and functionally segregated. The well-known “motor circuit” of the basal ganglia projects to the frontal motor areas, while other circuits project to the frontal areas corresponding with the type of information being processed. When we view syntax and a set of rules governing sequences of lexical items, the Declarative-Procedural model predicts that syntactic processing will be driven by the basal ganglia and its connections to frontal areas dealing with language processing.

The declarative memory system, on the other hand, is largely governed by the hippocampus and surrounding temporal areas (Squire, 2004). A multitude of neuropsychological

and lesion studies have indicated that the hippocampus is vital for the formation of declarative memories (see Eichenbaum, 2000, Tulving & Markowitsch, 1998 for reviews). More recently, noninvasive neuroimaging has been used to more deeply investigate the role the hippocampus plays in the declarative memory system. The body of literature supports the theory that the hippocampus binds together multiple inputs to create representations of the relationships between the different elements of scenes and events (see Cohen et al., 1999 for a review).

Prior research investigating the neuroanatomical source for the N400 and P600 effects has suggested similar probable sources for the N400 and P600 effects as for the declarative and procedural memory systems, respectively. The P600 has been theorized to originate from Broca's area and surrounding parts of the left inferior frontal gyrus (LIFG) (Brouwer & Hoeks, 2013). This theory has been supported by several fMRI studies showing increased activation in the LIFG to syntactic violations (van de Meerendonk et al., 2011, Brouwer & Hoeks, 2013). A network including the LIFG has been shown to be active when parsing sentences with syntactic errors (Kuperberg et al., 2008, Ye & Zhou, 2009). Studies using magnetoencephalography (MEG) and simultaneous EEG and fMRI have suggested that the source of the N400 response lies in the temporal lobes, specifically in or near the left temporal sulcus, hippocampus, and the middle temporal gyrus (Halgren et al., 2002, Kiehl, Laurens, & Liddle, 2002, Simos, Basile, & Papanicolaou, 1997).

1.4.2 Specific Language Impairment.

Support for this model comes in large part from studies of children with Specific Language Impairment (SLI), which is a genetic disorder causing impairments to language attainment especially in grammatical production (such not using past tense or using helper verbs

like “be”). Studies have shown that children with SLI also are impaired on tests of procedural memory, and that the degree of procedural memory impairment correlates with the degree of grammatical impairment (Conti-Ramsden, Ullman, & Lum, 2015, Gabriel et al., 2013, Hsu & Bishop, 2014, Kemény & Lukács, 2010, Lum et al., 2014).

Ullman’s theory suggests that in children with SLI, it is the impairment to the procedural memory system that causes the grammatical difficulties. The little grammatical functionality they show is a result of the children relying on their declarative memory system to rote-memorize simple grammatical rules (Bishop & Hsu, 2015, Poll, Miller, & van Hell, 2015). Additionally, this theory posits that individuals with SLI form the extreme end of a continuum of procedural, and therefore grammatical, abilities.

1.4.3. Variation in Normal Populations.

A few studies have examined whether this relationship between procedural memory skill and language proficiency holds in individuals without any impairments. Generally, it has been found that there is a relationship between procedural memory ability and language skill, where better procedural abilities lead to better language skills (Hamrick, 2015, Lee & Tomblin, 2015). This field of research is still very young, however, and has largely been based on studies involving atypical populations. Therefore, replication in a neurotypical population would help strengthen the argument that grammatical and procedural memory abilities are linked not only in individuals with SLI, but in the general population as well.

1.4.4. Relationship to Handedness and Familial Sinistrality

Ullman's Declarative-Procedural model of language also makes predictions about how individuals who are left handed or who have family members who are left handed (also called familial sinistrality status). This model predicts that familial sinistrality affects brain anatomy, with those individuals who are positive for familial sinistrality (FS+) have less-strongly lateralized language. This prediction has been supported by MRI studies (Hecaen et al., 1981, Szaflarski et al., 2006, Tzourio-Mazoyer et al., 2010). It is already known that left-handed individuals are more likely to have non-left lateralized language from MRI studies (Pujol et al., 1999, Szaflarski et al., 2002, Szaflarski et al., 2012) and use of the Wada procedure on individuals who require brain surgery for epilepsy (Binder et al., 1996, Wada & Rasmussen, 1960, Yetkin et al., 1998). Behavioral evidence also suggests differences in individuals' sensitivity to linguistic information depending on their familial sinistrality status, with FS+ individuals being more sensitive to the semantic and lexical information of language and FS- individuals more attuned to the syntactic information (Bever et al., 1989, Townsend & Bever, 2001, Townsend, Carrithers, & Bever, 2001).

1.4.5. Predictions for Linguistic ERPs.

When we connect Ullman's Declarative-Procedural Model of language to the posited explanations of the N400 and P600, where the N400 is driven by lexical fit and the P600 reflects syntactic analysis, it follows that this theory would predict that individuals with weak procedural memory abilities would fail to elicit a P600 to syntactic errors because of their weak procedural skills. Instead, they would be expected to show an N400 as they would be relying on their declarative memory system to parse the grammar, which in the Declarative-Procedural model is linked to the semantic system, which is implicated in the N400 response.

Additionally, in Ullman's model, the activity of the two memory systems is negatively correlated, which is the same as the relationship between the size of the N400 and P600 to syntactic errors (see Figure 1). There is converging evidence from animal and human studies indicating that the declarative and procedural memory systems are indeed negatively correlated (Poldrack & Packard, 2003). Further, these memory systems are in competition when individuals solve problems (Foerde, Knowlton, & Poldrack, 2006).

This same competition can be seen in studies examining L2 learners: in the beginning stages of learning the N400 effect dominates the ERP response to syntactic errors, while with increased experience the P600 effect takes over (McLaughlin et al. 2010, Tanner et al., 2013). This negative relationship has been suggested to arise from the underlying processes resulting in an N400 and a P600 originating from separate brain areas, leading to competition with one another when processing a syntactic error (Kuperberg, 2007, Osterhout et al., 2012, see Jackendoff, 2007, MacWhinney, Bates & Kliegl, 1984, for processing models that similarly propose a competitive dynamic between lexical/conceptual and syntactic cues, see also Morgan-Short, Faretta-Stutenberg, Brill, Carpenter & Wong (published online March 1. 2013).

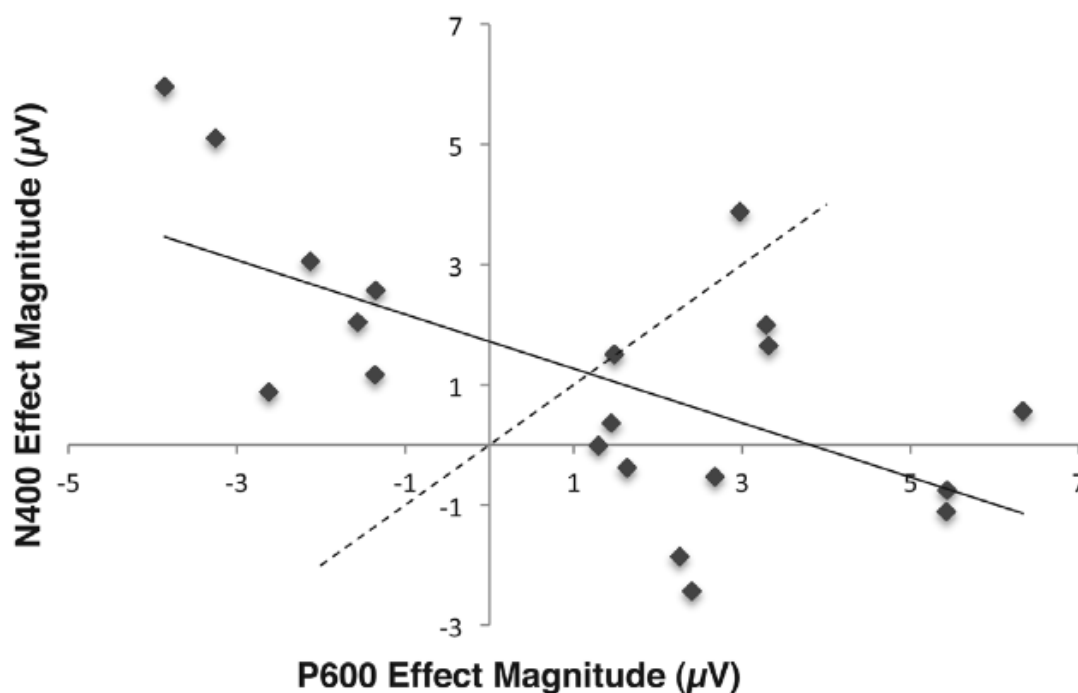


Figure 1. Example data (McLaughlin et al., 2010) showing the negative correlation between the N400 and P600 effect magnitudes to a single type of error (here a syntactic error). Points are individual subjects.

Linking this to the predictions the Declarative-Procedural model makes for individuals who are FS+ and/or left-handed, we would expect left-handed individuals to be more likely to use their declarative memory when parsing sentences with grammatical errors, leading to an N400. We would predict the same pattern for FS+ individuals when compared to FS- individuals.

However, it could also be the case that, being based largely on the SLI population, the Declarative-Procedural model of language is not generalizable to non-disordered populations. In this case, in the current study we would expect to see little to no relationship between an individual's procedural memory ability and their RDI.

1.5. Sex Differences in Language Abilities.

Another large field of research into linguistic abilities deals with the possibility of sex differences. Two main theories suggest that there are gender differences in motivation and early language abilities in young school-aged children. These two factors may create systematic differences in how men and women parse written language.

1.5.1. Motivation to Read.

Much of the research examining the reading achievement gap in school-aged children suggests that it is due in part to differences in socialization leading to differences in motivation to read. Boys tend to have less motivation to read (McGeown et al., 2012, Logan & Johnston, 2009). This lack of motivation plays into the achievement gap because motivation has been extensively associated with reading proficiency (Logan, Medford, & Hughes, unpublished, Taboada et al., 2009, McGeown et al., 2012). Intrinsic motivation is the strongest predictor for reading proficiency (Wang & Guthrie, 2004, Wigfield & Guthrie, 1997), and boys particularly lag behind in intrinsic motivation to read (McGeown et al., 2012). This is therefore the main explanation for why boys lag behind their female counterparts in reading proficiency during early childhood (Logan & Johnston, 2009, McGeown et al., 2012).

1.5.2. Diminished General Language Abilities Entering School.

In addition to their low motivation to read, boys are less skilled in their language abilities when they enter kindergarten (Locke, Ginsborg, and Peers, 2002). This sex difference is found even across different language communities (Austrian German, Basque, Croatian, Danish, Estonian, French, Galician, Slovene, Spanish, Swedish) (Eriksson et al., 2011). This suggests

that the boys' disadvantage comes not from a specific type of language or culture, but some other, possibly biological, factor.

Neuroimaging studies have found differences in the language networks of males and females. A primary finding is that there is more hemispheric connectivity in women than men and that women's language tends to be more bilaterally distributed while men's language functions are more strongly left-lateralized (Bitan et al., 2010, Shaywitz, 1995, Jaeger et al., 1998). Additionally, studies have shown that men and women process visual vs. auditory language differently. Men seem to operate on a modal framework, with specific and different brain areas active when reading (visual association cortex) and listening (auditory association cortex), whereas women show activation of the fusiform gyrus, an area typically associated with processing visual word forms, regardless of stimulus modality (Burman, Bitan, & Booth, 2008). This suggests that women use an overarching general language network to process language regardless of modality, while men process these different modes of languages using different neural mechanisms (Burman, Bitan, & Booth, 2008). We hypothesize that this may result in women making more connections while reading, as they have more interactions between hemispheres and between modalities of language in their neural network for language. On the other hand men, operating in one modality at a time, may miss connections and process written language using a shallower processing system.

1.5.3. "Good Enough" Reading Strategy.

A diminished motivation to read leads naturally to less practice reading, which in turn leads to poorer reading proficiency (Wigfield & Guthrie, 1997). Add to this poorer general language abilities when entering school and it may result in boys developing a different and

perhaps less deep reading strategy than girls, since primary school still requires a certain amount of reading and level of proficiency to progress. Various qualitative differences between men and women in their reading strategies have been found. Girls have been found to have better grammatical usage (Kimura, 1999). Hannon (2014) found that reading comprehension in women was predicted by their text memory and knowledge integration skills, whereas word decoding was a significant predictor of comprehension for men.

This supports a “Good Enough” reading strategy, first suggested by Ferreira and colleagues (2002), which states that not all readers completely analyze all the deep syntactic structures when reading. Instead, some readers analyze the sentence just enough to successfully complete whatever task is being asked of them. This can even be as extreme as just relying on the meanings of the individual words in the sentence, without any analysis of the syntactic relationships (Ferreira, 2003). This type of reading strategy supports the research that has found that reading skill in boys is more strongly predicted by word decoding skills, hence word meaning analysis, rather than grammatical skills.

1.5.4. Predictions for Language ERPs.

Referring back to the hypothesis that the N400 reflects lexical information access while the P600 relates to grammatical reanalysis, the above difference in reading strategy by men and women provides specific predictions for which ERP response would be elicited by a grammatical error. Women, who have better grammatical skills, likely process sentences using a deeper syntactic analysis process. A larger proportion of men, on the other hand, may use a “Good Enough” reading strategy, driven by their preference for using word decoding skills. If these differences were reflected in the ERPs during reading, we would expect women to primarily

show P600s to grammatical errors, while men may demonstrate more variability and show N400s, reflecting a greater reliance on lexical processing.

Much of the research on gender differences in reading has looked at children, however. In this study, we examine an adult population, and it could be the case that children grow out of their difference in language processing. In that case, we would expect to see no difference in the ERP response to grammatical errors between men and women.

1.6. Processing Speed and Working Memory

Another variable of interest for predicting the ERP response to syntactic errors is processing speed. When the Osterhout lab first examined changes in the ERP response in second language learners longitudinally, during debriefing the participants were asked their general feelings on the experiment – how it felt to read in their second language, what they thought of the speed of the sentences, etc. It was discovered that the participants felt that during their first session, during their first quarter of instruction, the sentences were being shown too quickly for them to read properly. By the third session, their third quarter of instruction, most of the participants felt as if the sentences were being shown at a slower presentation rate, even though the rate remained the same throughout the entire experiment. It was also found that on average in the first session the participants showed an N400 effect to syntactic errors, and by the third session many had progressed to showing a P600 effect to the same errors (McLaughlin).

In this example, individuals' processing speed was being affected by their lack of knowledge of their L2, and as they grew more comfortable with their second language their processing speed was able to increase to a point where the presentation of the sentences in the

experiment felt comfortable to them. However, individuals vary in their speed of processing naturally, in their first language as well, and evidence suggests that this may play a role in how they process language. A study by Caplan et al. (2011) investigated the relationship between processing speed and the comprehension of sentences with relative clauses. They found that older participants, who had slower processing speed due to age, had poorer comprehension of the sentences when compared to individuals with faster processing speed (Caplan et al., 2011). Additionally, it has been found that individuals with faster processing speed were better at anticipatory language prediction, suggesting that they are better at integrating linguistic information because of their speed (Huettig & Janse, 2015).

Processing speed is closely linked to working memory. Being faster and processing information will not help if the individual's working memory capacity is too small to store the amount of information coming in. Conversely, having a large working memory capacity will not help if the information is coming in too slowly to efficiently use the capacity. Therefore, we also examined the relationship between verbal working memory and the ERP response to grammatical errors. Prior research suggests that greater working memory capacity is correlated with better comprehension of sentences and better anticipatory language prediction (Caplan et al., 2011, Huettig & Janse, 2015).

We would predict that individuals with faster processing speed and higher verbal working memory capacity would be more likely to process grammatical errors using their syntactic knowledge and abilities, as they have more resources to more deeply process the sentence. This would be evidenced by these individuals showing P600s to grammatical errors. Research has

suggested that individuals with greater verbal working memory capacity show larger P600s to grammatical errors (Oines, 2012, Ye & Zhou, 2008).

1.7. Goals of the Current Study.

The goal of the current study was to use ERPs to record real-time measurements of brain activity while participants read and processed sentences with and without grammatical errors. Using this data, we aimed to investigate what cognitive or biological factors may predict how an individual parses grammar. In so doing, we aimed to test Ullman's procedural-declarative model as well as explore what other individual differences may have an impact on one's ERP response to grammatical errors.

Ullman's model posits specific predictors for individual differences in the ERP response to grammatical errors. As the theory states that weak procedural memory skills will lead to weaker grammatical skills, we hypothesize that procedural memory ability and RDI will be positively correlated, such that greater procedural memory abilities will result in a greater P600 dominance in the ERP response to syntactic errors. On the other hand, individuals with weak procedural memory abilities will show more N400-like responses.

In addition to testing Ullman's model by examining the correlation between procedural memory ability and ERP response, we also sought to test factors that prior research found predicted the ERP response to grammatical errors. These factors include verbal working memory (Oines 2012), processing speed, handedness and familial sinistrality (Tanner and van Hell 2014), and gender (Osterhout lab, unpublished data). By examining these factors with a greater sample size, our goal was to see if we could replicate prior findings and link together the previous

research examining individual differences in ERP responses, as currently replication of findings in this domain has been lacking.

Chapter 2. Method

2.1. Participants.

Participants were recruited from Psychology 101 classes and participated for extra credit. 46 participants took part in in the experiment, but six were unable to complete the ERP session of the experiment, due to scheduling conflicts, resulting in 40 participants with complete datasets. 27 women and 13 men, ranging in age from 18 to 22 (mean 19.16, SD 1.24, no significant difference in age between women and men) completed both parts of the experiment. Left-handed participants were not excluded, in order to test any effect of handedness on the ERP effects. Handedness was tested using an abridged version of the Edinburgh Handedness Inventory (Oldsfield, 1971) and ranged from -1 (completely left-handed) to 1 (completely right handed, mean 0.65 +/- 0.399 SD). 15 participants had a first-degree left-handed family member (positive for familial sinistrality, or FS+) and 24 were FS-. See Table 1 for participant characteristics.

Table 1. Participant Characteristics and cognitive task scores.

Measure	Mean	St. Dev.	Range
Age at testing (years)	19.18	1.24	18.00 – 23.00
Handedness	0.65	0.39	-1.00 – 1.00
Gender	Men	Women	
	13	27	
Familial Sinistrality Status	FS+	FS-	
	15	24	

2.2. Cognitive Tasks

2.2.1. Declarative Memory Task.

Participants completed a paired associates task created in the lab, modeled on the paradigm in papers such as Paivio and Yarmey (1966). In this task, participants were shown twelve word pairs. The word pairs were presented in random order via a MATLAB program using the Psychophysics toolbox (Brainard, 1997, Pelli, 1997, Kleiner, Brainhard, and Pelli, 2007). Each word pair was shown on the computer screen for two seconds. After all the word pairs had been shown, the participant was given a 30 second break after which the word pairs were shown again in a different random order. After all the other cognitive tasks (described below) were completed, the participant was given a sheet of paper with the first word of the pair written and was instructed to take one minute to write down as many of the second words of the pairs as they could remember.

2.2.2. Procedural Memory Task.

The Serial Reaction Time Task (SRT Task) was used as a measure of procedural memory abilities. A MATLAB program was sourced from Owen Parsons and used the Psychophysics toolbox (Brainard, D.H., 1997, Pelli, D.G., 1997, Kleiner, M., Brainhard, D., and Pelli, D., 2007). In this task, the participant saw four boxes on the computer screen, corresponding to four keyboard responses (z, x, n, and m). An X appeared in one of the four boxes, and the participant was instructed to press the corresponding key as quickly as possible. The order of where the X appeared was calculated based on where the two prior X's appeared. The program looked up the next X location in a predetermined sequence. This sequence was too complex for the participants

to be consciously aware of it, as was confirmed by debriefing questions for a random selection of the participants. This order of presentation was the dominant order, referred to as trial type A, but occasionally an X would appear in a non-ordered location, referred to as trial type B. Participants were given 400ms plus or minus a jitter ranging from 0 to 200ms to respond to the X, otherwise the trial was counted as an error. Participants saw ten blocks of sixty trials each.

By comparing the reaction time (RT) between A and B-type trials across block, the participants' learning was assessed. The final score for correlating with ERP data was calculated by subtracting the mean RT of A trials for block 10 from the mean RT of B trials for block 10, then dividing by the mean RT of block 10 A trials, as this was where the difference in trial type was the largest.

2.2.3. Processing Speed.

To measure processing speed, participants completed a computerized nonword letter string speeded comparison task. This MATLAB program and the following were from the CogToolbox (Fraundorf et al., 2014) and used the Psychophysics toolbox (Brainard, D.H., 1997, Pelli, D.G., 1997, Kleiner, M., Brainhard, D., and Pelli, D., 2007).

Participants saw two rows of 3, 6, or 9 letters each and were instructed to indicate whether the strings were identical or different as quickly and accurately as they could via keyboard. Participants saw three blocks of each set size. Reaction time and number correct were recorded. The difference in reaction time and number correct between the first and last block were used as measures of processing speed.

2.2.4. Verbal Working Memory.

Participants completed the “rspan” task via a MATLAB program from the CogToolbox (Fraundorf et al., 2014) using the Psychophysics toolbox (Brainard, D.H. 1997, Pelli, D.G., 1997, Kleiner, M., Brainard, D., and Pelli, D., 2007). This version of the rspan task was based on Unsworth et al (2005) and Stine and Hindman (1994). In the rspan task, participants read a sentence, indicated whether it was a true or false statement, and then saw a letter that they had to remember. The participants had to remember the letters they saw after the sentences in the order that they saw them. The amount of time participants had to read the sentence and respond to the T/F prompt was based off of a calibration period prior to the actual task: the participant’s own mean RT + 2.5 SD. They had to remember two to six letters, and saw two blocks each of 2-6 letters (i.e. two blocks of 2 letters, two blocks of 3 letters, and so on).

Both the absolute and partial working memory scores were calculated from the data. The absolute score was the total number of letters recalled only from blocks where all the letters were remembered correctly. The partial score was the total number of letters recalled from all blocks.

2.3. Event-related Potentials

2.3.1. Sentence Stimuli. Sentence stimuli were the same as used in Mehravari et al. (2017).

There were 120 sentence quadruplets in a fully crossed 2 (semantic correctness) by 2 (grammaticality) design. Grammatical errors consisted of a subject-verb agreement violation, and semantic anomalies consisted of a word with poor semantic fit. This resulted in four types/conditions of sentences: 1) well-formed sentences, 2) sentences with a grammatical (syntactic) violation alone, 3) sentences with a semantic (meaning) violation alone, and 4) sentences with a double violation – a sentence with both grammatical and semantic violations. All violations, semantic and/or syntactic, were evident at the critical word in the sentence.

Critical words were either verbs in their base/uninflected form (e.g., belong) or in their third person singular present tense form (e.g., belongs). Each sentence condition (well-formed, grammatical violation, semantic violation, double violation) had two versions – one with the critical word in the base form and one in the –s form (see Table 2 for an example). This way the singular/plural status of the subject of the sentence could not be used to predict whether or not the sentence would contain an error. Therefore, there were only four different conditions of sentences (well-formed, grammatical violation, semantic violation, double violation), but with eight versions of each sentence (Table 2).

Table 2. Example Sentence Stimuli.

Condition	Sentences	Sentences with
Well-formed	The huge house still <u>belongs</u> to my aunt.	grammatical violations and
	The huge houses still <u>belong</u> to my aunt.	their grammatically correct counterparts used a set of 120
Grammatical Violation	The huge house still <u>belong</u> to my aunt.	unique verbs (in both their
	The huge houses still <u>belongs</u> to my aunt.	base and –s forms), and
Semantic Violation	The huge house still <u>listens</u> to my aunt.	sentences that contained a
	The huge houses still <u>listen</u> to my aunt.	semantic or double violation
Double grammatical & semantic violation	The huge house still <u>listen</u> to my aunt.	used a different set of 120
	The huge houses still <u>listens</u> to my aunt.	unique verbs. The two sets of

Note: the underlined word represents the critical word for ERP averaging (Mehravari et al., 2017).

verbs were chosen so that the average written word-form

log frequency (provided in the CELEX2 database (Baayen, Piepenbrock, & Gulikers, 1995)) of the verbs in the two sets was not significantly different (well-formed/grammatical verbs average

frequency = 0.59, semantic/double verbs average frequency = 0.56, $t = 0.441$, $p = 0.659$). This also took into account the average frequency of both the base and –s forms of the verbs in each set.

The eight versions of each sentence were distributed across eight experimental lists, so each participant only saw one version of each sentence. There were 15 sentences from each of the eight versions in each list, resulting in 30 sentences per condition in each list. Each list contained an additional 60 filler sentences, all grammatically correct. In total, each list contained 180 sentences. The sentence order in each list was randomized, and lists were divided into 3 blocks of 60 sentences each. Participants were pseudorandomly assigned one of the sentence lists.

2.3.2. EEG Recording.

During ERP recording, participants were seated in a comfortable recliner in front of a CRT monitor. Participants were instructed to relax and minimize movements and eye blinks while silently reading the stimuli.

Each trial consisted of the following events: a blank screen for 1000 ms, followed by a fixation cross, followed by a stimulus sentence presented one word at a time. The fixation cross appeared on the screen for 500 ms followed by a 400 ms interstimulus interval (ISI). Each word of the sentence appeared on the screen for 600 ms followed by a 200 ms ISI. After the final word of the sentence, there was a 1000 ms blank screen, followed by a “yes/no” prompt. Participants were instructed to indicate if the sentence was a good English sentence at the “yes/no” prompt, where “yes” was the response for sentences that were correct in all ways and “no” was the

response for sentences that were wrong in any way. Participants were instructed to make their best guess if they were not sure if the sentence was good or bad. The “yes/no” prompt remained on the screen until participants responded “yes” or “no”, as soon as a response was given, presentation of the next sentence began. Participants were pseudorandomly assigned to use either their left or right hand for the “yes” response.

Continuous EEG was recorded from 19 tin electrodes attached to an elastic cap (Electro-cap International) in accordance with the 10–20 system (Jasper, 1958). Eye movements and blinks were monitored by two electrodes, one placed beneath the left eye and one placed to the right of the right eye. Electrodes were referenced to an electrode placed over the left mastoid. EEG was also recorded from an electrode placed on the right mastoid to determine if there were experimental effects detectable on the mastoids. No such effects were found. EEG signals were amplified with a bandpass filter of 0.01–40 Hz (-3db cutoff) by an SAI bioamplifier system. ERP waveforms were filtered offline below 30 Hz. Impedances at scalp and mastoid electrodes were held below 5 k Ω and below 15 k Ω at eye electrodes.

Continuous analog-to-digital conversion of the EEG and stimulus trigger codes was performed at a sampling frequency of 200 Hz. ERPs, time-locked to the onset of the critical word in each sentence (underlined in the examples of Table 1) were averaged offline for each participant at each electrode site in each condition. Trials characterized by eye blinks, excessive muscle artifact, or amplifier blocking were not included in the averages. ERPs were quantified as mean amplitude within a given time window. All artifact-free trials were included in the ERP analyses.

2.4. Data Analysis

2.4.1. Grand Mean Analysis.

In accordance with previous literature, the following time windows were chosen: 300-500ms (N400), and 500-900ms (P600), relative to a 100ms prestimulus baseline (Mehravari et al., in press, Tanner et al., 2013, Tanner & van Hell 2014). Differences between sentence conditions were analyzed using a repeated-measure ANOVA separately for each condition: two levels of semantic correctness (semantically plausible, semantic violation), two levels of grammaticality (grammatical, ungrammatical). The double anomaly sentences were not examined for this study. ANOVA analyses for the data from midline (Fz, Cz, Pz), medial (right hemisphere: Fp2, F4, C4, P4, O2, left hemisphere: Fp1, F3, C3, P3, O1), and lateral (right hemisphere: F8, T8, P8, left hemisphere: F7, T7, P7) electrode sites were treated separately in order to identify electrode and hemispheric differences. ANOVAs on midline electrodes included electrode as an additional within-subjects factor (three levels), ANOVAs on medial electrodes included hemisphere (two levels) and electrode pair (five levels) as additional within-subjects factors, and ANOVAs over lateral electrodes included hemisphere (two levels) and electrode pair (three levels) as additional within-subjects factors. The Greenhouse-Geisser correction for inhomogeneity of variance was applied to all repeated measures on ERP data with greater than one degree of freedom in the numerator. In such cases, the corrected p-value is reported.

2.4.2. The Response Dominance Index.

The response dominance index, or RDI, was calculated from the response magnitudes for the N400 and P600 windows. These response magnitudes were calculated using mean amplitudes for the N400 and P600 windows comparing grammatical to ungrammatical stimuli in the syntactic condition. These mean amplitudes were averaged across the three midline

electrodes (Fz, Cz, and Pz), as these electrodes are where N400 and P600 effects are typically the largest (Tanner et al., 2014, Tanner & van Hell, 2014). The RDI compares the P600 effect magnitude to the N400 effect magnitude, quantifying which effect the participant's ERP most closely resembles (see Equation 1). The RDI was chosen as the outcome measure because it combines the participants' N400 response size and P600 response size to one error (grammatical) into one measure. This allows us to examine the participants' qualitative response to the error and allows us to categorize individuals, in contrast to just examining the P600 magnitude, which erases those individuals who show N400s to syntactic errors.

$$RDI = \frac{(P600_{ungram} - P600_{gram}) - (N400_{gram} - N400_{ungram})}{\sqrt{2}}$$

Equation 1. Equation for calculating the Response Dominance Index. Ungram: ungrammatical condition, gram: grammatical condition.

2.4.3. Individual Differences Analyses.

The RDI was compared to the individual difference variables by using simple correlations for the continuous measures (verbal working memory, procedural memory, processing speed, declarative memory, and handedness) and using independent samples t-tests for the categorical variables (gender and FS status).

2.4.4. Power Analyses.

Power analyses were carried out to both calculate power for a predicted effect size for the number of participants in the current study. See Table 3 for a summary of these findings.

Table 3. Power Analyses for simple correlation to detect $r = 0.30, 0.40$ and independent samples t-test to detect a difference of $2\mu\text{v}$ between groups.

Measure	Power for N=40
r of 0.30 between any variables	0.47
r of 0.40 between any variables	0.73
Difference of $2\mu\text{v}$ between groups	0.89

Chapter 3. Results

3.1. Grand Mean ANOVA Analyses.

Grand mean ERP results for semantic violations can be seen in Figure 2 and for grammatical violations in Figure 3. Data from the 300-500ms (N400) and 500-900ms (P600) time windows were analyzed separately.

3.1.1. 300-500ms (N400) Time Window.

There was a main effect of semantic correctness, with a larger N400 magnitude for the semantically incorrect sentences compared to the non-anomalous sentences (midline: $F(1,39) = 34.36, p < 0.001$, medial: $F(1, 39) = 34.25, p < 0.001$, lateral: $F(1, 39) = 33.845, p < 0.001$). These effects were larger in the posterior electrodes (electrode by condition interaction: midline: nonsignificant, medial: $F(2, 78) = 4.014, p = 0.034$, lateral: nonsignificant).

There was also a main effect of syntactic grammaticality during this time window, with a larger N400 magnitude to sentences with syntactic errors compared to grammatically correct sentences (midline: $F(1, 39) = 4.467, p = 0.041$, medial and lateral: nonsignificant). These effects were larger in frontal electrodes (condition by electrode interaction: midline: $F(2, 78) = 5.927, p = 0.041$, medial and lateral nonsignificant).

3.1.2. 500-900ms (P600) Time Window.

There was a main effect of syntactic grammaticality, where a larger P600 magnitude was evident in the grammatically incorrect sentences compared to the grammatical sentences (midline: $F(1, 39) = 16.885$, $p < 0.001$, medial: $F(1, 39) = 19.053$, $p < 0.001$, lateral: $F(1, 39) = 10.222$, $p = 0.003$). These effects were larger in posterior electrodes (condition by electrode interaction: midline: $F(2, 78) = 17.060$, $p < 0.001$, medial: $F(2, 78) = 11.102$, $p < 0.001$, lateral: $F(2, 78) = 13.457$, $p < 0.001$).

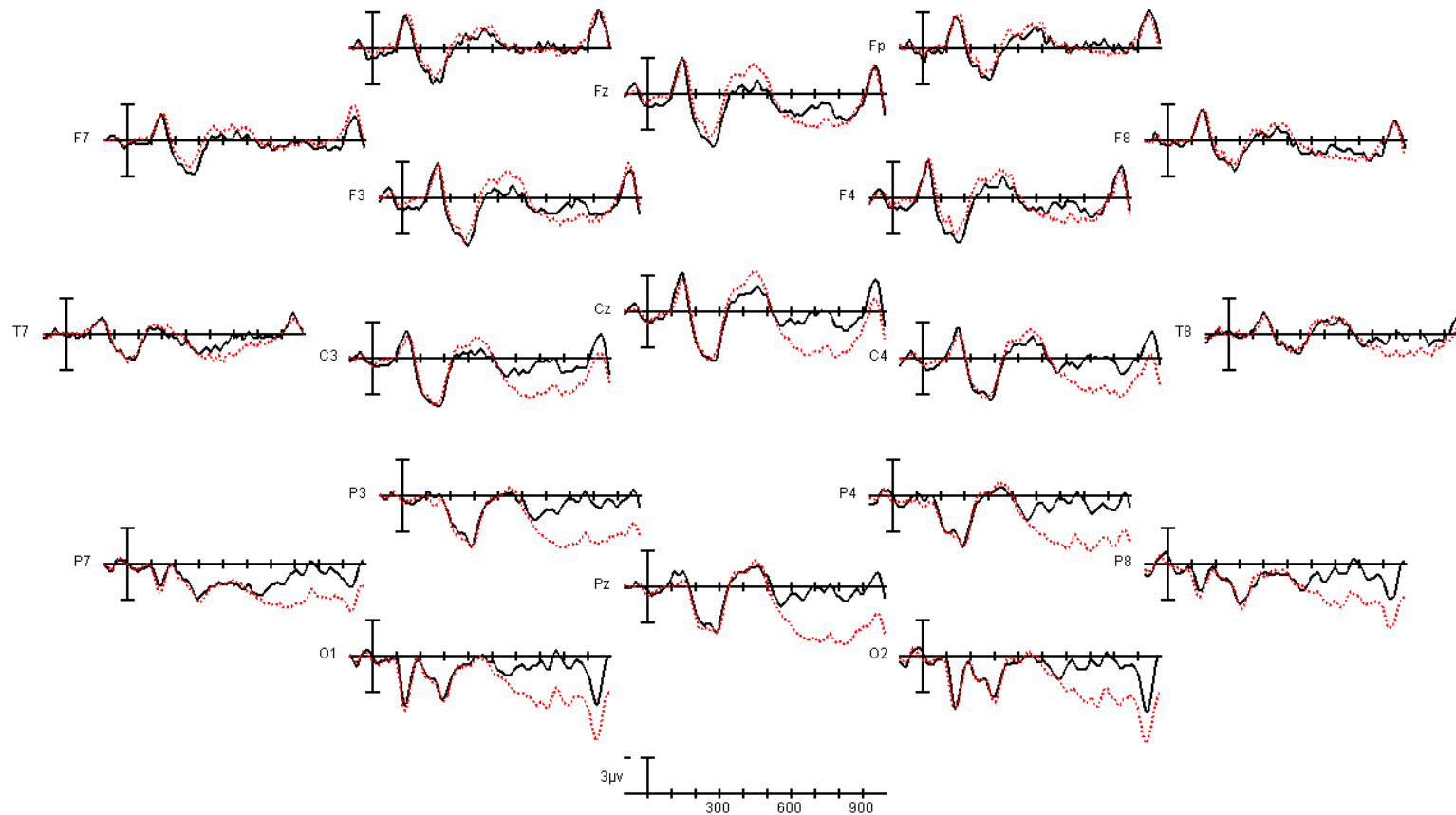


Figure 2. Grand mean ERP waveforms for sentences with syntactic violations (red line) and well-formed sentences (black line). Onset of the critical word in the sentence is indicated by the vertical bar. Calibration bar shows 3µV of activity, each tick mark represents 100ms of time. Negative is plotted up.

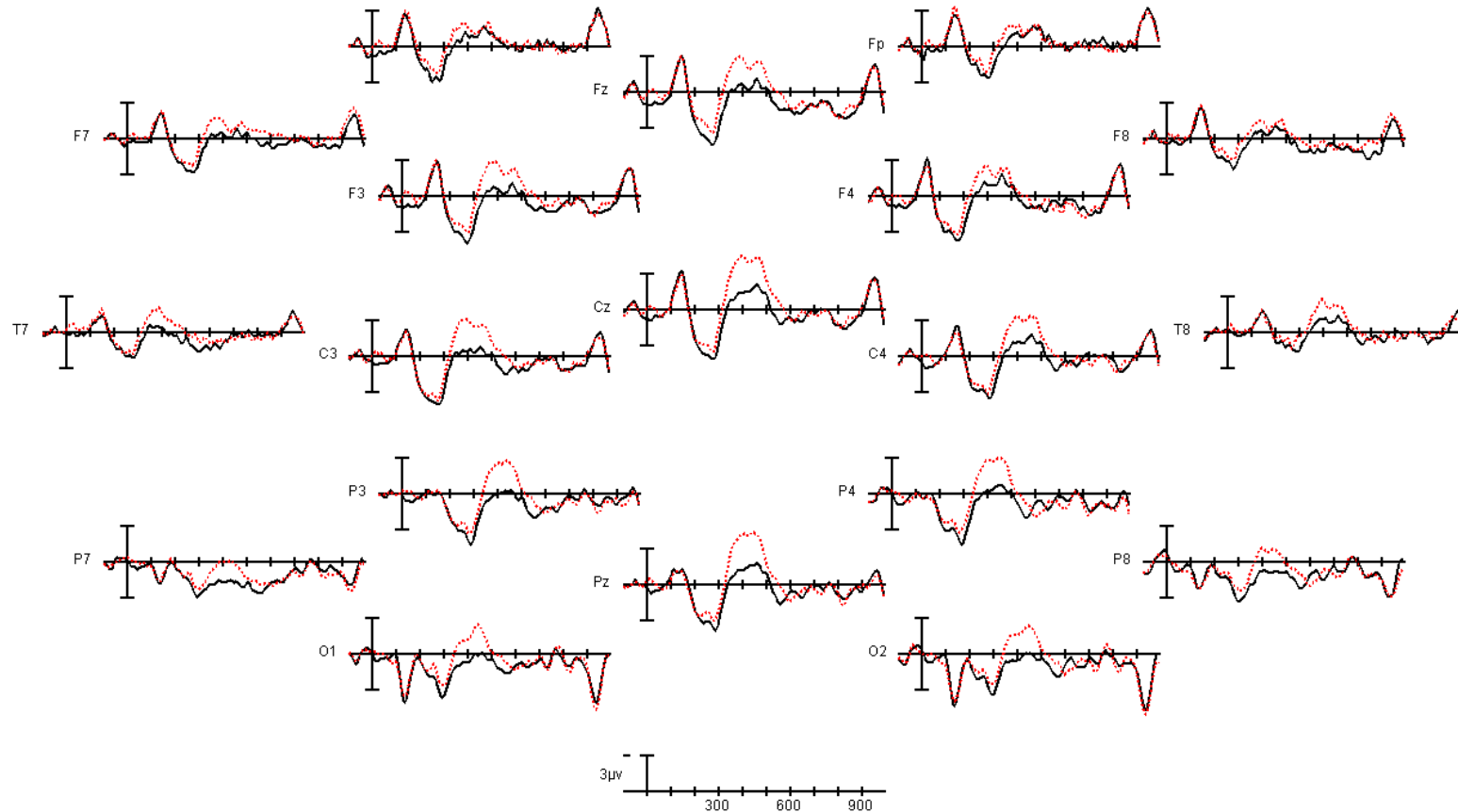


Figure 3. Grand mean ERP waveforms for sentences with semantic violations (red line) and well-formed sentences (black line). Onset of the critical word in the sentence is indicated by the vertical bar. Calibration bar shows 3µV of activity, each tick mark represents 100ms of time. Negative is plotted up.

3.2. Individual Differences Analyses

3.2.1. RDI.

As described in the methods section, effect magnitudes for the N400 and P600 window were calculated for the syntactic vs. grammatical conditions and used to calculate the RDI. When plotted against each other, the N400 and P600 effect sizes are negatively correlated (see Figure 4, $r(38) = -0.54, p < .001$). This replicates prior work indicating that the underlying processes resulting in an N400 and a P600 originate from separate brain areas and are in competition with one another when processing a syntactic error (Kuperberg, 2007, Osterhout et al., 2012, see Jackendoff, 2007, MacWhinney, Bates & Kliegl, 1984, for processing models that similarly propose a competitive dynamic between lexical/conceptual and syntactic cues, see also Morgan-Short, Faretta-Stutenberg, Brill, Carpenter & Wong (published online March 1. 2013).

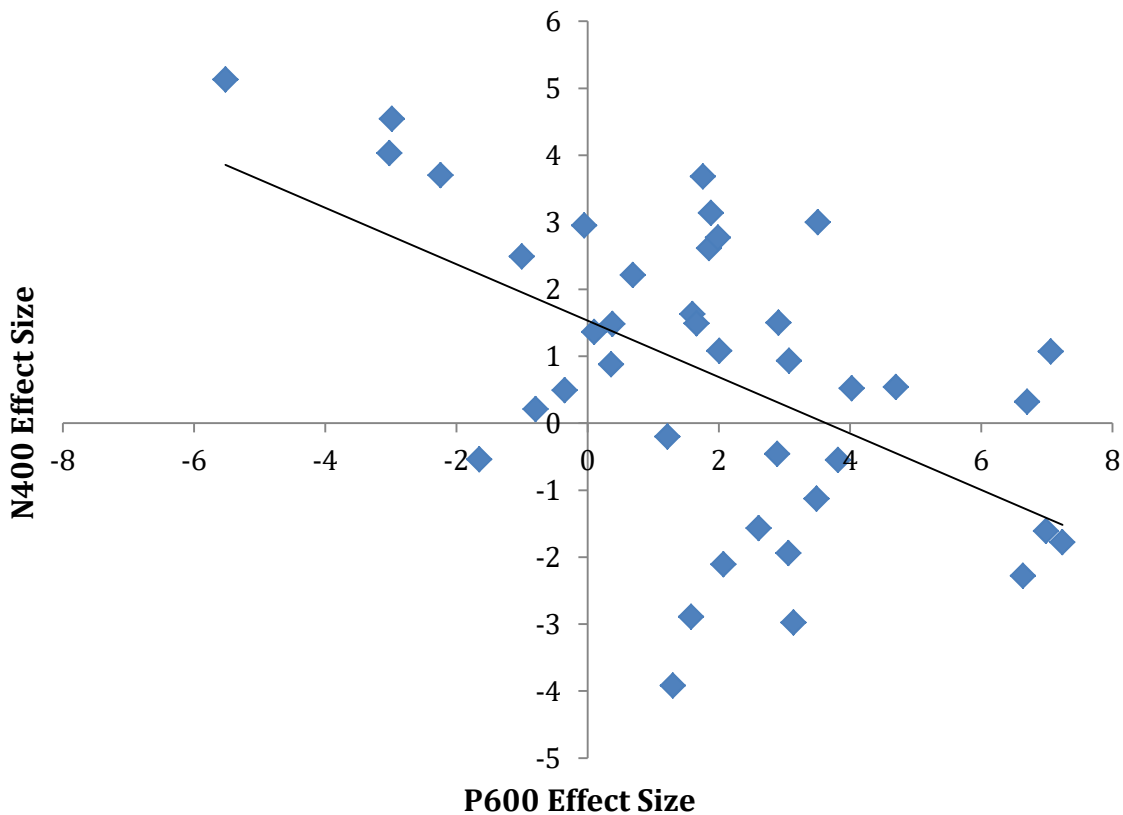


Figure 4. P600 effect magnitude plotted against N400 effect magnitude. Points are individual subjects. $r(38) = -0.54$, $p < .001$.

3.2.2. SRT Task Results.

The average reaction times by block and stimulus type can be seen in Figure 5. A within-subjects ANOVA indicated a main effect of experiment block ($F(9, 333) = 5.517$, $p < .001$) and of stimulus type ($F(1, 37) = 52.264$, $p < .001$). There was no significant interaction. Visual inspection indicates that participants' RT got faster with block and RT for A-type stimuli were

faster than for B-type stimuli (Figure 5).

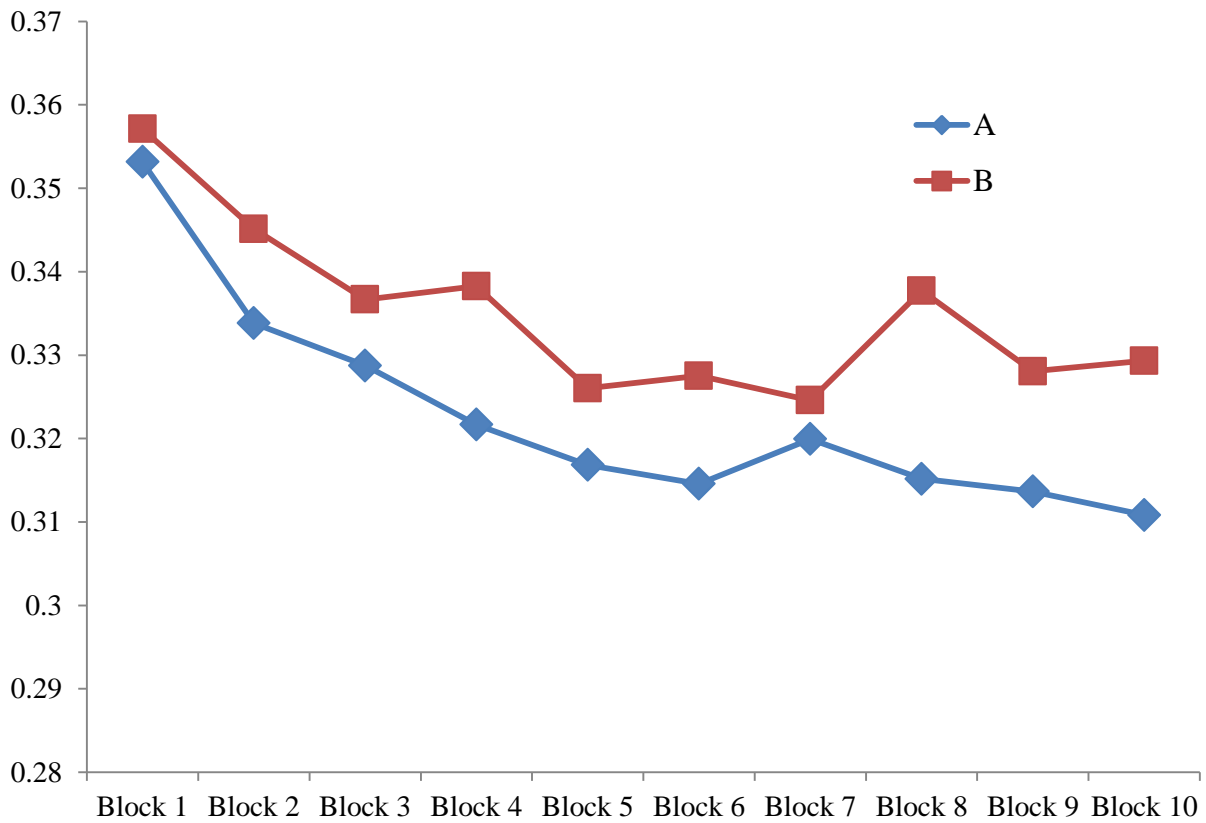


Figure 5. Reaction times (sec) by block and by stimulus type (expected – A vs. unexpected – B).

3.3.3. Correlations.

There were no significant correlations between the individual difference variables and RDI (see Table 4). See Table 5 for descriptive statistics for the measures used in these correlations.

Table 4. Correlations between predictor variables and RDI. All $p > 0.05$

Predictor Variables	r value with RDI
Handedness	0.123
Paired Associates	0.158
SRT Score	-0.141
RSpan Partial Score	0.099
Perceptual Speed RT Difference	0.002
Perceptual Speed # Correct Difference	-0.116
Overall D'	0.082

Table 5. Descriptive statistics for the cognitive tasks used in the correlational analyses.

Measure	Mean	St. Dev.	Range
Paired Associates Score	6.87	2.80	1.00 – 12.00
SRT Task Score	-0.06	0.09	-0.34 – 0.14
Processing Speed score (RT difference)	1.10	0.58	-0.11 – 2.67
Processing Speed score (# correct difference)	-23.67	5.39	-34.00 – -11.00
rspan score	28.27	8.29	9.00 – 40.00
Overall D'	2.75	0.94	1.22 – 5.77

3.3.4. T-Tests.

There was no significant effect of FS status on RDI, in contrast to prior research that did find such an effect ($t(37) = -1.336, p = .190$) (Tanner & van Hell 2014). There was no significant effect of gender on RDI ($t(38) = 1.109, p = 0.275$), in contrast to prior research in the Osterhout lab (unpublished). There was a significant difference in the size of the N400 to grammatical errors between men and women ($t(37) = -2.258, p = 0.03$), where men had larger N400 effect magnitudes ($M=1.836, SD=1.859$) to syntactic errors compared to women ($M=0.220, SD=2.232$) (Figure 6). There were no significant differences in the size of the P600 to grammatical errors for FS status or gender. Visual inspection of the waveforms for men and women suggest that women

showed a P600 alone to grammatical errors, while men showed both an N400 and P600 (see Figure 7).

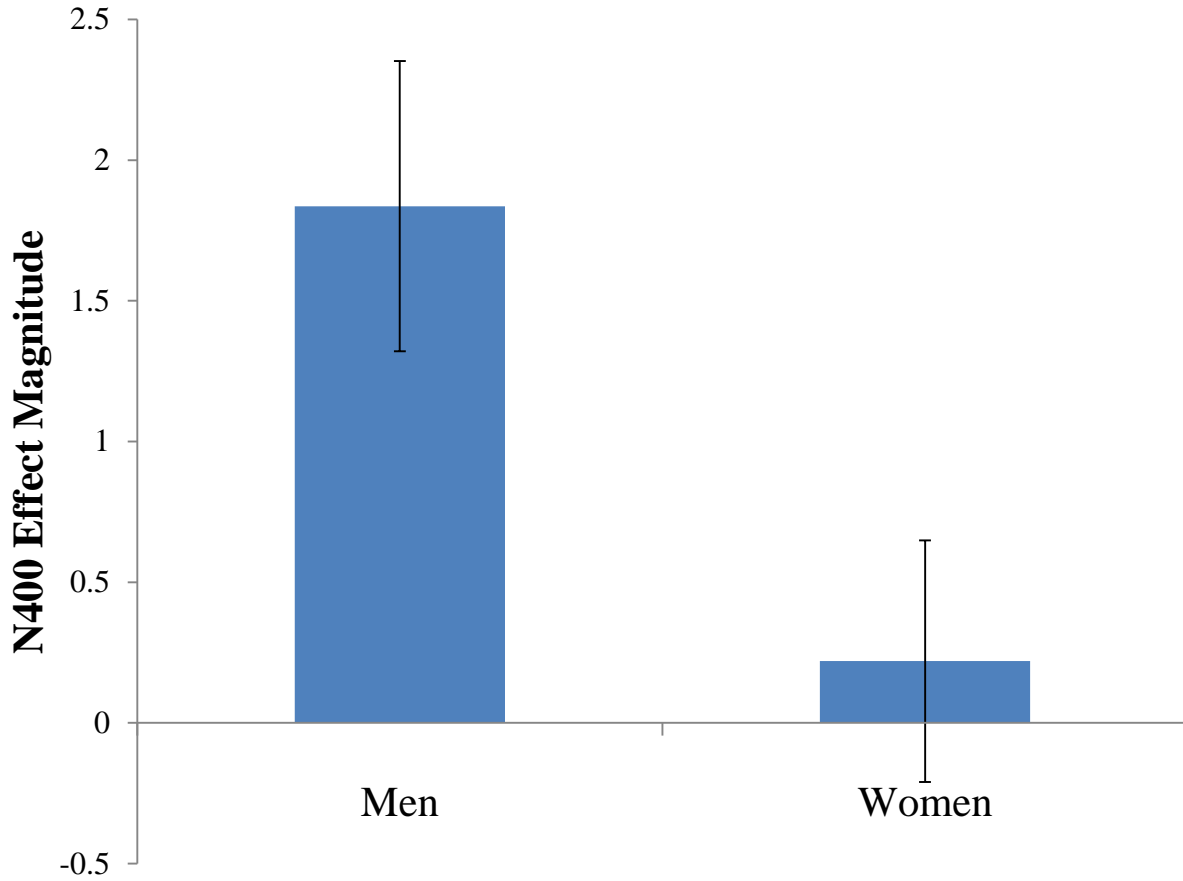


Figure 6. N400 Effect Magnitude to syntactic errors by gender. Error bars are ± 1 SE.

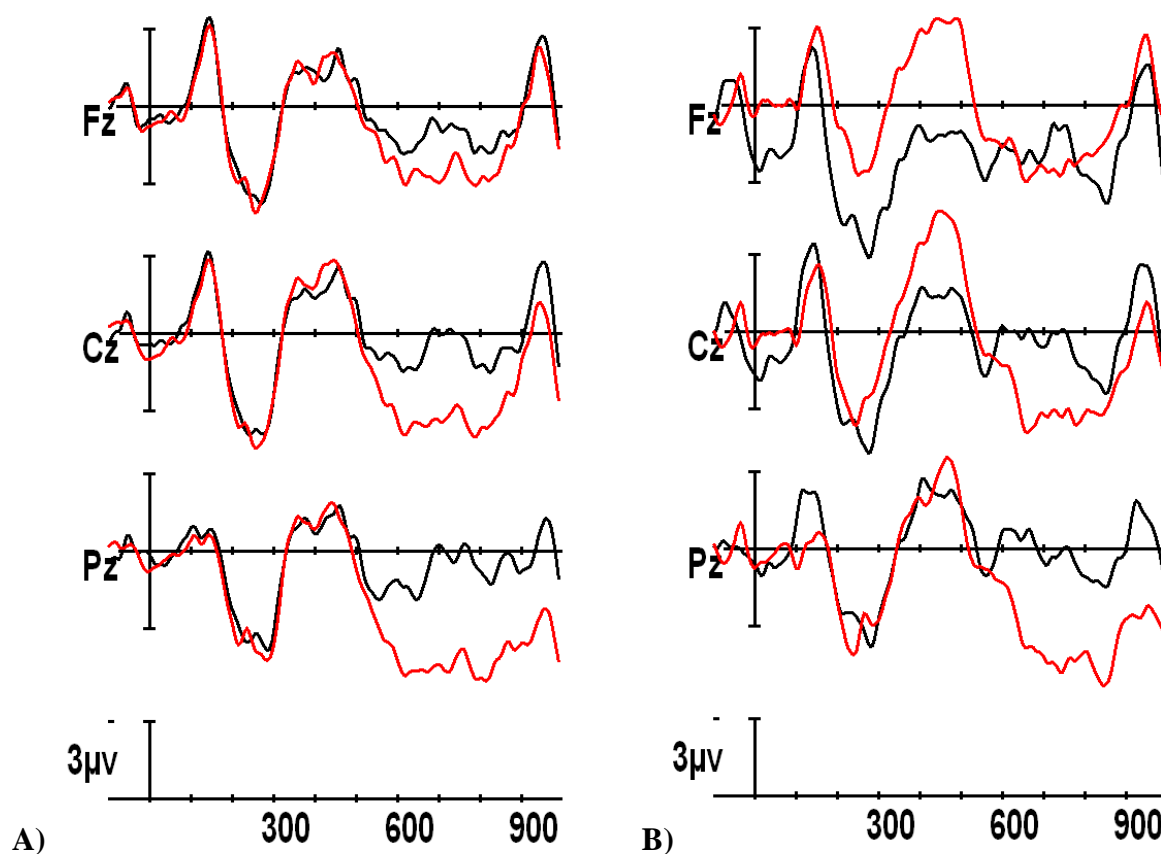


Figure 7. Grand mean waveforms for women (N=27, A) and men (N=13, B). Electrodes Fz, Cz, and Pz shown. Syntactic violations (red line) and well-formed sentences (black line). Onset of the critical word in the sentence is indicated by the vertical bar. Calibration bar shows 3µV of activity, each tick mark represents 100ms of time. Negative is plotted up.

Chapter 4. Conclusion

4.1. Summary of Results.

In this study, we examined the relationship between the RDI and various cognitive and biological factors. Procedural memory abilities did not correlate with the RDI, suggesting that Ullman's Declarative-Procedural model does not hold for individuals without SLI. None of the

other variables we examined correlated with RDI, and so we failed to replicate several earlier studies which found relationships between cognitive factors and the ERP response.

4.2. Relationship to Prior ERP Research.

Before discussing the implications of these results, it is important to place them in the context of earlier ERP studies.

4.2.1. Grand Mean Replications.

We replicated the typical pattern of N400s elicited by semantic errors and P600s elicited by grammatical errors as shown by the grand mean ANOVA results. Examining the syntactic errors in particular, our participants did show P600s, as shown by the main effect of grammaticality in the grand mean ANOVA analyses of the P600 window. This replicates prior studies (Osterhout, Holcomb, & Swinney, 1994, Osterhout & Holcomb, 1992, Osterhout & Nicol, 1999, among others).

4.2.2. Individual Difference Replications.

We also saw a main effect of grammaticality in the N400 window to sentences with grammatical errors alone compared to grammatically correct sentences, indicating that some of the participants showed N400s to the grammatical errors. This replicates more recent findings of individual differences in ERPs to grammatical errors (Tanner & van Hell 2014, Osterhout et al. 2004, Pakulak & Neville 2010). We also replicated the negative correlation between the N400 and P600 effect magnitudes first shown by Tanner, Osterhout, and Inoue (2009).

We failed to replicate many of the relationships previously found between the ERP response and cognitive ability or biological variables. We did not find a relationship between

verbal working memory and RDI, unlike Oines (2012). We also failed to replicate any relationship between handedness or familial sinistrality and the RDI, in opposition to research by Tanner and van Hell (2014). We found no gender differences in the RDI, failing to replicate our lab's unpublished data, but found differences in the size of the N400 effect to syntactic errors between men and women, suggesting that some of the gender differences found in children may stay through adulthood.

4.3. Implications for the Declarative-Procedural Model.

We did not find evidence supporting Ullman's Declarative-Procedural model, as there was no significant correlation between procedural memory ability and the RDI. This was true even though the participants did learn over the course of the procedural learning task, so it was not a failure of the task to measure procedural learning abilities. There was also a fair range of procedural memory abilities in the participants (see Table 5). This is not likely due to a lack of power in the study. The correlation found was very low ($r = -0.141$) and to find a significant result for this correlation coefficient, the sample size would have to be 393 participants (assuming $\alpha = 0.05$, $\beta = 0.20$, $N = [(Z_{\alpha} + Z_{\beta})/C]^2 + 3$, $C = 0.5 * \ln[(1+r)/(1-r)]$). At that large a sample size, the correlation would not be very meaningful, particularly as it would only account for 1.99% of the variance in RDI. Additionally, the small correlation found is in the opposite direction that the Declarative-Procedural model would predict for the relationship between procedural memory ability and ERP response to syntactic errors. Conversely, the Declarative-Procedural model predicts a robust correlation between procedural memory skill and grammatical processing.

The lack of relationship may be explained by an over-reliance on examining individuals with SLI in the previous literature where a relationship between procedural memory abilities and grammatical abilities was found. Specific language impairment reflects an extreme case of dysfunction, where it very well may be the case that procedural memory plays an important role in grammatical processing ability. However, in healthy adults working within their native language, this relationship may vanish because all parts of the system are functioning properly. Hence, procedural memory may be a necessary, but not sufficient component of native language syntactic processing. That is, when procedural memory systems fail, grammatical processing suffers, as in individuals with SLI. However, when procedural memory systems are intact, there are other factors which more heavily influence syntactic processing abilities.

Therefore, the Declarative-Procedural model of Language may overstate the role of the two memory systems in subserving linguistic abilities. From the current study, we cannot claim that individuals with lower than average procedural memory abilities rely on their declarative memory systems, as these were not the individuals who showed N400-like responses to grammatical errors. Consequently, individuals with SLI do not appear to be at the low end of a continuum of procedural and grammatical abilities. Instead, they more likely represent a qualitatively different medical disorder state where procedural memory abilities have an impact on grammatical abilities which is not seen in healthy individuals.

4.4. Implications for Gender Differences.

We failed to find a difference in the RDI between genders; however, we did find that men showed both N400s and P600s to grammatical errors, while in women only P600s were elicited. This suggests that men may be relying on their word decoding skills to a degree not seen in

women, but not to the point of not using syntactic analysis at all. Men appear to be more variable in their ERP response to grammatical errors than women, perhaps reflecting greater variation in which stream of processing they prefer when dealing with syntactic anomalies. This is consistent with prior research indicating that in children, reading comprehension is best predicted by word decoding skill in boys whereas girls' reading proficiency is better predicted by the ability to integrate information across the passage (Hannon, 2014).

4.4.1. The “Good Enough” Reading Strategy.

First proposed by Ferreira and colleagues (2002), the “Good Enough” reading strategy stands in opposition to the standard model of sentence processing, where complete syntactic structures are always computed during reading. In fact, sometimes studies showed that only word meanings were being processed, and syntactic computation was limited or even absent (Ferreira 2003). Due to lower motivation to read and poorer language skills when entering school (McGeown et al. 2012, Logan & Johnston date, Locke, Ginsborg, & Peers 2002), we hypothesized that men may use this “Good Enough” reading strategy, particularly as men have a strong relationship between their word decoding skills and reading comprehension (Eriksson et al. 2011, Hannon 2014, Locke, Ginsborg, and Peers 2002). This theory posed specific predictions for language ERPs: if women were analyzing syntactic structures, ungrammatical sentences should then elicit P600s, reflecting syntactic reanalysis. If men were processing word meanings to parse grammatical errors, they could be processed the same as semantic errors, and therefore elicit N400s.

The data do not suggest that men use a “Good Enough” reading strategy to the degree hypothesized, where they would only use word decoding skills, as they did show P600 effects to

grammatical errors. However, men also showed N400 effects in addition to the P600 effects, which may suggest that they are relying on their word decoding skills in addition to syntactic analysis to parse the sentences. Women, on the other hand, are relying only on their grammatical analysis, shown the syntactic violations only eliciting a P600 for the women.

4.4.2. Variation Across Studies of the P600 Effect

The gender difference found here may also help to explain the variability found across studies examining the P600 effect. Some studies claim that the P600 is purely syntactic, as they only found P600s elicited by syntactic anomalies. Other studies find something called the Left Anterior Negativity (LAN), a negativity to certain types of morphosyntactic anomalies most prominent over the left anterior electrodes (see Frederici, 2002, 2011 for a review). However, recent examination of the LAN suggests that it is actually caused by individual variation, with enough subjects eliciting N400s to syntactic errors to show a small negativity in the grand mean, which was considered a LAN, but could be better analyzed looking at individual differences (Tanner, 2015, Tanner & van Hell, 2014).

This variability could be due to differing gender ratios in the studies. A study with a greater proportion of men could have enough individuals showing an N400 effect to syntactic errors for it to show up in the grand mean. Conversely, a sample with a preponderance of women would be more likely to show a more “pure” P600 effect to syntactic errors. A meta-analysis examining the effect of the gender ratio of subjects to the size and/or existence of the LAN could help to clear up the controversy over the existence of the LAN and the variability in the size of the P600 effect to different types of grammatical anomalies.

4.5. Implications for ERP Research.

The field of using ERPs for individual differences research is still quite young. Only a few studies have looked at ERPs by individual, and even fewer have investigated these differences in the participants' native language. The results from this study provide another strong argument that ERPs can be used for individual differences research, as there was extensive variation in the response to grammatical errors.

This suggests that, contrary to prior opinions in the literature, not everyone processes grammar in the same way, even in their native language. The P600 effect is not universal, and so it is important to continue to explore what may be influencing how people respond to syntactic errors in sentences in order to better inform theories of reading and language processing. It is important to note that we must first understand how native speakers process their own language before being able to properly interpret research into learners of a second language. Prior research has found that L2 learners can show N400s to grammatical errors, and the conclusion drawn was that they were not yet processing their second language in a native-like way. However, the current study suggests that a non-insignificant minority of native speakers show N400s to grammatical errors. More research must be done to see if L2 N400 effects are truly a stepping stone towards "native-like" processing or if some individuals always show N400 effects to syntactic errors, in both their native and second languages.

4.6. Limitations.

There are, of course, limitations to what the results from this study can tell us. First, the participants in this study were adults. Inferences can be made about how learning to read in

childhood can inform adult language processing, however it would be useful to use a similar paradigm in children as they learn to read to investigate the gender differences at their source.

Second, the only measure of reading proficiency was the participants' d' score from the acceptability judgment of the sentences. While this was a good measure of whether the participant was, for one, paying attention and two, able to make relatively simple judgment calls on the grammaticality of a sentence, it lacks the nuance and power that a test designed to measure reading proficiency would provide. Further research using a reading proficiency test designed for the participant group, whether it be children or skilled adults, would add a great deal to our knowledge of how ERP responses relate to actual reading skill.

4.7. Final Conclusions.

This study was designed to investigate the individual differences in how grammatical errors are processed by examining the ERP response to syntactic errors. We failed to replicate prior predictions based on Ullman's Declarative-Procedural model of language and prior literature which found that handedness and verbal working memory related to the ERP response.

Our failure to support Ullman's Declarative-Procedural model of language does not necessarily mean that the procedural memory system is unrelated to syntactic processing. Instead, we suggest that this theory holds when examining individuals with SLI, where there is a disorder involving the procedural memory system as shown by many studies (Conti-Ramsden, Ullman, & Lum 2015, Gabriel et al. 2013, Hsu & Bishop 2014, Kemény & Lukács 2010, Lum et al. 2014). In these cases, there is a clear relationship between impaired procedural memory skills and the impairment of the grammatical processing system. However, in healthy adults, when

everything is functioning normally, other factors play a more important role in grammatical processing ability.

The difference in the size of the N400 effect to syntactic errors between men and women suggest that men are more variable in their processing of syntactic anomalies. This corresponds with research examining differences in reading proficiency in children, and suggests that men may rely more heavily on word decoding skills than women. It also may help explain the variation seen across studies looking at the ERP response to syntactic errors, where some studies find only a P600, but others find a LAN and P600.

The results from this study also strongly support the use of ERPs in individual difference research. The data reveal that variation exists even in populations previously thought to be homogeneous, which has important implications for future research using similar paradigms.

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