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UNIVERSITY OF CALIFORNIA, SAN DIEGO

Event-related brain potential investigations of

left and right hemisphere contributions to syntactic processing

A dissertation submitted in partial satisfaction of the
requirements for the degree Doctor of Philosophy

in

Cognitive Science

by

Laura Kemmer

Committee in charge:

       Professor Marta Kutas, Chair
       Professor Seana Coulson
       Professor Jeffrey Elman
       Professor Steven Hillyard
       Professor Robert Kluender

2009

The Dissertation of Laura Kemmer is approved, and it is acceptable in quality and form for publication on microfilm and electronically.

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Chair

University of California, San Diego

2009

DEDICATION

This dissertation is dedicated to the memory of my mother.

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CURRICULUM VITAE

Education

2009   **Ph.D.**, Department of Cognitive Science
                        University of California, San Diego
                        Thesis committee chair: Dr. Marta Kutas

2003   **M.S.**, Department of Cognitive Science
                        University of California, San Diego

1992   **M.A.**, Slavic Linguistics
                        Department of Slavic Languages and Literatures,
                        University of Washington; Seattle, Washington

1989   **B.A.**, *cum laude*, Macalester College; St. Paul, Minnesota
                        Majors: Russian Language and Literature; International Studies;
                        Russian Area Studies. Minor: Political Science

Professional History

2006   Teaching Assistant, Neuroanatomy and Physiology
2005- 06, 2000 - 01   Predoctoral Fellow, NIH/NIDCD Training Grant in Language,
                        Communication, and Brain to the Center for Research in Language
                        (2T32DC000041)
2004 - 05, 2002 - 03   Predoctoral Fellow, NIH/NIMH Training Grant in Cognitive
                        Neuroscience to Institute for Neural Computation (2T32MN020002)
1999 - 2006   Graduate Student Researcher, Kutas lab
2001   Teaching Assistant, Introduction to Human Development
2000   Teaching Assistant, Neurobiology of Cognition
2000   Teaching Assistant, Introduction to Cognitive Science: Minds and
                        Brains
1998   Instructor, Intensive Second Year Russian (summer quarter),
                        University of Washington
1991 – 1992   Instructor, Intensive First Year Russian (summer quarters),
                        University of Washington
1990 – 1992   Instructor, First Year Russian (academic year), University of
                        Washington
1991   Research Assistant for Dr. James Augerot, Slavic Department,
                        University of Washington

Publications and Presentations

Research articles.

Kemmer, L., Coulson, S., De Ochoa, E., and Kutas, M. (2004). Syntactic processing with
        aging: an event-related potential study. *Psychophysiology*, 41(3): 372-84.

Kemmer, L. (2001). Grammatical number agreement by the two cerebral hemisphere.
        Unpublished master's thesis. Department of Cognitive Science, University of
        California, San Diego.

Published abstracts.

Kemmer, L., Coulson, S., and Kutas, M. (2006). Salience of grammatical violations, but not verb (ir)regularity, affects the P600: an event-related brain potential study [Abstract]. Cognitive Neuroscience Society Meeting.

Kemmer, L. and Kutas, M. (2005). Salience and syntactic processing across the hemispheres: an event-related brain potential (ERP) study [Abstract]. Organization for Human Brain Mapping.

Kemmer, L., Coulson, S., and Kutas, M. (2004). Left and right hemisphere contributions to syntactic processing: an event-related brain potential study [Abstract]. Society for Neuroscience.

Kemmer, L., Coulson, S., De Ochoa, E., and Kutas, M. (2004). Spanning the ages: an electrophysiological analysis of grammatical number agreement [Abstract]. Cognitive Neuroscience Society Meeting.

Groppe, D., Kemmer, L., Kutas, M., & Makeig, S. (2004). Within-subject reliability of independent component analysis of the electroencephalogram in two text processing tasks [Abstract]. Cognitive Neuroscience Society Meeting.

Kemmer, L., Coulson, S., and Kutas, M. (2003). Grammatical number agreement processing using the visual half-field paradigm: an event-related potential study [Abstract]. Cognitive Neuroscience Society Meeting.

Kemmer, L., Coulson, S., De Ochoa, E., and Kutas, M. (2002). A point of agreement between generations: an electrophysiological study of grammatical number and aging [Abstract]. *Psychophysiology, 39, Supplement 2,* S46.

Awards and Honors

Graduate:
Fellowships:
Fellowship, Center for Research in Language NIH/NIDCD Training Grant, 2000-01; 2005-06
Fellowship, NIH/NIMH Training Grant in Cognitive Neuroscience, 2002 – 2003; 2004 – 2005
Fellowship, US Department of Education Foreign Language and Area Studies, 1998
Social Science Research Council Fellowship (administered through CIEE), 1991

Travel awards:
NIH/OHBM Travel Award, Organization for Human Brain Mapping conference, June 2005
UCSD Social Science Dean's Travel Fellowship, Spring 2005
UCSD Department of Cognitive Science Travel award, 2004-2005
UCSD Department of Cognitive Science Travel award, 2003-2004
UCSD Social Science Dean's Travel Fellowship, Fall 2002
Travel grant for ICPSR Summer Program in Quantitative Methods of Social Research, 2001

Undergraduate:
4 year National Merit Scholarship, awarded 1985
National Association of Letter Carriers four year scholarship, 1985-1989
CSC Alumnae Honor Scholarship, 1985
Georgiana P. Palmer Scholarship, 1986-89
International Study Scholarship, 1988
Homer P. Cochran Scholarship, 1988-89
Virginia McKnight Binger prize, 1989
ACTR Grant, 1989: full grant for studying Russian at Bryn Mawr College, summer 1989

ABSTRACT OF THE DISSERTATION

Event-related brain potential investigations of

left and right hemisphere contributions to syntactic processing

by

Laura Kemmer

Doctor of Philosophy in Cognitive Science

University of California, San Diego, 2009

Professor Marta Kutas, Chair

Syntactic processing is widely held to be a left hemisphere (LH) phenomenon, a view influenced by a large body of research showing lesions to certain LH areas are far more devastating than are lesions to corresponding right hemisphere (RH) areas. Although few studies have examined whether RH damage causes subtle syntactic processing deficits, there is evidence it does. This dissertation investigated the relative contribution of each hemisphere to syntactic processing in neurologically normal individuals using event-related potential (ERP) and behavioral studies in combination with the visual half-field paradigm. Central presentation ERP studies were conducted as a baseline against which to compare

the results of the lateralized studies. The first experiment series (chapters two, three) examined processing of (in)correct grammatical number agreement marked either lexically or morphologically. Both behavioral and ERP results suggested the hemispheres are equally able to appreciate lexically marked agreement. In contrast, the RH appears to have greater difficulty than the left in processing morphologically marked agreement. The second experiment series (chapters four, five) investigated whether this LH advantage for morphologically-marked agreement errors reflects a language-specific difference in hemispheric processing or a low level, perceptually-based difference. Stimuli included both morphological and lexical conditions; salience of lexical markings was manipulated to adjudicate between these alternatives. Behavioral results suggested that the observed processing differences were based at the perceptual level. However, the ERP results obtained were not in accord with the predictions and did not lend themselves to any clear conclusions with respect to the hypothesis investigated. The central presentation studies in chapter two also investigate how aging affects syntactic processing. ERPs from elderly compared to young participants showed no evidence of an age-related delayed or diminished P600 effect, although there were changes in its scalp distribution, suggesting a qualitative, rather than any strictly quantitative, age-related change in speed of processing. Chapter four provides data relevant to the debate concerning the mental representation(s) of regular and irregular words, and the mental processes underlying the left anterior negativity component. Overall, we find that the RH is sensitive to certain grammatical manipulations, although not always in the same manner as the LH.

Chapter 1

Overview of the dissertation

1.1. Introduction

The overarching goal of this dissertation was to investigate syntactic

processing of language with an emphasis on investigating what each of the

hemispheres contributes to syntactic processing. It has long been assumed that the

right hemisphere contributes little, if anything to syntactic processing. There is a

great deal of research, particularly with patient populations, which suggests that the

left hemisphere's contribution to syntactic processing is far more important than that

of the right. To a great extent, this is due to the finding that lesions to certain areas

of the left hemisphere can produce serious deficits in syntactic processing, whereas

lesions to the same areas of the right hemisphere generally do not cause easily

apparent deficits in syntactic processing. However, the observed dominance of the

left hemisphere for syntactic processing does not necessarily imply exclusivity. It

may be the case that the right hemisphere contributes in some way to syntactic

processing (or to certain aspects of syntactic processing) but because of the left

hemisphere's dominance and/or the subtle nature of the right hemisphere

contribution, deficits after right hemisphere damage may not be as easily apparent.

Relatively few studies have investigated a potential right hemisphere

contribution to syntactic processing, but there are studies which suggest that it does

contribute; these studies are discussed in the Introduction sections of chapters 3

and 5 of this dissertation. Such studies make it clear that additional research is

necessary to achieve an understanding of what contribution the right hemisphere

may be making. Most of these studies have involved patient populations who have experienced neurological damage and in whom neural processing, including syntactic processing, may be atypical. Thus, in the studies presented in this dissertation, we examined the processing capabilities of each hemisphere using individuals without any history of neurological problems. To this aim, we combined the visual half-field paradigm with event-related brain potentials (ERPs) and behavioral measures. Although with normal brains there is no experimental way to test the functioning of one hemisphere independent of the other, the visual half-field paradigm allows researchers to approximate such a hypothetical experiment. The differences in processing which are frequently observed as a function of which hemisphere the stimulus goes to initially provide a window through which we can begin to understand hemispheric contributions to processing.

1.2. Chapter 2

Chapter 2 presents two ERP experiments examining processing of grammatical number agreement in younger (college age) and older (aged 60 to 80 years) adults. For the purposes of this dissertation, the results from the younger participants are of most interest as all other studies presented examine grammatical processing in young adults. In this study, we examined processing of violation and corresponding control sentences using subject/verb number agreement and reflexive pronoun/antecedent number agreement (see Table 2.1 in chapter 2 of this dissertation for sample sentences) with critical words presented to central visual field. The results from this study provide an important baseline of the ERP effects elicited by our experimental stimuli for central presentation, against which our

experiment using lateralized presentation of critical words (see chapter 3 of this dissertation) could be evaluated.

1.2.1. Results from the younger participants

We had some idea of what ERP effects our stimuli should elicit, as Osterhout and Mobley (1995) had previously examined grammatical number using subject/verb and reflexive pronoun/antecedent number agreement. In a series of experiments, they found for both sentence types that violations relative to controls elicited an ERP waveform which was more positive going beginning at about 400 ms post-stimulus and centro-parietally distributed – in other words, a P600 effect. Additionally, in one of Osterhout and Mobley's experiments (experiment 1), they observed a left anterior negativity (LAN; see chapter 4 for extensive discussion of the LAN and the P600 components) for the 300 to 500 ms time window; however, this effect did not replicate in their experiment 3, for reasons which were unclear. Indeed, as discussed in chapter 4, reports of LANs in the literature are inconsistent. Thus, we expected that our violations would elicit a P600 for ungrammatical violations compared to grammatical controls but were uncertain whether we would observe a LAN. Our results showed no LAN whatsoever. The P600 we observed was consistent with other reports of P600s in the literature: the ERPs in the ungrammatical condition were characterized by a sustained centro-parietal positivity with an onset at about 450 ms and lasting about 800 ms over posterior sites.

1.2.2. LAN

In this experiment, our stimuli did not elicit a LAN – there was absolutely no hint whatsoever of one (in either the younger or older adults). This finding is important to the issue of elucidating what processes the LAN reflects and what the

antecedent conditions for LAN elicitation are. Chapter 4 discusses in detail the

often conflicting findings in the literature on the LAN. Although named "left anterior

negativity", the LANs reported in the literature are not always "left": they may be

more prominent over left sites but still fairly prominent over right sites, or they may

be bilaterally distributed (Angrilli et al., 2002; Coulson, King, & Kutas, 1998; Hagoort

& Brown, 2000; Osterhout & Mobley, 1995; Rossi, Gugler, Hahne, & Friederici,

2005).

Friederici (2002) hypothesized that the LAN reflects morphosyntactic

processing and correlates specifically with morphosyntactic errors. However, a

considerable percentage of studies in the literature do not support this hypothesis.

For example, LANs were not elicited by violations of subject/verb agreement

(English: Coulson et al., 1998; Kemmer, Coulson, De Ochoa, & Kutas, 2004;

Osterhout, McKinnon, Bersick, & Corey, 1996; Osterhout & Mobley, 1995 (LAN

reported for exp. 1 but not exp. 3); Dutch: Hagoort & Brown, 2000 (exp. 1, visual);

Hagoort, Brown, & Groothusen, 1993; German: Munte, Szentkuti, Wieringa,

Matzke, & Johannes, 1997) or to violations of verb inflections (Gunter, Stowe, &

Mulder, 1997 (exp. 1, Dutch); Newman, Ullman, Pancheva, Waligura, & Neville,

2007 (English); Osterhout & Nicol, 1999 (English)). Additionally, the LAN is not

always elicited across experiments using (nearly) identical stimuli, conducted by the

same researchers (e.g., Gunter et al., 1997; Osterhout & Mobley, 1995).

Furthermore, LANs have been reported to syntactic violations or temporary syntactic

ambiguities that were not morphosyntactic in nature (Hagoort & Brown, 2000 (only

for exp. 2, auditory); Osterhout & Holcomb, 1992, 1993) and in syntactically complex

sentences without any overt violations, presumably varying with working memory

demands of storing a filler or retrieving it for filler-gap assignment (Kluender &

Kutas, 1993).

This study (as well as the study detailed in chapter 4) adds to a fairly large

body of studies (given the total size of this literature) which have not reported a LAN

for conditions involving morphosyntactic violations. These exceptions weaken any

theory which explains the LAN as a simple reflection of morphosyntactic processing.

Further weakening this theory is the number of studies in which a LAN has been

observed for conditions which did not involve morphosyntactic violations, but

involved instead other types of syntactic violations or temporary syntactic

ambiguities. Additionally, the failure of LANs to replicate across nearly identical

experiments remains to be explained. As we discuss in chapter 4, these studies

suggest that inclusion of morphosyntactic violations is neither a necessary nor

sufficient condition for LAN elicitation; it remains to be specified what these are, as

well as what cognitive function(s) the LAN reflects.

1.2.3. Contributions to the literature on the effects of aging on language comprehension

The study presented in chapter 2 contributes to the literature on the effects

of aging with its examination of syntactic processing using ERPs in older adults.

Previously, there were no previous published studies examining how the P600

elicited by syntactic processing changes with advancing age: Few

electrophysiological studies have examined how comprehension of language

changes with time and none had examined the P600, an ERP component generally

elicited by violations of syntactic expectancy (although also by syntactic complexity).

A frequently discussed issue in the aging literature concerns the nature of age-

related slowing. However, investigations of the effects of normal aging on syntactic processing have generally used off-line measures (for example, examining how the syntactic complexity of an individual's writing changes with age). The few studies that have examined syntactic processing online generally have used response time as the dependent measure. Response times, however, are end-product measures which reflect the totality of cognitive processes involved in performing an experimental task. ERPs, in contrast, are multidimensional measures which provide millisecond-by-millisecond temporal resolution and thus, can provide more direct information about the ongoing neural processing, sometimes well before any response can be made. Comparisons of the timing and scalp distribution of the various language-related ERP components can provide important information about how aging affects various aspects of language comprehension.

The experimental manipulation reported in chapter 2 of grammatical number in subject/verb and reflexive/antecedent agreement involved relatively simple syntactic structures which are likely to rely minimally on working memory. This is important as previous researchers have found age-related limitations in working memory resources (Craik, Morris, & Gick, 1990; Gilinsky & Judd, 1994; Salthouse & Babcock, 1991; Wingfield, Stine, Lahar, & Aberdeen, 1988). For example, Norman, Kemper, Kynette, Cheung, and Anagnopoulos (1991) found that age correlated with working memory capacity for processing of right- and left-branching sentences, but not of simpler, single-clause sentences. On the basis of this finding, they hypothesized that age-related reductions in working memory resources limits older adults' ability to fully process more complex syntactic structures. If this hypothesis

is correct, we reasoned that there should be smaller, if any, age-related effects on the processing of our structurally simpler experimental sentences.

Our results showed that neither the onset latency nor the amplitude of the P600 was delayed in the older adults compared to younger adults, a somewhat surprising result given that other late components of the ERP such as the P3 (Kutas, Iragui, & Hillyard, 1994; Pfefferbaum & Ford, 1988; Pfefferbaum, Ford, Roth, & Kopell, 1980; Pfefferbaum, Ford, Wenegrat, Roth, & Kopell, 1984; Polich, 1991; Yamaguchi & Knight, 1991) and N400 (Gunter, Jackson, & Mulder, 1992; Kutas & Iragui, 1998; Woodward, Ford, & Hammett, 1993) have shown robust delays in onset latency with age. In contrast to the lack of age-related differences in P600 latency, our behavioral data showed that older adults were significantly less accurate and slower than the younger adults in indicating at the end of each sentence whether it was grammatically well formed. This dissociation between the findings for P600 latency versus response times, however, is not surprising as others have suggested that response-related processes are more affected by aging than are other late, pre-response cognitive processes (Bashore & Smulders, 1995; Ford, Roth, Mohs, Hopkins, & Kopell, 1979; Hartley, 2001). Additionally, the grammaticality judgment was delayed until the end of the sentence, likely increasing the contributions of memory, motor, and strategic processes to the overall response time. Thus, the response time difference between the two age groups was unlikely due purely to syntactic processes.

We did, however, find that the distribution of the P600 component over the scalp varied with age, along both the anterior-posterior and lateral axes. The P600 grammaticality effect in older adults was more laterally symmetric and more

pronounced over frontal sites, while in younger adults the P600 was right-lateralized and did not extend as far in the anterior direction as it did for the older adults. The finding of a lateralized P600 in the younger adults and a symmetrically-distributed P600 in the older adults is consistent with the suggestion that older adults rely on both hemispheres to process grammatical number, whereas in younger adults, processing tends to occur primarily in one hemisphere or the other. Consistent with this suggestion, various investigations have reported less lateralized activation in older compared to younger adults for various perceptual and memory processes (Cabeza et al., 1997; Grady, Bernstein, Beig, & Siegenthaler, 2002; Grady et al., 1994; Reuter-Lorenz et al., 2000; Reuter-Lorenz, Stanczak, & Miller, 1999; Stebbins et al., 2002) which may represent an attempt to compensate for reduced efficiency that occurs with aging by distributing the processing load across the two hemispheres (Cabeza, 2002; Reuter-Lorenz et al., 1999).

1.3. Chapter 3

Chapter 3 presents the findings from three experiments using lateralized presentation of critical words. The stimuli used in these experiments are identical to the stimuli use in experiment 2 (central presentation with ERPs as the dependent measure); experimental procedures in these experiments were almost identical to those used in experiment 2 (changes were those necessitated by the introduction of lateralized presentation, as described in the Methods sections of chapter 3).

1.3.1. Experiments 1 and 2

Experiments 1 and 2 use behavioral responses (response times and accuracy) as the dependent measures. Critical words were presented either centrally, or lateralized to either left or right visual field. In experiment 1, we used a

very short duration for critical words (100 ms), in line with what is generally used in behavioral experiments where the electrooculogram is not recorded. The primary finding from experiment 1 was that for the reflexive (lexically marked) condition, accuracy and response times generally did not differ reliably for lateralized presentation to left visual field (LVF) and right visual field (RVF). In contrast, for the subject/verb (morphologically marked) condition, responses were faster and more accurate for RVF compared to LVF presentation. The behavioral data thus show that the right hemisphere seems to experience greater difficulty than the left hemisphere in processing morphologically marked number agreement, whereas the similar response times and accuracy in the reflexive condition suggest that both hemispheres can process number agreement of these types under these conditions.

Our results showed that accuracy, in particular for ungrammatical items, seemed to be unduly influenced by the short duration time (100 ms) used for critical words and thus, in experiment 2, we ran the experiment a second time with a longer duration (200 ms); this is also the critical word duration we used for the ERP study (experiment 3). With the longer critical word duration, response times were overall much faster and accuracy generally higher. Overall, the pattern of results from experiment 2 replicated those from experiment 1 extremely well. Our results from these two experiments suggest that for the reflexive condition (lexical marking), both the left and right hemisphere are equally able to appreciate grammatical number. However, the findings across the two experiments for the subject/verb condition suggest that the right hemisphere does have more difficulty processing these stimuli, compared to the reflexive stimuli. Such a conclusion is in agreement with Zaidel's (1983) proposal that the right hemisphere finds certain linguistic categories

easier to process than others, including grammatical number marked lexically compared to morphologically. However, an alternative possibility is that the hemispheres differ at a lower, perceptual level, rather than a high, language-specific level (see discussion below).

We also examined the performance gains in experiment 2, compared to experiment 1, due to the increased critical word duration. Overall, the subject/verb condition showed greater performance gains in most condition, compared to those for the reflexive condition. However, we also observed a difference across the sentence types in terms of whether greater performance gains in experiment 2 were seen for RVF or LVF presentation. This pattern of performance gains provides evidence that the differences we observed between the hemispheres as a function of marking type occur at the perceptual level. We discuss these patterns in terms the global/local view of hemispheric asymmetry.

1.3.2. Experiment 3

In experiment 3, we used ERPs as the dependent measure; critical words are presented to either LVF or RVF. As no previous study had examined syntactic processing combined with hemifield presentation, we were uncertain what components might be elicited. Previous studies investigating syntactic violations with central presentation had generally produced P600s and occasionally produced LANs, thus, these were the components of most interest. In chapter 2, we present our findings with the same stimuli for central presentation, in which we observed only a P600.

In the reflexive condition, we observed a P600 for both LVF and RVF presentation, with an onset at about 600 ms and lasting about 400 ms at posterior

sites. The similar P600 responses to violations relative to controls for both LVF and RVF presentation suggests similarities between the hemispheres in appreciating lexically marked grammatical number agreement, in terms of the processes reflected in the P600 response. In contrast, in the subject/verb condition, we observed a P600 for only RVF presentation; for LVF presentation, there was no P600 effect whatsoever (rather, an anteriorly distributed, sustained negativity was observed). With respect to elicitation of the P600, our ERP results pattern very well with the results from the two behavioral experiments. In those experiments, response time and accuracy date for the reflexive condition suggested that both the right hemisphere (RH) and left hemisphere (LH) are equally able to appreciate grammatical number. The elicitation of a P600 in the reflexive condition for both LVF and RVF presentation is consistent with this conclusion. Moreover, the P600 for lateralized presentation was similar to that for central presentation in terms of its distribution, although (not unexpectedly), for lateralized presentation, the onset was delayed, duration was shorter, and amplitude smaller. In contrast, in the subject/verb condition, behavioral results suggested that the right hemisphere has greater difficulty than the left in appreciating grammatical number agreement. The ERP findings of a P600 for RVF but not LVF presentation are consistent with this conclusion.

There were some differences, however, in the ERP results for the reflexives as a function of visual field. For LVF presentation, we observed an anteriorly distributed sustained negativity (larger over left than right hemisphere sites), beginning at about 400 ms and lasting a few hundred milliseconds (until 1,500 ms over two left frontal electrodes). In contrast, for RVF presentation, we observed a

broadly distributed N400-like negativity (lasting only a few hundred milliseconds), most prominent at medial sites and largest at frontal and central sites. Although it is unclear what cognitive functions these negativities reflect, the differences in the negativity as a function of visual field suggest that processing is not identical in the two hemispheres.

For the subject/verb condition, we also observed negativities which differed as a function of visual field of presentation. Violations presented to the LVF elicited an enhanced frontal negativity, larger over left than right hemisphere sites, beginning at about 500 ms and sustained until at least 1,500 ms. For RVF presentation, in addition to the P600 effect, a less pronounced anterior negativity with an onset at about 1,000 ms was observed for RVF presentation as well. Further investigation is necessary to determine what neural processes these negativities reflect.

As mentioned above, the differences we observed for the reflexive and subject/verb experiments as a function of visual field of presentation may reflect some high level, language-specific difference between the hemispheres in their processing capabilities. Alternatively, they may reflect hemispheric differences in low-level perception. A possible design confound in the experiments presented in chapters 2 and 3 involves the visual salience difference in the way grammatical number is marked across the two sentence types. Grammatical number marking is perceptually relatively more salient for reflexive pronouns (*himself/herself/themselves*), whereas it is quite subtle for subject/verb agreement where number is marked on the verb by the presence or absence of a word-final /–s/. Studies of global/local differs have shown that the right hemisphere tends to be

less adept at appreciating local aspects of a stimulus whereas the left hemisphere tends to be less adept at appreciating global aspects of a stimulus. One proposal is that these global/local differences emerge because of differences between the hemispheres at the perceptual level for processing spatial frequencies: the right hemisphere amplifies the relatively lower spatial frequencies of a visual stimulus– which tend to be more important for global aspects of stimuli, while the left hemisphere amplifies the relatively higher spatial frequencies – which tend to be more important for local aspects of stimuli (Ivry & Robertson, 1998; Robertson, Egly, Lamb, & Kerth, 1993; Robertson & Lamb, 1991; Sergent, 1982; Shulman, Sullivan, Gish, & Sakoda, 1986; Shulman & Wilson, 1987).

Given the possible confound in salience of our stimuli, our results from the experiments discussed in chapters 2 and 3 do not allow us to determine whether the pattern of results we observed is due to high-level processing differences between the two hemispheres or to low-level processing differences. In chapters 4 and 5, we present a series of experiments using stimuli without this confound to investigate which of these two possibilities is more likely.

1.4. Chapters 4 and 5

The experiments presented in chapters 4 and 5 investigate whether the differences we observed in the experiments presented in chapters 2 and 3 are due to low-level or high-level processing differences between the two hemispheres. To this end, we examined processing of critical words in sentences requiring the past participle forms of verbs, both irregular and regular. Violations were formed by substituting the infinitival form of the verb. The participle form for all the regular verbs ends in –ed. The irregular verbs – which represent a lexical marking – were

divided into two groups: high and low salience. Verbs were "high salience" if the forms used in grammatical and ungrammatical conditions differed noticeably (defined as differing by two or more letters, e.g., caught vs. *catch) and "low salience" if the forms used in grammatical and ungrammatical conditions were visually quite similar (defined as differing by only one letter, e.g., flung vs. *fling). For irregular verb forms, there was one condition ("high salience") where violations were perceptually salient (as was the case with the reflexive condition in the experiments presented in chapters 2 and 3). There was also one condition ("low salience") which is perceptually less salient (as was the case with the subject/verb condition in the experiments presented in chapters 2 and 3). Thus, we eliminated the confound of marking type with perceptual salience.

We reasoned that if the ERP and behavioral responses for the high and low salience irregular forms were similar across LVF and RVF, while the pattern for the regular verb forms was different, this would be support for high level, language-specific processing differences between the hemispheres. In contrast, if the patterns for the high and low salience irregular forms differed from each other, this would provide support for low level, perceptual differences between the hemispheres. In chapter 4, we present the ERP findings for central presentation of the stimuli, while in chapter 5, we present two experiments (one behavioral, one ERP) using lateralized presentation.

1.4.1. Chapter 4

In chapter 4, we present an ERP experiment using central presentation which establishes a baseline for a "normal" reading condition (central presentation) against which the results for the lateralized ERP experiment presented in chapter 5

can be compared. This experiment also contributes to the ERP literature examining syntactic violations (using central visual field presentation) in a number of ways. First, to our knowledge, this is the first ERP study to examine past participle processing using English sentences, although others (e.g., Newman et al., 2007) have examined processing of the simple past tense. Additionally, syntactic violations primarily have been associated with two ERP components: the P600 and the LAN. Elicitation of the P600 with syntactic violations has been fairly consistent across a large number of studies across a number of languages. However, elicitation of the LAN has been far less consistent across studies, as discussed briefly above and extensively in chapter 4.

In addition to some researchers associating the LAN with morphosyntactic processing, others have used the LAN to study regular and irregular word forms. The nature of the neural representation of these two forms has been widely debated in the psycholinguistics literature. On the connectionist approach, there is no qualitative difference in how regular vs. irregular word forms are represented and accessed; a single mechanism is presumed to account for both (Rumelhart & McClelland, 1986). In contrast, other approaches such as the dual system view (Ullman et al., 2005) invoke two different mechanisms to deal with regular and irregular word forms with only the latter being stored in the lexicon; regular (morphologically complex) words are claimed to be represented as stems and affixes which are combined as needed via rules.

Both behavioral and ERP studies have investigated the neural representation of regular and irregular words. Many studies have shown dissociations between the two which are interpreted as evidence for the

connectionist view. In the ERP literature, a few studies have examined processing of regular and irregular word-forms in sentences and claimed an association between the LAN and application of morphological rules (Penke et al., 1997; Rodriguez-Fornells, Clahsen, Lleo, Zaake, & Munte, 2001; Weyerts, Penke, Dohrn, Clahsen, & Munte, 1997). However, the critical "words" in these studies were actually pseudowords, formed by improperly applying morphological rules to stems which are irregular ("regularizations"), or by treating stems which are regular as if they were irregular. Moreover, results across these studies were not entirely consistent: Weyerts et al. (1997) and Penke et al. (1997) found that regularizations elicited LAN, but in the Rodriguez-Fornells et al. (2001) study, regularizations failed to elicit a LAN. Overall, although there may be differences in how regular and irregular word forms are processed, ERP data to date do not support any obvious or consistent distinction between the two classes.

Thus, of interest in this study was whether we would observe a LAN to violations in any of our verb conditions. Our findings speak to claims that the LAN reflects morphosyntactic processing. In addition, given claims in the literature that the LAN reflects processes associated with application of morphological rules, our findings contribute to the debate regarding the neural representation of regular and irregular verb forms.

1.4.1.1. Results

An important result from this experiment is the lack of a LAN in any of the three verb conditions, including for the regular verb condition. This finding adds to the number of studies which have failed to observe a LAN to morphosyntactic

violations. At the very least, then, such results suggest that an account of the LAN which appeals only to morphosyntactic processing in general is incomplete.

The second finding is that in all three verb conditions, a P600 was elicited by violations, which is in agreement with many studies reporting P600s to syntactic violations (Angrilli et al., 2002; Coulson et al., 1998; Gunter et al., 1997; Hagoort & Brown, 2000; Hagoort et al., 1993; Hinojosa, Martín-Loeches, Casado, Muñoz, & Rubia, 2003; Kemmer et al., 2004; Munte, Heinze, Matzke, Wieringa, & Johannes, 1998; Munte et al., 1997; Osterhout, Allen, McLaughlin, & Inoue, 2002; Osterhout et al., 1996; Osterhout & Mobley, 1995; Osterhout & Nicol, 1999; Palolahti, Leino, Jokela, Kopra, & Paavilainen, 2005; Rossi et al., 2005). The P600 effects in the regular and irregular/high salience conditions did not reliably differ from each other. These P600 effects did, however, reliably differ from the P600 observed in the irregular/low salience condition, for which the onset of the P600 effect was later, and its amplitude smaller. The scalp distribution of the P600 was similar across all three verb conditions, as were the current source density maps: taken together, these findings suggest that the neural generators of the P600 in each condition are similar.

Our finding of similar P600s for the regular and high salience verb conditions, with the low salience condition differing in terms of onset latency and amplitude, and the suggestion that the neural generators of the P600 do not vary across verb condition, argue against dual mechanism theories which propose qualitative differences in processing of regular vs. irregular verbs. Had the regular verb and both irregular conditions systematically differed, our data would have lent support to dual mechanism accounts. Overall, however, the data from the regular and high salience irregular conditions pattern together and are reliably distinct from

the data for the low salience irregular condition. In other words, in these data, it is

visual salience – not regularity – that seems to determine the pattern of effects

observed. Whatever processes the P600 are presumed to reflect, the pattern of

P600 results observed fails to support any dual mechanism account whereby all

regular word forms are processed in one way and irregular word forms in another.

1.4.2. Chapter 5

In chapter 5, we report the findings from two lateralized experiments, the first

using response times and accuracy as the dependent measures; the second using

ERPs. The aim of these experiments was to determine whether the results we

obtained in the experiments described in chapter 3 were due to a high level,

language-specific difference between the hemispheres in their processing

capabilities, or whether they reflected lower level, perceptual differences.

The results from experiment 1 showed response times and accuracy data for

the regular and high salience verb condition generally patterning together across all

visual fields. Response times were generally faster and accuracy higher for the

regular verb condition compared to the low salience condition. Additionally, for

comparisons between central and LVF presentation, the ungrammatical high

salience condition showed reliably faster and more accurate responses compared to

the ungrammatical low salience condition. These results suggest that the right

hemisphere is more sensitive than the left to differences in salience, providing

evidence that the results we report in chapter 3 reflect hemispheric differences at

the perceptual level. Additionally, the fact that the two irregular conditions do not

pattern together as well as being distinct from the pattern observed for the regular

verb condition speaks to the debate about the neural representation of regular and

irregular word forms. Our results here do not support claims of qualitatively separate neural representations.

In experiment 2, we observed a P600 for all verb types with both LVF and RVF presentation. For RVF presentation, the P600 elicited in the high salience condition had a significantly smaller mean amplitude compared to that elicited by either the regular or low salience verb condition. In contrast, the P600s did not differ reliably between regular and low salience conditions for RVF presentation. For LVF presentation, there were no reliable difference between any of the verb types. Moreover, we did not observe any reliable differences in P600 onset for any verb type as a function of visual field of presentation. This pattern of results is different from that observed in experiment 1. In experiment 1, regular and high salience verb conditions patterned together across the visual field, whereas in experiment 2, regular and low salience verb conditions patterned together for LVF presentation, with no differences for RVF presentation as a function of verb condition.

The results from experiment 2 do not provide a clear answer to the issue of whether results from our previous studies were due to high level, language specific differences across the hemispheres or due to lower level differences in perception. The data do not support the language-specific explanation because we did not observe a split between morphological and lexical markings: results for regular (morphological) and low salience (lexical) conditions patterned together. Alternatively, we had argued that in order for hemispheric differences in perception to account for our previous findings, then high salience should pattern with the regular condition (with LVF presentation) as in these conditions, violations are relatively more salient that for the low salience condition. However, we observed no

differences in the mean amplitude of the P600 between the three verb conditions for LVF presentation.

　　　　With regard to the regular/irregular debate, the results from both experiment 1 and experiment 2 do not provide support for the view that there are qualitative differences in the neural representation of regular and irregular word forms. However, the conflicting patterns of results for experiment 1 (high salience and regular patterning together) versus experiment 2 (low salience and regular patterning together) do not provide clear support for single mechanism accounts either.

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Chapter 2

Syntactic processing with aging: an event-related potential study

2.1. Abstract

To assess age-related changes in simple syntactic processing with normal aging, event-related brain potentials (ERPs) elicited by grammatical number violations as individuals read sentences for comprehension were analyzed. Violations were found to elicit a P600 of equal amplitude and latency regardless of an individual's age. Instead, advancing age was associated with a change in the scalp distribution of the P600 effect, being less asymmetric and more frontal (though still with a parietal maximum) in older than younger adults. Our results thus show that the brain's response to simple syntactic violations, unlike those reported for simple binary categorizations and simple semantic violations, are neither slowed nor diminished in amplitude by age. At the same time, the brain's processing of these grammatical number violations did engage at least somewhat different brain regions as a function of age, suggesting a qualitative change rather than any simple quantitative age-related change in speed of processing.

2.2. Introduction

Undoubtedly, we all can think of instances where an elderly relative or acquaintance took a longer than usual amount of time to tie their shoelaces, sign a check, dial a phone number, or cross a street. Indeed, research indicates that hearing, vision, various motor skills, memory, and certain frontal lobe functions all deteriorate to some extent with advancing age (Butler & Lewis, 1977; Cavanaugh,

Grady, & Perlmutter, 1983; Elliott, Yang, & Whitaker, 1995; Kraus, Przuntek,

Kegelmann, & Klotz, 2000; Zec, 1993). A great deal of the empirical research

examining cognitive change with age has focused on age-related slowing, using

response times (RTs) as the dependent measure, as a ubiquitous finding is that

older adults on average are slower than younger, "irrespective of the task, cognitive

function being investigated, and experimental procedure" (Baron & Cerella, 1993, p.

175).

However, one widely debated issue in this literature is the nature of age-

related slowing (Bashore, 1994; Bashore, van der Molen, Ridderinkhof, & Wylie,

1997; Madden, 2001; Verhaeghen & Cerella, 2002). Some theories view slowing as

caused by generalized slowing of the nervous system but differ as to whether they

consider age-related slowing as global with only one general slowing function for all

processes and tasks (Cerella, 1990) or as more domain-specific, with different

functions for different domains (e.g., lexical vs. nonlexical), although still general

across processes within a given domain (Lima, Hale, & Myerson, 1991). Still others

have argued for localized, or process-specific, slowing in which different processes

(e.g., central vs. peripheral processes) have different slowing functions that may

vary as a function of domain (Allen, Sliwinski, & Bowie, 2002; Allen, Sliwinski,

Bowie, & Madden, 2002; Allen, Smith, Jerge, & Vires-Collins, 1997; Fisk & Fisher,

1994; Sliwinski, 1997). Yet another view suggests that there may be global

component(s) which affect a large number (although not all) of cognitive processes

as well as some localized components which affect specific processes (Churchill et

al., 2002; Keys & White, 2000).

Critical to distinguishing between different models of age-related slowing is the choice of a dependent measure. Most models of age-related slowing are based on differences in older and younger adults' response times. As these reflect the totality of the cognitive processes invoked for a given experimental task performance, these issues are likely to benefit from the use of a dependent variable that provides more direct information about the neural processing between stimulus presentation and any subsequent decision or overt response, if one is given (Coles, Gratton, Bashore, Eriksen, & Donchin, 1985; Miller, Coles, & Chakraborty, 1996). This is especially the case given that equivalent behavior (e.g., response times) does not necessarily imply identical engagement or use of the same underlying cognitive and/or neural processes. Furthermore, because motor output is often slowed by normal aging (Keys & White, 2000), it is useful to employ methods that do not require participants to produce a motoric response or that can provide an index of perceptual, cognitive, and even motor processing that is relatively independent of motor processes/execution in those cases where overt motor responses are given. The event-related brain potential (ERP) methodology provides such a measure. ERPs provide a multidimensional, online record (on the order of milliseconds) of the brain's electrical activity detectable at the scalp, revealing information about neural processing immediately after a stimulus is presented and in many cases, well before a response is made (Kutas, Federmeier, Coulson, King, & Munte, 2000; Rugg & Coles, 1995).

Indeed, a number of investigators have reported dissociations between response speed and the speed of mental processes as reflected in the peak

latency of the P3, an ERP component thought to reflect cognitive processes related to stimulus evaluation and decision-making (Kutas, McCarthy, & Donchin, 1977; McCarthy & Donchin, 1981). In general, P3 latency is sensitive to variations in stimulus processing demands, being elicited whenever enough information has accrued to initiate an updating of working memory (Donchin & Coles, 1988; Duncan-Johnson & Donchin, 1982); P3 latency in these cases is relatively impervious to response selection processes (McCarthy & Donchin, 1981). Although both RTs and P3 peak latencies are slowed by aging to some extent, the slowing seems to be greater for RT than P3 latency measures (Bashore, Osman, & Heffley, 1989; Bashore et al., 1997). All in all, combined RT and ERP analyses have implicated the central response processing system much more than the central stimulus processing system in the slowing observed in normal aging (Bashore, 1993; Bashore & Smulders, 1995; see also Welford, 1977; support for this conclusion has come from non-ERP analyses as well, e.g., Allen, Madden, Weber, & Groth, 1993; Allen, Sliwinski, & Bowie, 2002; Allen, Sliwinski, Bowie, & Madden, 2002; Allen et al., 1997).

Furthermore, studies of aging that have employed P3 latencies as their chief dependent variable suggest that aging does not result in proportional slowing of all cognitive processes. For example, whereas stimulus encoding and response organization in a Sternberg task were slowed with age, serial comparison time was not (Ford, Roth, Mohs, Hopkins, & Kopell, 1979). Further, in a regression analysis of a large number of studies employing speeded decision-making tasks, Bashore et al. (1989) found that the pattern of age-related slowing in RTs was multiplicative,

consistent with a generalized slowing model, whereas the pattern in the P3 latencies was additive, consistent with a sensorimotor slowing model. Clearly, it is preferable to have converging evidence for major conclusions and to help researchers quantify the degree of (in)dependence of different types of age-related influences that may exist within and/or across mental processes and cognitive domains.

Although ERPs have been used to examine the effects of aging in cognitive domains such as attention and memory (see Kok, 2000, for a review), there are relatively few electrophysiological studies of the impact of normal aging on language comprehension; of those that exist, the great majority have focused on semantic analysis as indexed by the N400 component (Federmeier, McLennan, De Ochoa, & Kutas, 2002; Gunter, Jackson, & Mulder, 1992; Iragui, Kutas, & Salmon, 1996; Kutas & Iragui, 1998). The N400, a posteriorly-distributed negativity with an onset between 200 and 500 post-stimulus, has been shown to be inversely correlated with a word's semantic fit or its cloze probability in a context such as a sentence; the better the fit between a context and an item, the smaller the N400 elicited by that item (Kutas & Hillyard, 1984).

The N400 in language tasks has generally, although not always (Federmeier et al., 2002), been observed to be significantly reduced in amplitude and delayed in latency with advancing age for both written (Gunter et al., 1992) and spoken materials (Woodward, Ford, & Hammett, 1993). In a semantic categorization study in which a short spoken phrase was followed by a visually presented word that either did or did not fit, Kutas and Iragui (1998) observed a

reliable linear decrease in amplitude of the N400 effect of 0.05 to 0.09 μV per year and reliable linear increase in peak latency of the N400 effect of 1.5 to 2.1 ms per year (spanning six decades from 20s to 70s). Interestingly, however, this normal delay in N400 latency with age can be overridden when contextual constraint is high, as in an elaborate sentence context (Federmeier et al., 2002). By contrast, N400 amplitudes have been observed to be smaller in older than younger individuals whether or not there are accompanying age-related delays in N400 latency.

Online effects of aging on other aspects of language processing, such as grammar, have been much less systematically investigated in general or with the ERP methodology. Insofar as researchers have probed the consequences of aging on syntactic processing, they have concluded that even in normal aging there are decrements in both the production and comprehension of certain syntactic structures (Bates, Harris, Marchman, & Wulfeck, 1995; Kemper, 1987a; Kemper, Kynette, Rash, Sprott, & O'Brien, 1989; Kynette & Kemper, 1986). Specifically, common findings are that use of more complex structures declines with age (e.g., Bates et al., 1995; Bromley, 1991; Kemper, 1987a; Kemper, Greiner, Marquis, Prenovost, & Mitzner, 2001; Kemper, Marquis, & Thompson, 2001) and that as syntactic complexity increases, older adults have more difficulty recalling prepositional information from sentences (Kemper, 1987b; Stine & Hindman, 1994) and imitating sentences (Kemper, 1986). Bates et al., for example, found that although older adults produced fewer complex syntactic constructions, they were nonetheless as capable as the younger adults of using these constructions

correctly; they thus suggested that aging may be accompanied by reduced accessibility to structures lower in frequency or higher in complexity.

In one of the few online studies, Obler, Fein, Nicholas, and Albert (1991) examined the comprehension of spoken sentences varying in semantic plausibility and syntactic structure and found reliable age-related declines in the accuracy but not in the speed of processing of certain constructions. Comprehension was tested with yes/no questions immediately following each sentence, and although RTs were generally slowed with age, the various effects of plausibility and syntactic type were unaffected by age. Moreover, the age-related slowing of comprehension times disappeared when these were covaried with naming times on a Stroop task, suggesting that the slowing may not have been specific to syntactic or semantic processing per se.

Age-related limitations in working memory resources (Craik, Morris, & Gick, 1990; Gilinsky & Judd, 1994; MacPherson, Phillips, & Della Sala, 2002; Salthouse & Babcock, 1991; Wingfield, Stine, Lahar, & Aberdeen, 1988) have similarly been invoked to argue that at least some of the observed difficulties and slowness that older individuals experience when processing syntactically complex linguistic materials is not specific to language (Kemper & Sumner, 2001; King & Just, 1991; Kluender & Kutas, 1993; Norman, Kemper, & Kynette, 1992; Vos, Gunter, Kolk, & Mulder, 2001). Norman, Kemper, Kynette, Cheung, & Anagnopoulos (1991), for example, found that age correlated with working memory capacity for recall of right- and left-branching sentences but not of simpler, single-clause sentences. If, as they hypothesized, it is the reduction in working memory resources that limits

older adults' ability to fully process more complex syntactic structures, then we would expect to observe smaller, if any at all, age-related effects on the processing of structurally simpler sentences.

Very few studies, however, have actually examined the effects of aging on the processing of relatively simple syntactic structures, and what few findings there are appear to be mixed. Glosser and Deser (1992), for example, found no significant differences in either the syntactic complexity or the number of syntactic omissions (subject, main verb, required functions, and grammatical morphemes) of the speech produced by middle-aged (43-61 years) versus elderly (67-88 years) adults (although there was a nonsignificant trend for decreasing complexity with age). By contrast, Kynette and Kemper (1986) observed age-related changes in the use of both simple and complex syntactic structures: the speech of individuals in their 70s and 80s (relative to those in their 50s and 60s) was more likely to include omissions of obligatory grammatical morphemes, articles, and possessive markers, as well as more grammatical errors (e.g., incorrect past tense inflections, subject and verb person errors).

For these reasons, we decided to investigate the effects of aging on the engagement of a simple syntactic process--grammatical number agreement--that makes minimal demands on working memory during word-by-word reading with a measure of online brain processing (ERPs). In young adults, violations of grammatical number agreement (among other types of syntactic violations and anomalies) relative to grammatical controls are known to generate a centroparietally-distributed positivity (P600) with an onset at about 500 ms and a

duration of at least several hundred milliseconds (Coulson, King, & Kutas, 1998b; Hagoort, Brown, & Groothusen, 1993; Munte, Matzke, & Johannes, 1997; Osterhout, McKinnon, Bersick, & Corey, 1996; Osterhout & Mobley, 1995).

Since the initial description of the P600 (Osterhout & Holcomb, 1992), it has been used by many researchers to assess various aspects of syntactic processing in young adults. Remarkably little, however, is known about how the P600 varies with advancing age. This study is aimed at filling this void: specifically, we compared the latency, amplitude, and scalp distribution of the P600 to grammatical number violations from younger and older adults with the aim of assessing the effect of normal aging on this relatively simple syntactic process. As in younger adults, we expected syntactic violations to elicit a P600 in the older adults, which, if it behaves like the response to semantic violations, would be smaller in amplitude and later in latency. However, given that syntactic processing is only mildly affected in early stages of Alzheimer's dementia (Bickel, Pantel, Eysenbach, & Schroder, 2000) and the few reports of age-related differences in syntax use other than for more complicated structures (Byrd, 1993; Kemper, 1987a; Kemper, 1987b), we expected to find that the P600 to number violations would be relatively immune to normal aging.

2.3. Methods

2.3.1. Materials

There were 240 experimental sentences (ranging in length from 5 to 12 words; critical words ranged from 5 to 10 letters) and 60 filler sentences (see Table 2.1 for sample experimental sentences). Half of the experimental sentences were

grammatically well-formed whereas the other half included one of two types of number agreement errors. Specifically, there were 60 sentences with a subject/verb number agreement error and 60 with an antecedent/reflexive pronoun number agreement error.

In the subject/verb number agreement condition, the critical word (the verb) always occurred as the third word in the sentence and was followed by at least two words. For grammatical sentences, all verbs were in the third person plural simple present tense form; for ungrammatical sentences, all verbs were in the third person singular simple present tense form. Verb frequency was restricted to a range of 8 to 353 per million (Francis & Kucera, 1982). Each main verb appeared only once across all sentence types (including practice, filler, or experimental). Most of the subject nouns and adjectives were not repeated across sentences; the few that were are high frequency words in English.

In the reflexive pronoun number agreement condition, half of the sentence subjects were plural and half singular. The critical word (the reflexive pronoun) was always the fifth word in the sentence. Ungrammatical sentences included a number violation: a singular subject co-referenced with "themselves" or a plural subject co-referenced with "himself" or "herself". Reflexive pronouns were always gender appropriate, of the gender most likely for that subject, or in the case of gender neutral subjects, randomly split between "himself" and "herself."

Two stimulus lists each consisting of 300 sentences in random order were created. Each list included 60 grammatical subject/verb, 60 violation subject/verb, 60 grammatical reflexive pronoun, 60 violation reflexive pronoun, 30 grammatical

fillers, and 30 violation fillers. A given list included for each sentence either the number violation or its grammatical counterpart, never both. Violations in the filler sentences involved syntactic structures different from those in the experimental sentences. Each participant viewed only one list.

2.3.2. Participants

Sixteen University of California, San Diego (UCSD) undergraduate students participated in the experiment for course credit or pay (6 were women; ages ranged from 18 to 24; average age was 20 years) and 16 older adults recruited from the San Diego area (8 were women; ages ranged from 60 to 80; average age was 69 years) were paid $8/h to participate. All participants provided health and medical information, including history of psychiatric disorders, drug use, neurological disease, medications currently being taken, vision, and others; participants were excluded from the experiment as appropriate. In addition, older participants were screened (in a separate session) via a neuropsychological battery which includes both verbal and nonverbal tests; all of our older participants are required to be within normal range on all the tests. All participants were monolingual, right-handed (assessed using the Edinburgh Inventory; Oldfield, 1971), and had normal or corrected-to-normal vision.

2.3.3. Experimental procedure

Participants were tested in a single experimental session lasting a little over 3 h. Participants were seated 40 in. in front of a monitor in a sound-proof, electrically shielded recording chamber. Experimental and filler sentences were presented one word at a time every half second for a duration of 200 ms. Before

each sentence, a fixation cross appeared for 900 ms, followed by a random interval between 17 and 300 ms in duration. Participants were instructed to read each sentence for comprehension, fixate the fixation point until after the sentence ended, and to attempt not to blink or move during this period. Participants also were asked to make an acceptability judgment at the end of every sentence: after the final word of a sentence disappeared, participants were to indicate as quickly and as accurately as possible whether or not the sentence was well-formed.

In addition, to ensure that participants read the entire sentence for comprehension and to discourage them from engaging in any strategies due to the presence of grammatical violations, a random half of the sentences was followed by a comprehension probe sentence that appeared in its entirety in a red font. Participants were asked to indicate whether this comprehension probe had approximately the "same content" as its associated experimental sentence. As response times were not of interest here, participants were instructed to strive for accuracy at the expense of speed (minimum response interval ranged from 5,017 to 8,017 ms).

First, participants were familiarized with the stimulus presentation parameters and the task via a practice block of 30 sentences. Experimental sentences were then presented in 10 blocks of 30 trials each, with short breaks between blocks and a longer break halfway through the experiment. The same hand, counterbalanced across participants, was used to indicate a "good sentence" and "same content" and was switched halfway through the experiment. The

practice block was presented again after the mid-break until participants were accustomed to the hand mapping switch.

2.3.4. Recording procedures

The electroencephalogram (EEG) was recorded from 26 tin electrodes, embedded in an electrode cap, each referenced to the left mastoid. Right mastoid was recorded as well; ERP averages were re-referenced off-line to the average of activity recorded at the right and left mastoids. Scalp recording sites included: Prefrontal: left lateral (LLPf), left medial (LMPf), midline (MiPf), right medial (RMPf), right lateral (RLPf); Frontal: left lateral (LLFr), left mediolateral (LDFr), left medial (LMFr), right medial (RMFr), right mediolateral (RDFr), right lateral (RLFr); Central: left mediolateral (LDCe), left medial (LMCe), midline (MiCe), right medial (RMCe), right mediolateral (RDCe); Parietal: left mediolateral (LDPa), midline (MiPa), right mediolateral (RDPa); Temporal: left lateral (LLTe), right lateral (RLTe); and Occipital: left lateral (LLOc), left medial (LMOc), midline (MiOc), right medial (RMOc), right lateral (RLOc). Lateral eye movements were monitored via electrodes placed at the outer canthus of each eye in a bipolar montage. An electrode was placed on the infraorbital ridge of the left eye and referenced to the left mastoid to monitor blinks. Electrical impedances were kept below 3 KΩ. The data were sampled at 250 Hz. The EEG and electrooculogram (EOG) were amplified by Nicolet amplifiers set at a bandpass of 0.016 to 100 Hz.

2.3.5. ERP data analysis

Prior to analysis, data were examined for artifacts such as eye movements, blinks, amplifier blocking, and excessive muscle activity; for the young, 19.5% of

the grammatical trials (20.5% for subject/verb; 18.6% for reflexives) and 21.6% of the ungrammatical trials (23.1% for subject/verb; 19.9% for reflexives) were rejected; for the elderly, the percentages were only slightly higher (25.5% for grammatical, 25% subject/verb; 26% for reflexives; 24.7% for ungrammatical, 23.1% for subject/verbs; 26.2% for reflexives). ERP averages were re-referenced offline to the average of activity recorded at the right and left mastoids. A 100 ms prestimulus baseline was used for all analyses.

Based on previous reports in the literature, we examined three latency windows synchronized to the onset of the critical word: 250-400 ms, 300-500 ms, and 500-800 ms. For each age group, we first conducted an omnibus ANOVA for each time window with three within factors including Sentence Type (subject/verb vs. reflexive number agreement), Grammaticality (grammatical vs. ungrammatical), and Electrode (26 levels); this analysis is referred to as the "full analysis." We also conducted a hemispheric analysis which included factors of Sentence Type, Grammaticality, and Hemisphere (left vs. right); 22 electrodes were used in this analysis which represented all but midline scalp electrodes. When the full analysis revealed an interaction of Electrode with either Sentence Type or Grammaticality, a distributional analysis consisting of an ANOVA with five within-subject factors including Sentence Type (subject/verb vs. reflexive pronoun/antecedent number agreement), Grammaticality (grammatical, ungrammatical), Hemisphere (left vs. right), Laterality (lateral vs. medial electrodes), and Anteriority (four prefrontal electrodes [LLPf, LMPf, RLPf, RMPf], four frontal electrodes [LLFr, LMFr, RLFr, RMFr], four central or temporal electrodes [LLTe, LMCe, RLTe, RMCe], four

occipital electrodes [LLOc, LMOc, RLOc, RMOc]) was conducted (see Figure 2.1).

In addition, we conducted planned omnibus ANOVAs for each sentence type

separately with two within factors: Grammaticality and Electrode, and followed these

with distributional analyses as needed. Both the full and distributional analyses also

were done with the added between factor of Age. Our significance level was set at

$p \leq .05$ and for all analyses involving more than one degree of freedom, the

Geisser-Greenhouse (1959) correction for violations of sphericity was applied;

uncorrected degrees of freedom but corrected p values are reported.

Early sensory components were measured for each age group as follows

(collapsing across conditions): the P1 as the average positive peak between 50 and

125 ms, the N1 as the average negative peak between 75 and 175 ms, and the P2

as the average positive peak between 150 and 250 ms.

2.4. Results

2.4.1. Overt Behavior

As expected, participants were overall significantly more accurate in

classifying grammatical (mean = 94%; range = 75-100%) than ungrammatical

sentences (mean = 78%; range = 34-99%), main effect of Grammaticality,

$F(1,30) = 27.32$, $p = .000$. Younger participants were both more accurate (90% vs.

82%) and faster (994 ms vs. 1675 ms; a 681 ms difference for correct trials) than

the elderly, main effect of age for accuracy, $F(1,30) = 4.70$, $p = .038$; for response

time, $F(1,30) = 24.27$, $p = .000$. Hit and false alarm rates for each participant were

used to calculate d' and β, signal detection estimates of discriminability and bias,

respectively (see Table 2.2 for values for hits, misses, correct rejects, and false

alarms). ANOVA of the *d'* values showed a main effect of Age, $F(1,30) = 4.48$, $p = .043$, indicating greater discriminability of grammatical from ungrammatical sentences by younger (*d'* = 2.57) than older adults (*d'* = 2.02). For β, the Age factor was not significant, $F(1,30) = .76$, $p = .390$, while the main effect of Sentence Type was marginally significant, $F(1,30) = 4.09$, $p = .052$, indicating a bias for participants to respond "grammatical" to Reflexives (β = .72) but not to Subject/Verbs (β = 1.03; a β of 1.0 represents no bias at all).

2.4.2. Comprehension probes

Although our younger adults were significantly more accurate (mean 93%, range 75-98%) than our older adults (mean 86%, range 57-97%) on the comprehension probes, $F(1,30) = 7.33$, $p = .01$, the overall high accuracy rate indicated that both groups were attending to and comprehending the experimental sentences they were reading.

2.4.3. ERPs

An omnibus ANOVA with Age as a between factor was run on grand average raw ERPs for grammatical versus ungrammatical critical words collapsed across violation type. Between 300 and 500 ms responses in the reflexive condition were overall more positive (0.80 μV) than those in the subject/verb condition (0.33 μV), main effect of Sentence type, $F(1,30) = 5.20$, $p = .030$. There were, however, no amplitude differences due to Age or Grammaticality. By contrast, between 500 and 800 ms, the ERPs of younger participants were more positive (3.11 μV) than those of the older (0.84 μV), main effect of age, $F(1,30) = 15.07$, $p = .000$. And, as expected, ungrammatical responses (2.80 μV)

were more positive than grammatical responses (1.15 μV), albeit to the same extent for younger and older participants, main effect of grammaticality, $F(1,30) = 19.46$, $p = .000$.

Because the raw ERP waveforms for the two age groups were markedly different but the between-groups full analysis revealed no interaction of Age with either sentence type or grammaticality, all age group comparisons were based on difference ERPs (point-by-point subtraction of the ERP to the grammatical condition from the ERP to the ungrammatical condition). Below, we present results for each age group separately, followed by the between-age-group comparison.

2.4.3.1. ERPs in Young adults

Grand average ERPs elicited by sentence type for grammatical versus ungrammatical critical words for young participants ($N = 16$) are shown in Figure 2.2 for a representative subset of electrodes. As is typical for ERPs to visually presented words, for all conditions we observed a P1 component peaking at around 98 ms, an N1 component peaking at around 117 ms posteriorly and about 10 ms earlier at more frontal sites, and a P2 component peaking at around 204 ms. Following these early sensory components, the ERPs in the ungrammatical condition were characterized by a sustained centro-parietal positivity with an onset at about 500 ms (and lasting about 800 ms at posterior sites), slightly larger over right hemisphere sites. Prefrontal sites show a positivity with an earlier onset and shorter duration, beginning at about 300 ms and lasting only a few hundred milliseconds.

2.4.3.1.1. Analyses of mean amplitudes: 300 – 500 ms

The hemispheric analysis (all electrodes except the four midline), with factors of Sentence Type, Grammaticality, and Hemisphere, showed a significant Type x Grammaticality x Hemisphere interaction, $F(1,15) = 7.08$, $p = .018$, reflecting greater positivity over right hemisphere sites for the ungrammatical subject/verb condition and over left hemisphere sites for the ungrammatical reflexive condition. The distributional analysis showed significant Type x Laterality and Type x Anteriority interactions which were modulated by a three-way interaction of Sentence Type x Laterality x Anteriority, $F(3,45) = 8.79$, $p = .001$, $\varepsilon = .65$, reflecting greater positivity for the reflexive than subject/verb conditions at all medial electrode sites and posterior lateral sites and the reverse at lateral anterior sites.

2.4.3.1.2. Analyses of mean amplitudes: 500 – 800 ms

Between 500 and 800 ms, ungrammatical items (3.87 μV) were significantly more positive than grammatical items (2.35 μV), main effect of Grammaticality, $F(1,15) = 6.40$, $p = .023$, across both sentence types. The potentials were asymmetric, being larger over right (3.24 μV) than left (2.75 μV) hemisphere sites, main effect of Hemisphere, $F(1,15) = 5.960$, $p = .028$, although more so by about 0.5 μV for ungrammatical than grammatical items, Grammaticality x Hemisphere, $F(1,15) = 6.95$, $p = .019$.

Grammaticality effects were larger at medial than lateral sites, especially over posterior sites, Grammaticality x Laterality x Anteriority, $F(3,45) = 4.08$, $p = .028$, $\varepsilon = .62$. ERPs were generally more positive at medial than lateral sites,

especially at the frontal, central, and temporal sites; furthermore, over all medial sites and anterior lateral sites, the mean amplitudes for the subject/verb condition were more positive than those for the reflexives, whereas over posterior lateral sites, the reflexive condition was slightly more positive, Sentence Type x Anteriority, $F(3,45) = 9.15$, $p = .007$, $\varepsilon = .45$; Sentence Type x Laterality x Anteriority, $F(3,45) = 5.21$, $p = .011$, $\varepsilon = .71$.

Analysis of the subject/verb sentences showed reliably greater positivity for ungrammatical items (4.08 μV) than grammatical ones (2.43 μV), main effect of grammaticality, $F(1,15) = 8.88$, $p = .009$. This grammaticality effect was larger over medial (1.97 μV, grammatical = 3.06 μV; ungrammatical = 5.03 μV) than lateral sites (0.64 μV; grammatical = 1.14 μV; ungrammatical = 1.78 μV), Grammaticality x Laterality, $F(1,15) = 7.45$, $p = .016$.

Reflexive sentences also showed an overall trend for ungrammatical items (3.66 μV) to be more positive than grammatical ones (2.27 μV), with essentially no grammaticality effect over prefrontal sites (grammatical 3.09 μV vs. ungrammatical 3.16 μV) and greater positivity to ungrammatical than grammatical items at all other locations, especially over central, temporal, and occipital sites, Grammaticality x Anteriority, $F(3,45) = 6.62$, $p = .020$, $\varepsilon = .36$.

2.4.3.1.3. Analyses of mean amplitudes: 250 – 400 ms

Between 250 and 400 ms, there was no sign of difference between grammatical and ungrammatical items for reflexive sentences. By contrast, for the subject/verb condition, ungrammatical sentences were associated with somewhat more negative potentials than grammatical sentences, primarily over the

left hemisphere, (ungrammatical vs. grammatical for *left hemisphere*: 0.41 vs. 1.05 μV; *right hemisphere*: 1.13 vs. 1.26 μV), Grammaticality x Hemisphere, $F(1,15) = 3.81$, $p = .070$. The same analysis for the reflexive condition revealed no significant main effects or interactions.

2.4.3.2. ERPs in older adults

Grand average ERPs elicited by sentence type for grammatical versus ungrammatical critical words for older participants ($N = 16$) are shown in Figure 2.3 for a representative subset of electrodes. As with the younger participants, grammatical violations elicit a centroparietal positivity with an onset at about 500 ms (and lasting about 800 ms at posterior sites); for this age group the positivity is bilaterally symmetric. As is typical of older adults with visually presented sentences, their early sensory evoked potentials (EPs) are characterized by a large N1 peaking around 120 ms posteriorly and 114 ms anteriorly, and a small P2 component peaking around 201 ms.

2.4.3.2.1. Analyses of mean amplitudes: 300-500 ms

Between 300 and 500 ms, the ERP to reflexives was significantly more positive than that to subject/verb (0.69 vs. 0.06 μV, respectively), $F(1,15) = 7.19$, $p = .017$, and there was no reliable difference between grammatical and ungrammatical sentences, $F(1,15) = .09$, $p = .768$.

2.4.3.2.2. Analyses of mean amplitudes: 500-800 ms

Between 500 and 800 ms, however, the ERP to ungrammatical items was significantly more positive than that to grammatical items (1.73 vs. -0.6 μV), main effect of Grammaticality, $F(1,15) = 15.84$, $p = .001$. This difference was greater for

the reflexive pronoun than the subject/verb condition, due primarily to difference in the ungrammatical items (1.32 vs. 2.14 μV, grammatical = -0.04 vs. -0.08 μV; Sentence Type x Grammaticality, $F(1,15) = 5.18$, $p = .038$).

The hemispheric analysis revealed that although overall ungrammatical were more positive than grammatical and the right hemisphere sites were more positive than the left hemisphere sites, the grammaticality difference was larger medially (2.39 μV) than laterally (1.10 μV), especially over frontal sites, and the hemispheric differences were more pronounced in the lateral relative to medial sites, Grammaticality x Laterality, $F(1,15) = 12.90$, $p = .003$, Sentence Type x Hemisphere x Anteriority, $F(1,15) = 6.90$, $p = .003$; Sentence Type x Laterality x Anteriority, $F(1,15) = 3.71$, $p = .035$; Sentence Type x Grammaticality x Laterality x Anteriority, $F(3,45) = 4.06$, $p = .029$, $\varepsilon = .60$; Sentence Type x Hemisphere x Laterality x Anteriority, $F(3,45) = 4.28$, $p = .024$, $\varepsilon = .65$; and Grammaticality x Hemisphere x Laterality x Anteriority, $F(3,45) = 4.51$, $p = .008$, $\varepsilon = .90$.

Planned comparisons revealed a significantly greater positivity for ungrammatical than grammatical items for both sentence types, *subject/verb*: 1.32 vs. -0.04 μV, $F(1,15) = 8.33$, $p = .011$; *reflexive sentences*: 2.14 vs. -0.08 μV, $F(1,15) = 19.41$, $p = .001$. The grammaticality effect was larger medially than laterally for both sentence types, Grammaticality x Laterality interaction, *subject/verb*: $F(1,15) = 7.92$, $p = .013$, 1.9 vs. 0.6 μV; *reflexives, $F(1,15) = 15.40$, $p = .001$; 2.86 vs. 1.29 μV.

Although visual inspection of these difference ERPs suggested that the onset of the P600 may be earlier for reflexive than subject/verb violations, this impression was not confirmed by statistical analysis.

2.4.3.2.3. Analyses of mean amplitudes: 250 – 400 ms

There were no reliable effects of interest in this window.

2.4.3.3. Between-group comparison: Young vs. Elderly

As expected, the two age groups were characterized by large differences in their early sensory evoked potential (EP) components. Relative to the younger adults, the older adults had larger visual N1s, and much smaller P2 components over fronto-central sites. By contrast, the two age groups showed much smaller differences in the later components. In fact, the younger and older adults both responded to grammatical violations with a centro-parietal positivity between 500 and 800 ms (P600) and beyond. Remarkably, the onset and peak latencies of the P600 appeared to be about the same in the two age groups (e.g., for electrode MiPa: onset latency: 651 ms (younger) vs. 652 ms (older), $F(1,15) = 0.00$, $p = .99$; peak latency: 744 ms (younger) vs. 779 ms (older), $F(1,15)$ 1.65; $p = .21$.[1] However, although the overall amplitude of the grammaticality effect was about the same in the two age groups, the older participants showed a larger effect over frontal sites, and, unlike the slightly right-lateralized effect in younger adults, theirs was bilaterally symmetric.

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[1] The onset latency of the positivity for each sentence type at each electrode was measured by finding the maximum positive value between 300 and 1,100 ms and then determining the latency at which 7% of this value was reached. With the exception of two sites (LLTe and RMPf), there was no significant difference in onset latency for reflexive versus subject/verb sentences (results were similar for 3% and 15% of maximum as well).

Given the age-related differences in the raw ERP waveforms, mean amplitudes calculated in the difference ERPs (Ungrammatical - Grammatical) were used for between-groups analyses (see Figure 2.4).

2.4.3.3.1. Analyses of mean amplitudes: 300-500 ms

There were no reliable age-related effects between 300 and 500 ms.

2.4.3.3.2. Analyses of mean amplitudes: 500-800 ms

Between 500 and 800 ms, younger adults showed a somewhat larger grammaticality effect than older adults for subject/verb sentences (0.82 vs. 0.68 μV) whereas the reverse was true to the reflexives (0.70 vs. 1.11 μV), such that older adults showed a marginally larger difference to the two violations types, Sentence Type x Age, $F(1,30) = 2.92$, $p = .098$.

The distributional analysis corroborated our observation that the ERP between 500 and 800 ms was bilaterally symmetric in the older adults, but had a slight right-greater-than-left asymmetry in the younger adults, Age x Hemisphere, $F(1,30) = 5.90$, $p = .021$. According to the hemisphere analysis, the grammaticality effect was larger over right than left hemisphere sites in the younger adults (1.16 vs. 1.70 μV), and about the same size over the two hemispheres in the older adults (1.80 μV vs. 1.63 μV), main effect of hemisphere, $F(1,30) = 6.87$, $p = .013$; Age x Grammaticality x Hemisphere, $F(1,30) = 7.20$, $p = .012$; see Figure 2.5 for voltage maps showing the scalp distribution for the 500-800-ms time window.

2.5. Discussion

This experiment was aimed at examining the effects of normal aging on the brain's response to certain simple grammatical violations. To that end, ERPs were

recorded from younger adults and older adults as they read sentences one word at a time for comprehension. Approximately half of the sentences contained one of two types of grammatical number violation, both known to elicit a P600 component in young adults. The results clearly showed that relative to syntactically well-formed control sentences, number violations elicit a widely-distributed positive-going wave (P600) regardless of an adult's age. Remarkably, unlike the typical effects of normal aging on many early sensory evoked potentials and on many later endogenous potentials (for reviews, see Kok, 2000; Kugler, Taghavy, & Platt, 1993; Onofrj, Thomas, Iacono, D'Andreamatteo, & Paci, 2001), the P600 effects associated with grammatical number violations were neither smaller in amplitude nor delayed in latency in the older adults relative to the younger ones. However, there was a reliable effect of aging on the distribution of the P600 grammaticality effect across the scalp along both the anterior-posterior and lateral axes: the P600 effects in older adults were more laterally symmetric and more pronounced over frontal sites than those of younger adults. These P600 effects were observed against a backdrop of lower accuracy and slower response times in the older than younger adults for discriminating grammatical from ungrammatical sentences, as well as of lower performance on the subsequent comprehension probes.

The results from the young adults corroborate reports across a number of different languages that grammatical number violations, be they subject/verb or reflexive pronoun/antecedent grammatical number agreement or other violations, elicit a P600 component (English: Coulson et al., 1998b; Osterhout et al., 1996; Osterhout & Mobley, 1995; Dutch: Hagoort et al., 1993; Hagoort & Brown, 2000;

Vos et al., 2001; German: Munte et al., 1997). However, there was no early anterior negativity in the ERPs to these types of violations as has been reported by some investigators (Hagoort & Brown, 2000; Osterhout & Mobley, 1995, exp. 1), but not found by others (e.g., Hagoort et al., 1993; Osterhout et al., 1996; Osterhout & Mobley, 1995, exp. 3).[22] Nor did the current data show an enhanced P2 as described by Osterhout and Mobley (1995).

The P600 response to the grammatical number violations, however, was quite reliable and it is to that we turn to examine the effect(s) of normal aging on this aspect of syntactic processing. As noted above, normal aging seems to have surprisingly little, if any, effect on the timing or amplitude of the brain's response to grammatical number violations despite the associated age-related decrements in accuracy and speed of the overt, albeit intentionally-delayed, grammaticality judgments. Both the young and the elderly responded to these violations with a posteriorly-distributed late positivity starting around 500 ms post-stimulus onset and lasting for a little less than a second. The ungrammatical minus grammatical difference ERPs were statistically indistinguishable from each other in the onset and the peak latency of the grammaticality effect (Figure 2.5).[3]

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[2] The absence of an early negativity, such as a left anterior negativity (LAN), in our data is not surprising, as its elicitation by grammatical violations is inconstant. On occasion, it has failed to replicate even when the same materials were employed (Osterhout et al., 1996; Osterhout & Mobley, 1995, exp. 3). Moreover, even when some negativity has been observed, its laterality as well as its anterior-posterior distribution has been variable (Coulson et al., 1998; Kutas & Hillyard, 1983; Osterhout & Mobley, 1995).

[3] In any study, caution must be exercised in interpreting a null effect, as it could be due to a lack of power. However, the similar peak and onset latencies, as well as the consistent lack of any significant difference observed for each electrode, suggest this finding is unlikely to be due to a lack of power.

This apparent absence of a delay in P600 latency with normal aging is especially notable given that older adults are usually slower than younger adults on many different information-processing tasks employing many different measures (Obler et al., 1991; see Salthouse, 1985, for a review), and robust delays have been reported for other late components of the ERP such as the P3 and N400 (N400: Gunter et al., 1992; Kutas & Iragui, 1998; Woodward et al., 1993; P300: Kutas, Iragui, & Hillyard, 1994; Pfefferbaum & Ford, 1988; Pfefferbaum, Ford, Roth, & Kopell, 1980; Pfefferbaum, Ford, Wenegrat, Roth, & Kopell, 1984; Polich, 1991; Yamaguchi & Knight, 1991). In fact, by some accounts, the P3 and the P600 belong to the same family of ERP components (see below). In contrast to the absence of any age-related differences in P600 latency are the behavioral data showing that older adults were significantly less accurate and slower than the younger adults in indicating at the end of each sentence whether or not it was grammatically well-formed. This dissociation -- slower response times with equivalent ERP latencies -- is consistent with other reports suggesting that response-related processes are more affected by aging than are other late, pre-response cognitive processes (Bashore & Smulders, 1995; Ford et al., 1979; Hartley, 2001; Madden, Pierce, & Allen, 1993). However, since the grammaticality judgment task was delayed until the end of the sentence, it is unlikely that the dissociation between the P600 and behavioral results (older adults were over 600 ms slower than younger adults) was purely due to "syntactic" processes; indeed, memory, motor, and strategic processes all may have come into play to some degree.

2.5.1. Functional significance of the P600

At this point, one might ask what is the P600 component and what psychological process(es) does it index? Although there is a consensus that the P600 component is elicited by grammatical violations in these types of experiments, there is no clear agreement on exactly what mental operation its elicitation reflects. Some have hypothesized that the P600 indexes processes related to re-analysis after anomaly detection (Friederici, Hahne, & Mecklinger, 1996; Neville, Nicol, Barss, Forster, & Garrett, 1991; Osterhout, Holcomb, & Swinney, 1994); proponents of this view typically further maintain that the P600 and P3 components are functionally and anatomically dissociable. Other researchers, by contrast, have linked P600 elicitation to more general cognitive processes (Coulson, King, & Kutas, 1998a; Coulson et al., 1998b), such as context-updating in working memory, presumably associated with elicitation of a P300 component (Donchin, 1981; Donchin & Coles, 1988). Munte et al. (1997), for example, found that a P600 was elicited by number mismatches in real German sentences but not by morphosyntactic violations in a pseudoword condition (in which there was a number disagreement between a pseudoword in the subject sentence position and the pseudoword in verb position). They thus concluded that the P600 reflects sentence re-processing, initiated by the number mismatch but contingent on the semantics of the sentence.

The nature of the process(es) indexed by the P600 thus remains controversial, as does the evidence for and against the P6-P3 identity (Friederici, Mecklinger, Spencer, Steinhauer, & Donchin, 2001; Hahne & Friederici, 1999). The

current results speak to this latter debate only indirectly and similarly offer mixed evidence. On the one hand, the lack of an age-related difference in P600 latency is at odds with the general finding that P3 latencies are typically longer in older participants regardless of modality (see Kugler et al., 1993, for a review), and thus might be taken as evidence that the P6 and P3 are distinct. On the other hand, the flatter distribution of the P600 characterizing the older (but not younger) adults accords well with similar findings for the P3 in older relative to younger participants. This result then suggests that the P600 and P3 may indeed be related. Clearly, both of these comparisons would benefit from their being made in the same individual, rather than on the average.

2.5.2. Aging and the distribution of the P600 component

Although the size and the timing of the P600 did not change, it was differently distributed over the scalp of younger and older adults. In the younger participants, the P600 was large over posterior electrodes, small anteriorly, and slightly larger over right than analogous left hemisphere sites. In older adults, the P600 was broadly distributed (including more frontal sites) and bilaterally symmetric. The distribution of the P600 thus differed in two ways with advancing age: (1) it was larger over frontal sites, and (2) it was more bilaterally symmetric. Neither the physiological causes nor psychological concomitants of the change in distribution are clear as yet, though taken at face value neither the greater involvement of frontal areas nor the greater symmetry with advancing age is without precedent.

The ERPs of younger and older adults often differ more over frontal regions than over other brain areas. For example, a number of investigators have noted that the P3 appears to have a flatter distribution across the scalp with advancing age, manifest in some reports as an equipotential distribution and in others as greater amplitudes over frontal than posterior sites (Fabiani, Friedman, & Cheng, 1998; Friedman, Kazmerski, & Fabiani, 1997; Iragui, Kutas, Mitchiner, & Hillyard, 1993; Polich, 1997; Segalowitz, Wintink, & Cudmore, 2001; Smith, Michalewski, Brent, & Thompson, 1980; Strayer, Wickens, & Braune, 1987; Wintink, Segalowitz, & Cudmore, 2001; Yamaguchi & Knight, 1991). However, given the nature of ERP conduction to the scalp, without converging evidence there is no guarantee that the electrophysiological changes observed at frontal scalp sites are generated in the frontal brain regions; they may also reflect, for example, a change in the orientation of a generator in a different brain area.

The current observations of a bilaterally symmetric P600 in older adults in contrast to the right-lateralized P600 in younger participants is consistent with the suggestion that older adults use both hemispheres to process grammatical number whereas younger adults tend to use primarily one hemisphere or one hemisphere more than the other. Indeed, a variety of reports support the hypothesis that there is less lateralized activation (especially in frontal areas) in older compared to younger adults in a number of perceptual and memory processes including retrieval and encoding of episodic memories, semantic retrieval, and working memory (Cabeza et al., 1997; Grady, Bernstein, Beig, & Siegenthaler, 2002; Grady et al., 1994; Madden et al., 1999; Reuter-Lorenz et al., 2000; Reuter-Lorenz,

Stanczak, & Miller, 1999; Stebbins et al., 2002). Furthermore, neuroimaging data (positron emission tomography and functional magnetic resonance imaging) suggest that prefrontal activity becomes less lateralized with advancing age (Reuter-Lorenz et al., 1999, 2000), perhaps in an attempt to compensate for reduced inefficiency (of the aging brain) by distributing the processing load across the two hemispheres (Cabeza, 2002; Reuter-Lorenz et al., 1999).

2.5.3. Cognitive aging versus cognitive slowing

There is no doubt that across a wide range of tasks, behavioral responses become slower with advancing age. Although slowed response must be the result of slowing in some combination of perceptual, motoric, and cognitive processes, there is vigorous theoretical debate surrounding how widely distributed slowing is among the candidate processes. For instance, according to a generalized slowing account of aging (e.g., Cerella, 1985; Myerson & Hale, 1993; Salthouse, 1985), the cognitive deficits of old age are a consequence of a decrease in the efficiency of information processing in the central nervous system. It is now generally acknowledged that there are differences in both the extent to which particular processes are slowed and in the extent to which overall performance is slowed across tasks (e.g., Salthouse, 1996); researchers, however, differ substantially in what quantitative functions they believe best describe the relationship(s) between the latencies of younger and older adults as well as in what factors (speed of processing, working memory, motivation, attention, strategies, etc.) they believe contribute to the differences in processing efficiency.

Although the behavioral literature suggests that the most reliable differences with age are obtained with difficult syntactic constructions, ERPs can sometimes provide evidence of quantitative or qualitative differences in processing even when no such differences are observed in overt behavioral responses. Thus ERPs and behavior do not always lead to the same conclusions about the nature and/or time course or processing alterations with age. Bashore et al. (1989), for example, found that P3 latency and reaction time measures show very different patterns of age-related slowing, indicating that not all processes are equally slowed by increased age. Moreover, as also briefly mentioned, a large body of evidence attests to the remarkable sensitivity of the timing of various ERP components to simple operations--N400 to appreciation of semantic anomalies and P3b to appreciation of improbable stimuli--to normal aging. It is, therefore, highly unlikely that the mere simplicity of the cognitive processing involved in the appreciation of a grammatical number violation accounts for the absence of an age-related difference in the P600 component in the present study. In fact, this is a very important finding because it is not that the ERP to grammatical number violations is insensitive to normal aging, for it is--in its distribution--just not in its timing. What distinguishes the processing of this sort of grammatical violation from that engaged by binary decisions or lexical semantic violations remains an open question, and although these ERP results have little to say about any of the specific proposals on generalized slowing with aging, they do have some implications for such theories in general.

To the extent that the differences in P600 distributions in the younger and older adults observed here are not due to some general anatomical change (such as sulcal widening in older adults that results in a change in the orientation of the P600 generator(s)), the age-related differences in scalp distributions of the P600 effect are evidence for age-related differences in the processing of simple grammatical violations. Furthermore, because P600 latency of younger and older adults was the same (in contrast with the well-attested age-related increases in P300 and N400 latency), the data provide no discernible evidence for age-related slowing in the processing of these simple grammatical violations. These two points, if correct, together entail that although processing of simple grammatical violations does indeed change with age, the change is not, at least in any obvious sense, a matter of slowed processing at all; neither general slowing nor selective slowing across a cognitive domain (e.g., language comprehension) nor slowing of any specific cognitive function. These data are prima facie evidence that there is more to cognitive aging than cognitive slowing. Regardless of the specific role that slowing plays in cognitive aging--and it surely must--the P600 results (the distributional aspects) are not readily explained in terms of slowing of any sort. The theoretical implication is that no empirically adequate model of cognitive aging will be just a model of slowing.

The reduction in P2--a component linked to visual processing (Kutas & King, 1996)--with age parallels other reports of a disproportionate effect of visual degradation on older adults' behavioral performance in visual word identification tasks (Allen et al., 1993; Madden, 1988, 1992). Combined with the fact that the

older adults were slower in their grammaticality judgments but not in their P600 latencies, the overall pattern of the present results is consonant with the hypothesis that aging may have a greater negative impact on early encoding processes and later production of responses (especially in binary decision tasks) than on more intermediate central information processing operations (Balota & Duchek, 1988; Madden et al., 1993).

Chapter 2, in full, is a reprint of material as it appears in *Psychophysiological Research, 41*, 372-384. Kemmer, Laura; Coulson, Seana; De Ochoa, Esmeralda; Kutas, Marta; Blackwell Publishing, Inc. The dissertation author was the primary investigator and author of this paper.

Table 2.1. Sample sentences from each condition.

Subject-verb agreement	

Grammatical:	Industrial scientists *develop* many new consumer products.
Ungrammatical:	*Industrial scientists *develops* many new consumer products.

Reflexive pronoun-antecedent number agreement	

Grammatical:	The grateful niece asked *herself* how she could repay her aunt.
Ungrammatical:	*The grateful niece asked *themselves* how she could repay her aunt.

An asterisk preceding a sentence conventionally indicates it is ungrammatical; asterisks were not included in experimental stimuli.

Table 2.2. Accuracy data.

	Grammatical (Hits)	Ungrammatical (Correct rejects)	Misses	False alarms
Younger adults:				
Subject/Verb	96.4 (.7)	83.6 (3.3)	3.6 (.7)	16.4 (3.2)
Reflexives	96.0 (.6)	82.3 (3.8)	4.0 (.6)	17.7 (3.8)
Older adults:				
Subject/Verb	90.9 (2.0)	70.9 (5.5)	9.1 (2.0)	29.1 (5.5)
Reflexives	92.4 (1.9)	74.6 (5.4)	7.6 (1.9)	25.4 (5.4)

Note. Accuracy (as percent); standard error of the mean in parentheses. Main effects of Age, $F(1,30) = 4.70$, $p = .038$, and Grammaticality, $F(1,30) = 27.32$, $p = .000$, are significant. Analyses based on data for younger adults only showed a main effect of Grammaticality, $F(1,15) = 15.85$, $p = .001$; as was the case for older adults, $F(1,15) = 13.35$, $p = .002$.
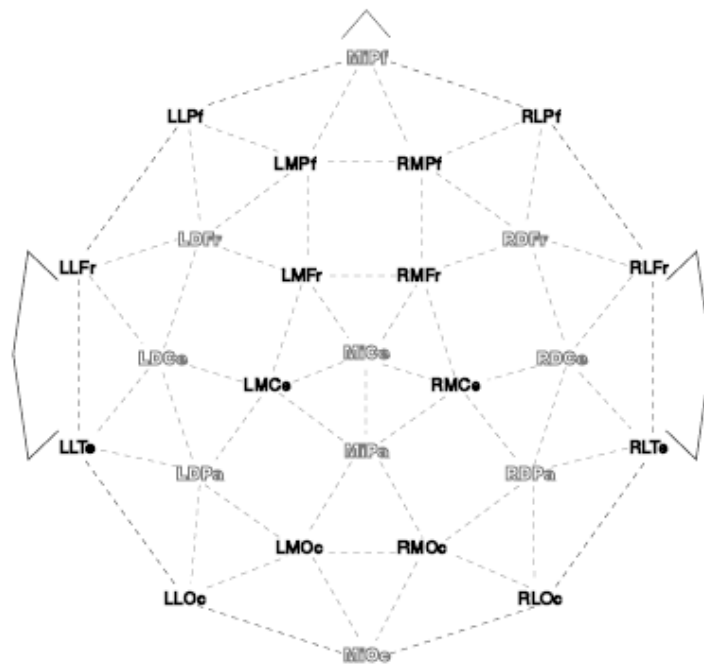
Figure 2.1. Schematic diagram of the locations of the 26 scalp electrodes, all of which were used for the full statistical analysis. The distributional analysis was restricted to the 16 electrodes with labels shown in bold print.
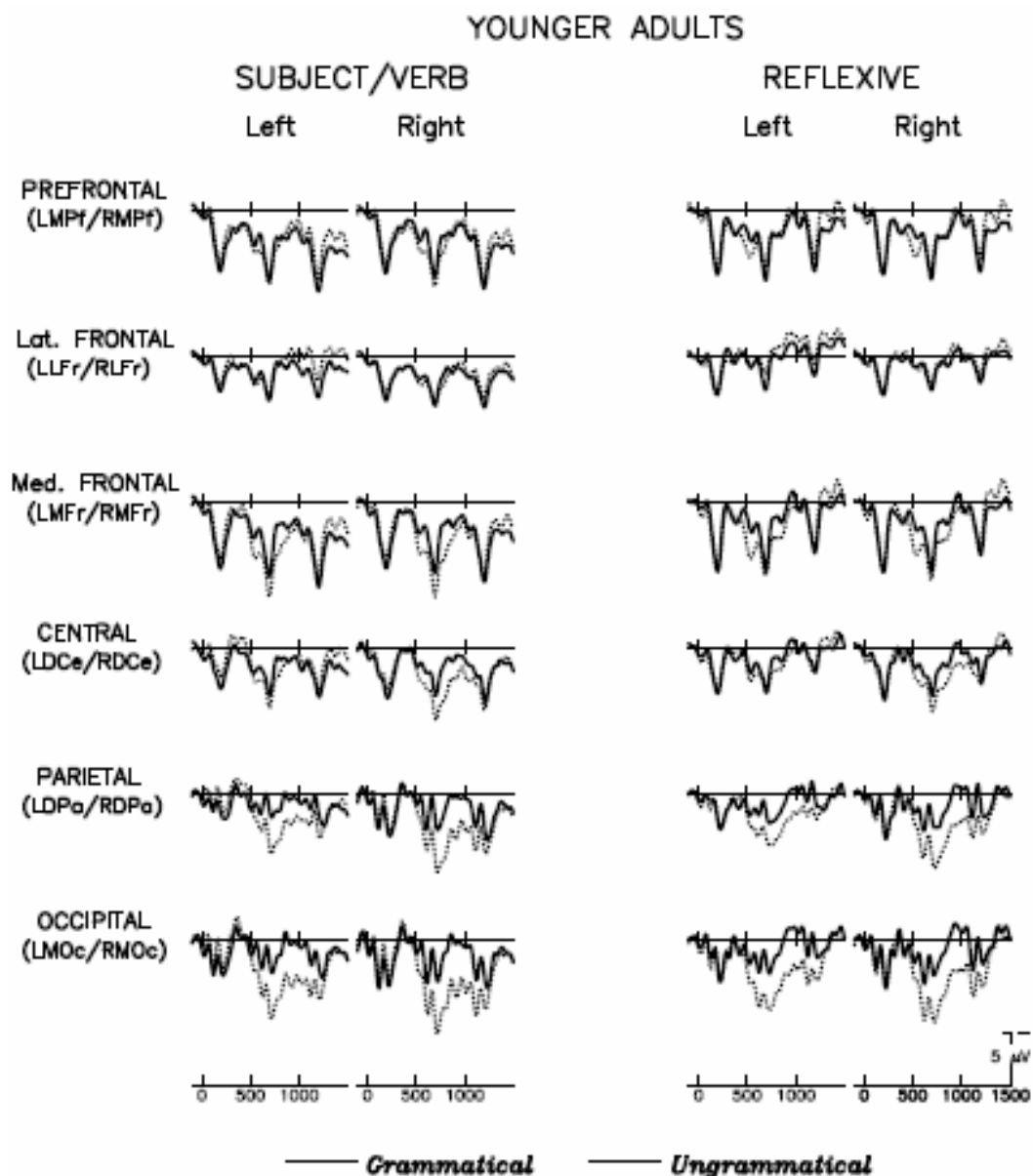
Figure 2.2. Grand average (N = 16) ERP waveforms elicited by grammatical number violations (solid line) and corresponding control sentences (dotted line) in younger adults for each sentence type. Electrodes shown are a representative subset, including left and right medial prefrontal electrodes (LMPf, RMPf), lateral frontal (LLFr, RLFr), medial frontal (LMFr, RMFr), mediolateral central (LDCe, RDCe), mediolateral parietal (LDPa, RDPa), and medial occipital (LMOC, RMOc).
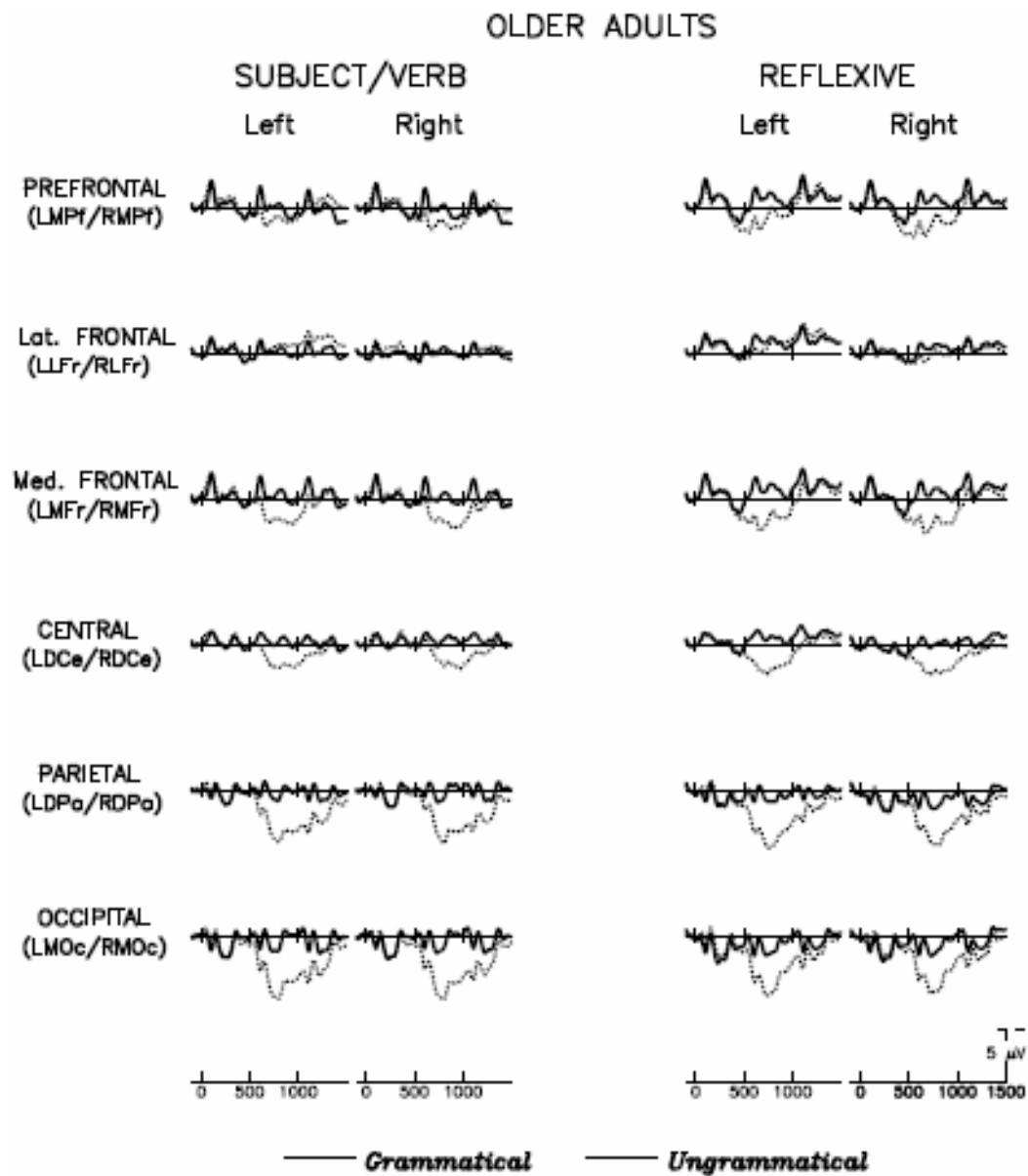
Figure 2.3. Grand average (N = 16) ERP waveforms elicited by grammatical number violations (solid line) and corresponding control sentences (dotted line) in older adults for each sentence type. Electrodes shown are a representative subset, including left and right medial prefrontal electrodes (LMPf, RMPf), lateral frontal (LLFr, RLFr), medial frontal (LMFr, RMFr), mediolateral central (LDCe, RDCe), mediolateral parietal (LDPa, RDPa), and medial occipital (LMOC, RMOc).
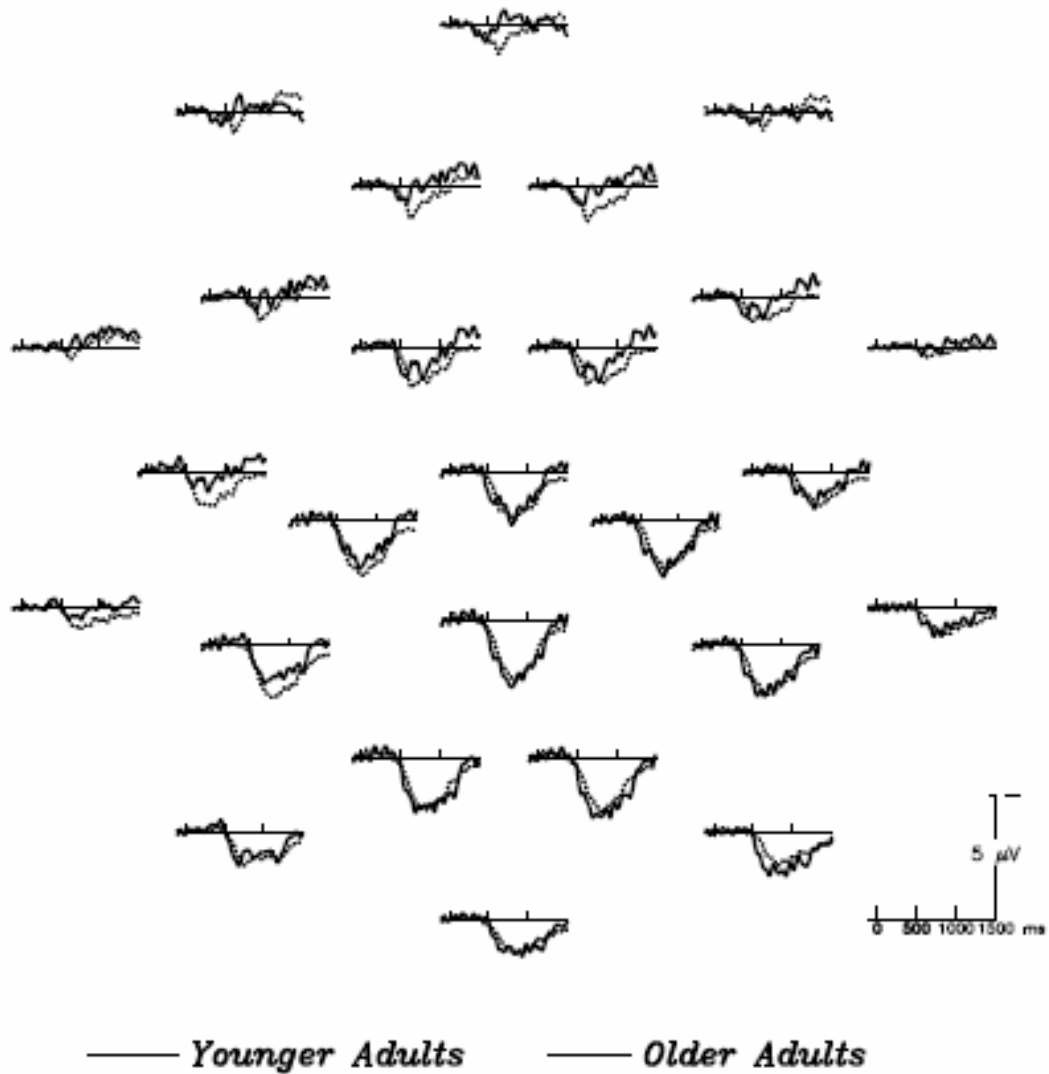
Figure 2.4. Difference ERPs, formed by subtracting grammatical from ungrammatical ERPs, showing the P600 effect for younger (N = 16; solid line) and older (N = 16; dotted line) adults.
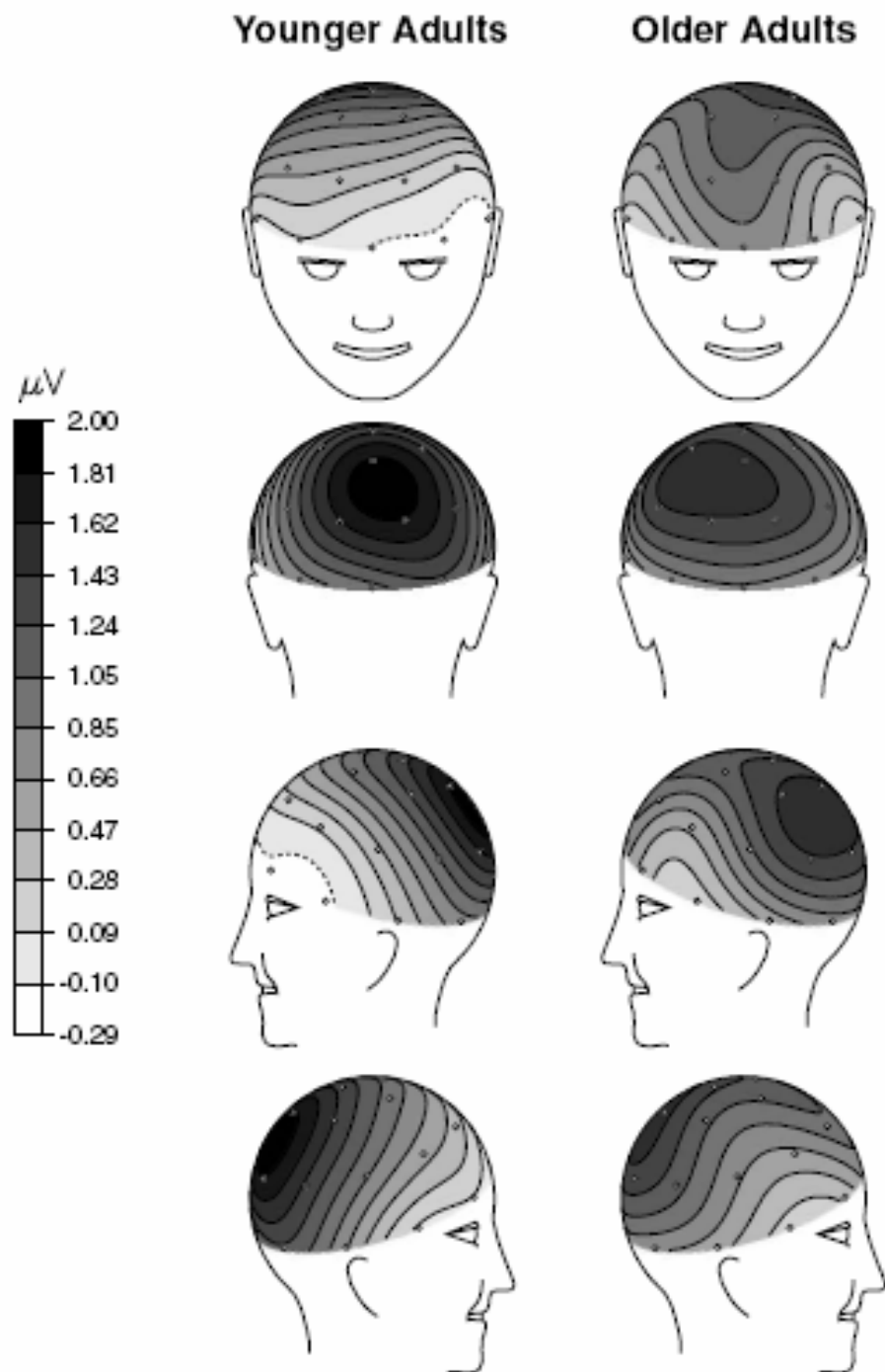
Figure 2.5. Voltage maps showing the scalp distribution of the P600 effect (mean amplitude in 500 800 ms time window) in younger adults and older adults.

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Chapter 3

Grammatical number agreement processing using the visual half-field paradigm: an event-related brain potential study

3.1. Abstract

On the dominant view of language processing, syntax is a left hemisphere function. Despite indications in the split-brain and lesion literatures that the right hemisphere is capable of some syntactic analysis, few studies have investigated its contributions to language processing in intact brains. In two studies, we used a visual half-field paradigm to examine each hemisphere's processing of correct and incorrect grammatical number agreement marked either lexically, e.g., antecedent/reflexive pronoun ("The grateful niece asked herself/*themselves...") or morphologically, e.g., subject/verb ("Industrial scientists develop/*develops..."). For reflexives, response times and accuracy of grammaticality decisions in both experiments suggested similar processing regardless of visual field of presentation. By contrast, in the SV condition, we observed similar effects for central and right visual field (RVF) presentations that differed from that for left visual field (LVF) presentations. Simultaneously recorded event-related brain potentials (ERPs) in the second study with LVF or RVF presentations showed a P600 component typical of number agreement violations whose appearance was consistent with behavioral data. For lexically marked violations on reflexives, P600 was elicited by stimuli in both the LVF and RVF; for morphologically marked violations on verbs, P600 was elicited only by stimuli in the RVF. These data suggest that both hemispheres can process lexically marked agreement, and do so in a qualitatively and quantitatively

similar fashion. The left hemisphere advantage for morphologically marked

agreement errors may reflect a language-specific hemispheric difference in syntactic

processing, although it might also reflect a salience difference between the two

types of errors.

3.2. Introduction

At first glance, the two hemispheres of the brain may seem to be mirror

images of each other. However, research has shown that there are differences

between the hemispheres on many levels. At the anatomical, for example, various

asymmetries between the hemispheres have been noted. The planum temporale is

usually larger in the left than right hemisphere (Geschwind & Levitsky, 1968). The

lateral sulcus differs, extending further horizontally in the left hemisphere, while in

the right hemisphere, it makes a sharper upward turn sooner (Rubens, Mahowald, &

Hutton, 1976). Broca's area in the left hemisphere shows greater (higher order)

dendritic branching than does the homologue in the right hemisphere (Scheibel,

1984). There are asymmetries in neurotransmitter concentrations in various areas,

including the thalamus (Oke, Keller, Mefford, & Adams, 1978) and globus pallidus

(Glick, Ross, & Hough, 1982).

Differences across the hemispheres have also been shown at the functional

level. For example, right hemisphere lesions (in particular, to the posterior parietal

lobe) are likely to cause more severe disorders of visuospatial attention (for

example, hemineglect) than are left hemisphere lesions. Although right hemisphere

lesions cause more severe deficits, the left hemisphere also contributes to

visuospatial processing, albeit to a different degree, because left hemisphere

lesions do cause visuospatial disorders (Bisiach & Vallar, 1988; Halligan, Fink,

Marshall, & Vallar, 2003; Vallar, 1993; , 1998). Furthermore, right hemisphere

damage is more likely to be associated with difficulty in noticing the more global

aspects of hierarchical visual patterns, while left hemisphere damage tends to be

associated with difficulty in attending to more local aspects of those patterns. For

example, when patients with left or right hemisphere damage were asked to draw

figures from memory with both global and local aspects, patients with right

hemisphere deficits tended to re-create the local but not the global aspects,

whereas patients with left hemisphere damage tended to re-create the global but not

the local aspects (Delis, Robertson, & Efron, 1986); other researchers have reported

similar findings (e.g., (Lamb & Robertson, 1989; Robertson & Delis, 1986;

Robertson, Lamb, & Knight, 1988). Similarly, a right hemisphere bias for global

processing and a left hemisphere bias for local processing has been demonstrated

in neurologically intact individuals (Heinze & Munte, 1993; Martin, 1979; Martinez et

al., 1997; Robertson, Lamb, & Zaidel, 1993). These findings suggest that the

hemispheres differ in their ability to process information at the two levels (Lamb,

Robertson, & Knight, 1990) and led to the proposal that there are two lateralized

neural subsystems (operating independently and in parallel) involved in processing

global and local aspects of stimuli: one associated with the right hemisphere which

is biased for global processing, and the other associated with the left hemisphere

which is biased for local processing. Although this proposal holds that the two

systems weight global and local information differently, it does not claim that either

system responds exclusively to one level or the other (Robertson & Lamb, 1991;

Robertson, Lamb et al., 1993).

In the realm of language, the idea that language is a lateralized system has its roots in Broca's observation that an insult to the left hemisphere caused a patient to lose the ability to speak (Broca, 1865). Research carried out in the last few decades, however, has shown that the neural basis of language is much more complex. Whereas the classical model held that language processing was under the control of Broca's and Wernicke's areas in the dominant, left hemisphere, evidence from neuropsychological, metabolic, and electrophysiological studies of both normal and brain-damaged individuals has led to the current consensus view that both hemispheres are involved in many aspects of language processing, especially at a semantic level (Damasio, 1997). In contrast to the traditional model, the current model considers the right hemisphere to be dominant for certain linguistic abilities, including processing prosodic cues such as intonation contours (Behrens, 1989; Ross & Mesulam, 1979), at least some aspects of discourse analysis (Brownell, Gardner, Prather, & Martino, 1995; Brownell, Michel, Powelson, & Gardner, 1983), and non-literal interpretation of humor in the form of jokes (Wapner, Hamby, & Gardner, 1981). Although the model has been revised to reflect right hemisphere competencies for certain domains of language, other aspects of the model have remained largely unchanged and untested. One such example is the view which regards syntactic processing as strictly a left hemisphere function. Despite suggestions from the split-brain and lesion literature that the nondominant right hemisphere may contribute to syntactic processing, few studies have investigated the potential right hemisphere contribution or capabilities in normal brains.

As a first step in investigating hemispheric contributions to syntax, one must first consider what "syntax" encompasses. Many different phenomena are found under the rubric of syntax; in the abstract, all have something to do with how the structure of the sentence indicates what the relationships between the linguistic units of a sentence are. There are multiple ways in which any language indicates these relationships. Word order is one. In English, word order provides relatively strong clues about such relationships: "John hit Mary" represents a different message from "Mary hit John". Relationships between words may also be indicated with various kinds grammatical agreement, such as grammatical number (e.g., singular or plural), grammatical gender (e.g., German nouns belong to one of three possible *grammatical* categories: *der, die, das*), and grammatical case (e.g., *He* is here (a non-oblique case in English) vs. I saw *him* (an oblique case in English). Moreover, languages vary in how they mark grammatical agreement. In English, lexical marking (e.g., *he* vs. *him*) and morphological marking (e.g., The boy$_{SG}$ see*s*$_{SG}$ Mary vs. The boy*s*$_{PL}$ see$_{PL}$ Mary) are two ways of marking grammatical agreement. When one considers the varied nature of the phenomena which fall under the rubric of syntax (the examples listed here are just a small subset), especially in light of the suggestions from the neuropsychological literature (discussed below), it becomes clear that there are likely different neural processes and areas involved in syntactic processing.

Schneiderman and Saddy (1988), for example, examined the performance of right brain damaged (RBD), left brain damaged (LBD), and non-brain-damaged (NBD) patients on two tasks requiring syntactic analysis. In two different tasks, participants were asked to insert a given word into a sentence to form a new,

grammatical sentence. In the Shift insertion task, proper insertion of the word

required role reassignment of a word in the original sentence. For example,

inserting the word *daughter* into the sentence "Cindy saw *her* take his drink" to

produce the sentence "Cindy saw *her daughter* take his drink" requires syntactic

reanalysis in that the pronoun *her* must be reinterpreted as the specifier of *daughter*.

For this task, the LBD group outscored the RBD group. However, in the Nonshift

insertion task, the RBD group outscored the LBD group. In the Nonshift task, role

reassignment is not required, but the syntactic structure of a noun phrase must be

reanalyzed. For example, participants were presented with the sentence "Susan

bought the sweater that was mended" and asked to insert the word "*wool*";

producing the sentence "Susan bought *the wool sweater* that was mended" requires

restructuring the noun phrase "*the sweater*". These results suggest that the right

hemisphere does have some syntactic competency, although the performance

differences between groups on each task suggests that the syntactic competency of

each hemisphere is not identical.

In another study, Caplan, Hildebrandt, and Makris (1996) investigated

syntactic processing in patients with either left or right hemisphere vascular lesions.

They found that both LBD and RBD patient groups were impaired relative to controls

on syntactically complex relative to syntactically simple sentences, although the

LBD group showed a greater degree of impairment than the RBD patients. Within

the RBD group, all but one of the patients showed impairment on the syntactically

complex relative to the syntactically simple sentences, leading the authors to

conclude this result was unlikely due to a small number of patients having atypical

right hemisphere dominance for language. The authors concluded that these

results provided support for views that the right hemisphere has some role in syntactic processing, although the greater impairment for the LBD group suggests that left hemisphere structures are more important for syntactic processing.

More recently, Murasugi and Schneiderman (2005) examined performance of RBD and LBD patients on another task which taps into syntactic abilities, the sentence anagram task. Sentence anagram tasks require patients to take a randomly ordered set of words and arrange them into a sentence. While the LBD patients in this study had previously been diagnosed as mildly to moderately aphasic, the RBD patients had not previously been diagnosed with any language disturbances. The sentence anagrams were divided into two type. The first type, "predicted", requires that an underlying empty category be replaced with a lexical item. An example sentence is "John considers himself intelligent and Doug does too"; successful completion of this sentence anagram requires realizing that "does" replaces the phrase "considers himself intelligent". The second type, "non-predicted", also involves empty categories; however, in these, the empty category remains empty in the sentence (e.g., "John seems easy to upset [ec]" in which the empty category refers to "John"). While both patient groups were impaired relative to the controls on the "predicted" items, only the LBD patients showed significantly impaired performance relative to the controls on the "non-predicted" items. These results suggest that RBD patients have some difficulty related to processing of empty categories, although the authors were unable to precisely specify what that difficulty is.

The commissurotomy literature also suggests that the right hemisphere may perform some syntactic analysis. Zaidel (1983b) reports results from two adult

split-brain patients which suggest that the right hemisphere may process

subject/verb grammatical number agreement in the third person better when it is

signaled lexically (using an auxiliary, such as "*is*" or "*are*": the cat <u>*is*</u> eating/the cats

<u>*are*</u> eating) rather than when it is signaled morphologically (by the presence or

absence of the third person singular simple present tense inflection "-*s*": the cat

eat<u>*s*</u>/the cats eat). In contrast, left hemisphere performance showed little difference

between the two. Furthermore, Zaidel (1990) reviews a number of previous studies

of complete commissurotomy and hemispherectomy English speaking patients and

concludes that the "disconnected right hemisphere can comprehend "… a variety of

grammatical and syntactic structures extending from functors to tense markers and

to simple syntactic transformations such as the passive or negative" (p. 124).

On the basis of data from multiple split-brain and hemispherectomy studies,

Zaidel (1990) suggests that the right hemisphere finds certain linguistic categories

easier to process than others. He proposes a hierarchy which, going in order from

easiest to most difficult for the right hemisphere, includes lexical items (nouns,

verbs, adjectives, adverbs, and prepositions), morphological constructions,

grammatical categories (case, number, gender, tense), and the most difficult are

syntactic structures such as predication and complementation. However, this

hierarchy is based on analysis of a small number of patients with brains that have

functioned abnormally for a significant part of each patient's life. Studies involving

small numbers of participants can be unrepresentative of a population, and

furthermore, the abnormal brain function of the population studied could well have

led to their brains being organized very differently from normal. Therefore, one must

exercise restraint in extending such findings to theories about normal brain organization.

While the studies listed above point toward a left hemisphere which is dominant for language, they do not as a whole lead to the conclusion that the left hemisphere is solely responsible for syntactic aspects of language. Indeed, the patient studies discussed above suggest that the right hemisphere plays some role as well.

3.2.1. Visual half-field paradigm

Ideally, one would like to investigate the right hemisphere's ability to process syntax using individuals who do not have a history of neurological problems. Although with normal brains there is no experimental way to test the functioning of one hemisphere independent of the other, the visual half-field paradigm allows one to approximate in normal individuals the isolation of the hemispheres seen in commissurotomy patients. . In a visual half-field paradigm, participants fixate a central point and stimuli are presented in either the right visual field (RVF) or left visual field (LVF) for 200 ms or less – about the time required to initiate and execute an saccade. Obviously, in normal individuals, the hemispheres remain connected via the corpus callosum and other commissures, but research suggests stimuli presented parafoveally to just one visual cortex are processed initially by the hemisphere directly receiving the information (Hellige, 1983; Zaidel, 1983a). The resulting differences in processing which are frequently observed as a function of which hemisphere the stimulus goes to initially provide a window through which we can begin to understand the

hemispheric contributions to processing contributions of each hemisphere (Chiarello, 1991), at least under laboratory conditions. Specifically, one can infer whether both hemispheres contribute to processing the stimulus and if so, whether there is any quantitative or qualitative difference in the contribution of each hemisphere.

Behavioral research has used the visual half-field paradigm extensively to investigate hemispheric differences for certain language phenomena but the vast majority of this research has looked at processing of individual words rather than sentence-level processing. Moreover, very little research has used the visual half-field paradigm to examine syntactic processing. In one study, Liu, Chiarello, and Quan (1999) combined behavioral measures with the visual half-field paradigm to investigate hemispheric differences related to specific syntactic phenomena in normal participants. They examined grammatical number agreement by asking participants to read three-word noun phrases in which an article and an adjective were presented centrally, followed by a noun target presented laterally. This study was aimed largely at determining the locus of grammatical priming for each hemisphere; in order to elucidate where that locus might be, they compared latency and accuracy in two different tasks. Participants participated in one of two task conditions: they made either a lexical decision or named the target. Some articles did not uniquely specify the grammatical number of the following noun (i.e., the noun could be either singular or plural) whereas other articles uniquely specified the upcoming noun as either grammatically singular or plural. There were three conditions: (1) Neutral, in which the article permitted the noun to be either singular or plural (e.g., *the brown duck* or *the brown ducks*), (2) Consistent (e.g., *these*

brown ducks), and (3) Inconsistent (**these brown duck*); the adjective was included to make the stimuli more "language-like". For grammatical (Consistent and Neutral) trials, they obtained a bilateral priming effect in the lexical decision task only. Since this priming was significant in pairwise comparisons of Consistent and Inconsistent conditions and pairwise comparisons of Neutral and Inconsistent conditions, but not of Consistent and Neutral conditions, they concluded that the grammatical priming effect was inhibitory. Since ungrammatical cues delayed recognition of the target words presented to either cerebral hemisphere, they concluded that at least for noun phrases, both hemispheres are sensitive to number agreement.

Liu et al. (1999) used noun phrases rather than complete sentences. However, it is not clear whether the processing done by participants with noun phrase stimuli is the same as that which would be done with natural language. Additionally, they examined only morphologically marked number agreement, thus, it is not clear if their results generalize to number agreement marked lexically. Furthermore, while accuracy and speed in a grammatical decision task can reveal certain things about the nature of hemispheric involvement in syntactic processing, these are end-product measures which reveal relatively little about hemispheric differences in this processing or about the neural events related to the processing which occurs between stimulus presentation and response execution. Moreover, equal behavior does not necessarily imply the same processes. Rather than looking at end-product measures only, one would also like to look at brain activity on-line, as a sentence is being processed, and use measures which would allow one to examine hemispheric differences in processing.

3.2.2. Event-related brain potentials (ERPs)

ERPs provide a multidimensional measure of online processing and allow for distinguishing between qualitative and quantitative differences in processing: one can examine the general wave shape as well as amplitude, latency, and scalp distributions of the various components. When different patterns of electrical activity over the entire scalp are observed between conditions, such differences can generally be inferred to indicate that the neural generators involved in one condition are not identical to those engaged during another condition. By combining ERPs with the visual half-field paradigm, one can investigate whether the data suggest that the hemispheres process the stimuli differently.[1] Regardless of what component is elicited by a study's stimuli, if there are differences in left and right hemisphere involvement in syntactic processing, one would expect to see asymmetries in the scalp distributions of the ERP wave forms elicited by syntactic violations.

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[1] There are a number of ways experimenters can ascertain that stimuli are indeed initially isolated to just one hemisphere. The electrooculogram (EOG) can be recorded and the experimenter can later remove any trials contaminated by eye movement. Additionally, monitoring the EOG during the experiment allows the experimenter to intervene to ensure as few trials are lost to movement artifact as possible. For example, feedback can be provided to the participants during the experiment whenever proper fixation is not maintained. If problems such as dry eyes are contributing to eye movements, the experimenter can take steps to mitigate them. Moreover, with ERP experiments, after movement-contaminated trials are removed, early visual field components such as the N1 can be examined for additional confirmation that stimuli were successfully lateralized to just one visual hemifield (and consequently, went initially to just one hemisphere). If lateralization is successful, one expects the amplitude of these early potentials to be asymmetric (Coulson & Van Petten, 2007; Neville, Kutas, & Schmidt, 1982). In other words, amplitude should be larger over posterior sites (where early visual potentials are most apparent) contralateral to the visual field of presentation (for example, the N1 should be larger over left than right posterior scalp sites for RVF presentation). The peak latency of the N1 should also be earlier over the hemisphere contralateral to visual field of presentation.

Although to our knowledge no previous ERP studies have investigated syntactic processing using a visual half-field paradigm, ERP studies using central presentation have investigated a number of syntactic structures, including verb subcategorization (Hagoort & Brown, 2000a; 2000b; Osterhout & Holcomb, 1992), phrase structure (Hagoort & Brown, 2000a; 2000b; Hahne, Schroger, & Friederici, 2002; Neville, Nicol, Barss, Forster, & Garrett, 1991); subject-verb number agreement (Coulson, King, & Kutas, 1998; Hagoort & Brown, 2000a; 2000b; Hagoort, Brown, & Groothusen, 1993; Kutas & Hillyard, 1983; Munte, Matzke, & Johannes, 1997; Osterhout, McKinnon, Bersick, & Corey, 1996; Osterhout & Mobley, 1995); reflexive-antecedent number and gender agreement (Osterhout & Mobley, 1995); pronoun inflection errors (Coulson et al., 1998); errors of noun number (Kutas & Hillyard, 1983); verb form errors (Friederici, Pfeifer, & Hahne, 1993; Gunter, Stowe, & Mulder, 1997; Kutas & Hillyard, 1983; Osterhout & Nicol, 1999); case inflection errors (Munte & Heinze, 1994); and unbounded dependencies, including wh-questions and relative clauses (Kluender & Kutas, 1993).

Many experiments investigating syntax compare ERPs elicited by grammatical and ungrammatical sentences, although some have used grammatically correct but temporarily ambiguous sentences. While no single ERP component has been unequivocally associated with ungrammatical relative to grammatical sentences, the two ERP components frequently reported are the P600, a broad, centro-parietally distributed positivity with an onset at about 500 ms and a duration of at least several hundred milliseconds, and early anterior negativities (the distribution of these negativities across the scalp varies; timing also is quite

variable). Findings in the literature are mixed: for the syntactic structures listed in the preceding paragraph (excluding unbounded dependencies), P600s have been reported; some studies report an anterior negativity as well (occasionally, only the negativity is reported).

In the studies reported here, we have combined the visual half-field paradigm with behavioral measures and ERPs with the aim of investigating in neurologically normal individuals the capabilities of each hemisphere for a relatively simple syntactic process: grammatical number agreement. The stimuli used in these experiments were also used in a previous ERP study (Kemmer, Coulson, De Ochoa, & Kutas, 2004) in which we reported the ERP response for central presentation of all critical words. The ERP study reported here used identical experimental procedures to Kemmer et al. with the exception that critical words are lateralized to either LVF or RVF.

Kemmer et al. (2004) found that relative to syntactically well-formed control sentences, grammatical number violations elicited a sustained centro-parietal positivity (P600) with an onset at about 500 ms (and lasting about 800 ms at posterior sites), slightly larger over right hemisphere sites. At prefrontal sites, the positivity had an earlier onset and shorter duration, beginning at about 300 ms and lasting only a few hundred milliseconds. This finding for central presentation is in agreement with reports across a number of different languages that grammatical number violations, be they subject/verb or reflexive pronoun/antecedent grammatical number agreement or other violations, elicit a P600 component (English: Coulson et al., 1998; Osterhout et al., 1996; Osterhout & Mobley, 1995;

Dutch: Hagoort & Brown, 2000a; Hagoort et al., 1993; Vos, Gunter, Kolk, & Mulder,

2001; Munte, Matzke et al., 1997)

Of interest for the three studies reported here is whether the behavioral and

ERP data provide evidence for right hemisphere competency for syntactic

processing. Furthermore, if the evidence suggests that both hemispheres can

process syntax to some degree, does it suggest that they differ in accuracy, speed,

timing of various processes, or the nature of processing (either qualitative or

quantitative differences)? Furthermore, as mentioned above, based on studies with

commissurotomy patients, Zaidel (1983b; 1990) concluded that the right hemisphere

finds it generally more difficult to deal with morphological constructions than lexical.

As our stimuli include both morphological (subject/verb number agreement

condition) and lexical (reflexive/antecedent number agreement condition; see

Methods), we can also investigate whether the right hemisphere in neurologically

intact individuals also has greater difficulty with morphological as compared to

lexical constructions.

3.3. Methods

3.3.1. Design

The design for experiments 1 and 2 was a 2 x 2 x 3 within-subjects design.

The factors included sentence type (subject/verb grammatical number agreement,

reflexive pronoun/antecedent grammatical number agreement), grammaticality

(grammatical, ungrammatical), and visual field (left, center, right). The dependent

variables were response times and accuracy; for response time analyses, data from

only correct responses were included in the analysis.

3.3.2. Materials

There were 240 experimental sentences (ranging in length from 5 to 12 words); critical words ranged from 5 to 10 letters) and 60 filler sentences (see Table 3.1 for sample experimental sentences). Half of the experimental sentences were grammatically well-formed whereas the other half included one of two types of number agreement errors. Specifically, there were 60 sentences with a subject/verb number agreement error and 60 with an reflexive pronoun/antecedent number agreement error.

In the subject/verb number agreement condition, the critical word (the verb) always occurred as the third word in the sentence and was followed by at least two words. For grammatical sentences, all verbs were in the third person plural simple present tense form; for ungrammatical sentences, all verbs were in the third person singular simple present tense form. Verb frequency was restricted to a range of 8 to 353 per million (Francis & Kučera, 1982). Each main verb appeared only once across all sentence types (including practice, filler, or experimental). Most of the subject nouns and adjectives were not repeated across sentences; the few that were are high frequency words in English. In the reflexive pronoun number agreement condition, half of the sentence subjects were plural and half singular. The critical word (the reflexive pronoun) was always the fifth word in the sentence. Ungrammatical sentences included a number violation: a singular subject co-referenced with "themselves", or a plural subject co-referenced with "himself" or "herself". Reflexive pronouns were always gender appropriate, of the gender most likely for that subject, or in the case of gender neutral subjects, randomly split between "himself" and "herself".

A total of four stimulus lists (each consisting of 300 sentences in random order) were created, with sentence type, grammaticality, and visual field counterbalanced across the lists. Each list included 30 grammatical LVF subject/verb, 30 grammatical RVF subject/verb, 30 violation LVF subject/verb, 30 violation RVF subject/verb, 30 grammatical LVF reflexive, 30 grammatical RVF reflexive, 30 violation LVF reflexive pronoun, 30 violation RVF reflexive pronoun, 15 grammatical LVF fillers, 15 grammatical RVF fillers, 15 violation LVF fillers, and 15 violation RVF fillers. A given list included for each sentence either the number violation or its grammatical counterpart, never both. Violations in the filler sentences involved syntactic structures different from those in the experimental sentences. Each participant viewed only one list.

3.3.3. Participants

Twenty-four UCSD undergraduate students participated in experiment 1 for course credit or pay (15 female; ages ranged from 18 to 28; average was 19.8 years). Twelve UCSD undergraduate students participated in experiment 2 for course credit or pay (7 female; ages ranged from 18 to 28; average was 20.0 years). All participants provided health and medical information, including history of psychiatric disorders, learning disorders, drug use, neurological disease, medications currently being taken, vision, and others; participants were excluded from experiment participation as appropriate. All participants were monolingual, right-handed (assessed using the Edinburgh Inventory, Oldfield, 1971), and had normal or corrected-to-normal vision.

3.3.4. Experimental procedure

Participants were tested in a single experimental session lasting about 3 hours. Participants were seated 40 in. in front of a monitor in a sound-proof, electrically shielded recording chamber. Experimental and filler sentences were presented one word at a time every half second for a duration of 200 ms; critical words were presented for 100 ms duration and followed by an inter-stimulus interval (ISI) of 800 ms. Before each sentence, a fixation cross appeared for a duration of 1,000 ms. Additionally, a small central fixation dot, positioned approximately 0.25 degrees below the bottom edge of words, remained on the screen permanently to facilitate correct fixation. Participants were instructed to read each sentence for comprehension, fixate the fixation point until after the sentence ended, and not to blink or move during this period. Participants were also asked to make an acceptability judgment for each sentence. All but one word of each sentence was presented in a blue font; the remaining word (always the critical word) was presented in black. Participants were told that at some point in each sentence a word would appear in black, either centrally or lateralized. Upon seeing this word, participants were to indicate as quickly and as accurately as possible whether the sentence was grammatical up through and including that word.

In addition, to ensure that participants read the entire sentence for comprehension and to discourage them from engaging in any strategies due to the presence of grammatical violations, a random one-half of the sentences were followed by a comprehension probe sentence that appeared in its entirety in a red font. Participants were asked to indicate whether this comprehension probe had approximately the "same content" as its associated experimental sentence. As

response times were not of interest here, participants were instructed to strive for accuracy at the expense of speed; the comprehension probe appeared on the screen until the participant made a response.

First, participants were familiarized with the stimulus presentation parameters and the task via a practice block of 30 sentences. Participants were monitored to ensure they remained fixated on the fixation point throughout the entire sentences, especially when words were presented lateralized. Feedback was provided to train them in this; as necessary, the practice block was repeated until participants demonstrated high accuracy while fixating properly. Experimental sentences were then presented in 10 blocks of 30 sentences each, with short breaks between blocks and a longer break halfway between the experiment. The same hand, counterbalanced across participants, was used to indicate a "good sentence" and "same content" and was switched halfway through the experiment. The practice block was presented again after the mid-break until participants were accustomed to the hand mapping switch.

3.3.5. Recording procedures

The electrooculogram (EOG) was recorded from 3 electrodes placed around the eyes. Lateral eye movements were monitored via electrodes placed at the outer canthus of each eye in a bipolar montage. Blinks were monitored with an electrode placed on the infraorbital ridge of the left eye (experiment 1) or right eye (experiment 2) and referred to the left mastoid. Electrical impedances were kept below 3.0 KΩ. The data were sampled at 250 Hz. The EOG was amplified by Nicolet amplifiers set at a bandpass of 0.016 to 100 Hz.

The EOG was monitored during the experiment to ensure that subjects were not making saccades to the critical word or blinking during presentation of the experimental sentence. Given the monitoring, plus the fact that planning and executing saccades requires on average at least 180 ms (Rayner, 1978), it is not likely participants were able to saccade to and read the lateralized word at either of our critical word durations.

3.4. Results

3.4.1. Accuracy: omnibus ANOVA

As expected, participants were overall significantly more accurate in classifying grammatical (mean: 91.7%) than ungrammatical items (mean: 77.7%), $F(1,23) = 33.93$, $p = .000$. Furthermore, accuracy was significantly higher for the reflexive (86.7%) than the subject/verb condition (82.7%), $F(1,23) = 15.03$, $p = .001$. There was also a significant main effect of Visual Field, $F(2,46) = 37.86$, $p = .000$, $\varepsilon = .82$: as expected, accuracy was highest for central presentation (90.3%), followed by RVF (85.8%), and was lowest for LVF (78.1%) presentation. Significant interactions included the two-way interactions of Type x Visual Field, $F(2,46) = 30.00$, $p = .000$, $\varepsilon = .87$, and Type x Grammaticality, $F(2,46) = 9.80$, $p = .005$; as well as the three-way interaction of Type x Grammaticality x Visual Field, $F(2,46) = 9.61$, $p = .000$, $\varepsilon = .93$. See Figure 3.1 for plots of accuracy (Figure 3.1.A) and response time (Figure 3.1.B) data for each condition; see Table 3.2 for results of statistical tests for response time and accuracy data.

3.4.1.1. Accuracy: planned two-way comparisons

Planned two-way comparisons showed that for each sentence type,

keeping constant visual field, participants were reliably more accurate to

grammatical than ungrammatical items (for reflexives presented to LVF, there was

only a trend, $F(1,23) = 3.56$, $p = .072$). There generally were no differences in

accuracy between sentence types: comparisons between responses to subject/verb

and reflexive sentences, keeping constant grammaticality and visual field of

presentation, showed only one reliable difference: for LVF presentation, responses

in the ungrammatical subject/verb condition were less accurate than for the

ungrammatical reflexive condition, $F(1,23) = 76.79$, $p = .000$.

Two-way comparisons between visual fields of presentation showed that for

each sentence type, responses for central grammatical presentation were more

accurate than responses for either RVF (subject/verb: $p = .011$; reflexive: $p = .002$)

or LVF (subject verb: $p = .000$; reflexive: $p = .001$) presentation. Comparisons of

LVF to RVF presentation of grammatical sentences, however, showed a difference

as a function of sentence type. For grammatical subject/verb sentences, responses

for RVF presentation were reliably more accurate than for LVF ($p = .001$). In

contrast, for the grammatical reflexive sentences, *no reliable difference* was

observed between LVF and RVF presentation ($p = .322$). For ungrammatical

subject/verb sentences, the same pattern was seen as for grammatical: responses

in the central presentation condition were more accurate than both RVF ($p = .025$)

and LVF ($p = .000$) presentation, and RVF was more accurate than LVF ($p = .000$).

In contrast, for ungrammatical reflexives, *no reliable differences* in accuracy were

found for any comparison between visual fields (central vs. RVF, p = .967; central vs. LVF, p = .474; RVF vs. LVF, p = .496).

3.4.2. Response times: omnibus ANOVA

As expected, participants' responses overall were faster for the reflexive (1,046 ms) than subject/verb (1,199 ms) condition, $F(1,23)$ = 26.80, p = .000, and for grammatical (1,055 ms) compared to ungrammatical (1,190 ms) conditions, $F(1,23)$ = 6.47, p = .018. There was also a significant main effect of Visual Field (central: 1,035 ms; RVF: 1,121 ms; LVF: 1,211 ms), $F(2,46)$ = 23.68, p = .000, ε = .84. Significant interactions included Type x Grammaticality, $F(2,46)$ = 12.08, p = .002, and Type x Visual field, $F(2,46)$ = 16.24, p = .000, ε = .75. The three way interaction of Type x Grammaticality x Visual Field just missed significance, $F(2,46)$ = 3.06, p = .057, ε = .98.

3.4.2.1. Response times: planned two-way comparisons

Planned two-way comparisons showed that responses to grammatical were not always reliably faster than to ungrammatical items: e.g., no difference was found for either sentence type for central presentation (subject/verb: p = .197; reflexive, p = .111), additionally, the reflexive condition showed no difference for RVF (p = .258); the difference just reached significance for LVF (p = .047). For the subject/verb condition, responses to grammatical were reliably faster than to ungrammatical for LVF (p = .002) and RVF (p = .002).

Responses for the reflexive condition were generally faster than responses in the subject/verb condition. Two-way comparisons between subject/verb and reflexive conditions with the same visual field of presentation showed that for

ungrammatical sentences, responses to reflexives were faster than for subject/verb

(RVF: p = .000; Central: p = .019; LVF: p = .000). For grammatical sentences, the

difference was reliable for LVF and central but not RVF presentation (LVF: p = .003;

Central: p = .024; RVF: p = .174).

Finally, two-way comparisons between visual fields of presentation showed

that responses for central presentation were always reliably faster than those for

LVF presentation (subject/verb: grammatical, p = .001, ungrammatical, p = .000;

reflexive: grammatical, p = .011, ungrammatical, p = .015). Comparisons between

central and RVF presentation were less clear: central was reliably fast than RVF for

the grammatical reflexive (p = .001) and ungrammatical subject/verb (p = .002)

conditions; however, there was no reliable difference for the ungrammatical reflexive

(p = .226) or the grammatical subject/verb (p = .117) condition. Finally,

comparisons between LVF and RVF showed that responses to subject/verb

sentences were faster for RVF than LVF presentation for both grammatical

(p = .002) and ungrammatical (p = .003) items. In contrast, responses for the

reflexive condition showed no difference between LVF and RVF presentation for

grammatical (p = .864) and just reached significance for ungrammatical (p = .049).

3.5. Discussion, Experiment 1

In this experiment, we examined processing of grammatical number marked

in two different ways: lexically (reflexive condition) and morphologically

(subject/verb condition). We used the visual half-field paradigm to present critical

words of sentences centrally, or lateralized to either RVF or LVF in order to

investigate the capabilities of each hemisphere for processing grammatical number

agreement marked in each of these ways. Of note in our results is that for the

reflexive condition (lexically marked number violations), LVF and RVF presentation yielded similar response times and accuracy, suggesting that both hemispheres can process number agreement of these types under these conditions. In contrast, for the subject/verb condition (morphologically marked number agreement violations), LVF and RVF presentation yielded significant differences in both response times and accuracy. While performance for both lateralized presentations were generally slower and less accurate than those to central presentation, responses to LVF presentation were significantly slower and less accurate than those to RVF presentation. The behavioral data thus suggest that the right hemisphere experiences greater difficulty than the left hemisphere in processing stimuli in our morphologically marked number agreement condition.

The results from this experiment provide evidence that both the right and left hemispheres are able to process, at least up to a point, grammatical number agreement when it is lexically marked. The data from the subject/verb condition suggest that the right hemisphere is less able to appreciate grammatical number when it is marked morphologically. Of interest is determining the source of the difference between the two hemispheres in processing the two types of number agreement. One possibility is that the difference reflects a language-specific difference between the two hemispheres for syntactic processing. This would be in accord with Zaidel's (1990) proposal that the right hemisphere finds certain linguistic categories easier to process than others, including grammatical number marked lexically (compared to morphologically, Zaidel, 1983b). Alternatively, the difference we observed may be due to hemispheric differences in low-level perception.

To investigate this issue, in experiment 3, we use ERPs to examine the brain's response online to critical words using the same stimuli as in experiment 1. However, due to the large decrease in accuracy for ungrammatical conditions in experiment 1, first we ran a second behavioral experiment with a longer critical word duration.

3.6. Introduction, Experiment 2

In experiment 1, we observed a large drop in accuracy in all ungrammatical conditions, relative to that seen in the grammatical condition (see Fig. 3.1.A.; the difference was 12% for central presentation; 15% for RVF, and 16% for LVF). This raised the concern that the short critical word duration time in experiment 1 (100 ms) was unduly affecting participants' performance. This performance drop was particularly dramatic for LVF presentation in the ungrammatical subject/verb condition; here, accuracy was close to chance performance (57.4%). Thus, we ran a version of experiment 1 in which we increased critical word duration from 100 to 200 ms (the ISI for critical words was correspondingly decreased by 100 ms, thus, the SOA was identical for experiments 1 and 2); otherwise, the procedures for experiment 2 are identical to experiment 1. We initially chose 100 ms duration because that duration is frequently used in the behavioral literature to ensure participants cannot make saccades when stimuli are presented laterally. However, unlike many behavioral experiments, we both recorded and monitored EOG during stimulus presentation and thus, were able to ensure participants were not making saccades during the 200 ms stimulus presentation.

Of interest in our results from experiment 2 is how increasing the critical word duration will affect the overall pattern of results. We expect that accuracy

should improve and response times become faster with the longer stimulus duration. Also of interest is whether these improvements will vary as a function of sentence type and visual field. For example, if it is true that the right hemisphere has greater difficulty with local processing, relative to the left hemisphere, we might expect greater performance gains for the subject/verb condition presented to LVF than we would for the reflexive condition. Such a finding would lend support to the view that the results we observed in experiment 1 reflect lower-level processing differences between the hemispheres, rather than higher-level differences.

3.7. Results

3.7.1. Accuracy: omnibus ANOVA

Participants' responses overall were more accurate for grammatical (95.7%) than ungrammatical (87.7%) items, $F(1,11) = 17.69$, $p = .002$. There was also a significant main effect of Visual Field, $F(2,22)$, $p = .000$, $\varepsilon = .87$ (LVF: 87.3%, central: 94.3%; RVF: 93.6%). The Type x Visual Field interaction, $F(2,22) = 9.64$, $p = .007$, $\varepsilon = .74$, was reliable, as was the Type x Grammaticality x Visual Field interaction, $F(2,22) = 3.60$, $p = .049$, $\varepsilon = .77$. See Figure 3.1 for plots of accuracy (Figure 3.1.C) and response time (Figure 3.1.D) data for each condition; see Table 3.3 for results of statistical tests for response time and accuracy data.

3.7.1.2. Accuracy: planned two-way comparisons

Two-way comparisons of grammatical vs. ungrammatical conditions (keeping constant sentence type and visual field) showed for central presentation, responses to grammatical items were reliably more accurate than responses to ungrammatical, regardless of sentence type (central: subject/verb, $p = .006$; reflexive, $p = .028$). For both LVF and RVF presentation in the subject/verb

condition, the difference between grammatical and ungrammatical just missed significance (LVF: p = .054; RVF: p = .061). For the reflexive condition, this difference was reliable for RVF presentation (p = .033) but not for LVF presentation (p = .190). This pattern resembles that seen in experiment 1, although in experiment 1, for both LVF and RVF presentation in the subject/verb condition, the differences were reliable, while in experiment 2, the difference just missed significance. Additionally, for the reflexive condition with LVF presentation, in experiment 1, the difference approached significance (p = .071) while in experiment 2, the difference was not reliable (p = .190).

None of the comparisons between the two sentence types (keeping constant grammaticality and visual field) showed reliable differences; this pattern of results replicates the results from experiment 1. One small difference can be noted: while in experiment 1, the difference was reliable for ungrammatical subject/verb vs. reflexive stimuli presented to LVF, in experiment 2, this was only a trend (p = .075).

Two-way comparisons between visual fields of presentation (keeping constant sentence type and grammaticality) showed no reliable differences in accuracy for central compared to RVF presentation of either grammatical (subject/verb, p = .074; reflexive, p = .902) or ungrammatical (subject/verb, p = .80; reflexive, p = .93) items. Comparisons of central vs. LVF presentation showed that for grammatical items, central was more accurate than LVF for both subject/verb (p = .003) and reflexive (p = .013). For ungrammatical items, central was more accurate than LVF for subject/verb (p = .012) but there was no reliable difference for the reflexive (p = .467) condition. Finally, comparisons between LVF and RVF presentation showed that for subject/verb sentences, responses to RVF

presentation were reliably more accurate than to LVF, for both grammatical (p = .020) and ungrammatical (p = .018) sentences. In contrast, for reflexive sentences, RVF was reliably more accurate than LVF for grammatical items (p = .015) but there was no difference for ungrammatical (p = .469).

For the subject/verb condition, two-way comparisons of central vs. LVF presentation, and LVF vs. RVF presentation showed an identical pattern for experiments 1 and 2: these differences were reliable for both grammatical and ungrammatical items. For the reflexive ungrammatical condition, results for these comparisons also replicated across the two experiments: neither of these comparisons was reliable for either experiment. For grammatical reflexive items, the reliable difference observed between central and LVF presentation also replicated. However, for comparisons of grammatical items in LVF vs. RVF presentation, there was a difference between the two experiments: the difference was not reliable in experiment 1 while in experiment 2, RVF (96.7%) was reliably more accurate than LVF (92.3%).

The pattern observed for central vs. RVF presentation differed between experiments 1 and 2. This difference likely is explained by a ceiling effect in experiment 2: Participants' accuracy was very high in all four conditions (central: subject/verb, 99.2%; reflexive, 97.0%; RVF: subject/verb, 97.6%; reflexive, 96.7%). This high accuracy likely accounts for why, in experiment 2, there were no reliable differences in any of the two-way comparisons between central and RVF presentation (although in experiment 2, subject/verb grammatical showed a trend for significance, p = .074). In contrast, in experiment 1, the shorter duration for critical words (100 ms, vs. 200 ms in experiment 2) made the task more difficult and

participants' accuracy wasn't as high, resulting in three significant comparisons between central and RVF: subject/verb grammatical, subject/verb ungrammatical, and reflexive grammatical; reflexive ungrammatical was not reliable in either experiment.

3.7.2. Response times: omnibus ANOVA

Participants' responses overall were slightly faster for subject/verb (1,019 ms) than reflexives (1,123 ms), main effect of Type, $F(1,11) = 19.13$, $p = .001$. Responses were faster for grammatical (981 ms) than ungrammatical (1,161 ms) sentences, $F(1,11) = 41.61$, $p = .000$. There was also a significant main effect of Visual Field (central: 1,010 ms < RVF: 1,046 ms < LVF: 1,057 ms), $F(2,22) = 45.42$, $p = .000$, $\varepsilon = .83$. No interactions were reliable although Type x Grammaticality showed a trend for significance, $F(2,22) = 4.03$, $p = .070$.

3.7.2.1. Planned two-way comparisons

Two-way comparisons between grammatical and ungrammatical conditions (keeping constant sentence type and visual field) showed that responses for grammatical critical words were reliably faster than for ungrammatical with one exception: for RVF, there was no reliable difference between grammatical and ungrammatical reflexives. The pattern seen in experiment 2 was the same as that for experiment 1 for RVF and LVF presentation. For central presentation, however, the results differed between experiments: in experiment 2, grammatical was reliably faster than ungrammatical for both sentence types; this difference was not reliable in experiment 1 for either sentence type.

Comparisons between sentence types (keeping constant visual field and grammaticality) showed that responses to ungrammatical reflexives were reliably

faster than to ungrammatical subject/verb for RVF (p = .025) and LVF (p = .010)

presentation; the difference for central presentation just missed significance

(p = .054). The difference between sentence types for grammatical sentences,

however, was not reliable for any visual field. For ungrammatical items, the pattern

seen for experiment 2 was the same as that for experiment 1 for all three visual

fields. For grammatical, it was the same for RVF, but for central and LVF

presentation, the difference between sentence types was reliable in experiment 1

but not in experiment 2.

Two-way comparisons between visual fields of presentation (keeping

constant sentence type and grammaticality) showed faster responses for central

compared to. LVF presentation for both grammatical (subject/verb, p = .005;

reflexive, p = .024) and ungrammatical (subject/verb, p = .001; reflexive, p = .028)

conditions. For central vs. RVF presentation, no comparisons were reliable,

although for grammatical sentences, both subject/verb (p = .058) and reflexive

(p = .056) just missed significance (ungrammatical: subject/verb, p = .151; reflexive,

p = .415). Responses to RVF were generally faster than for LVF presentation. For

the ungrammatical condition, RVF responses were faster than LVF for both

sentence types (subject/verb, p = .013; reflexive, p = .023). For the grammatical

condition, the difference was reliable for subject verb (p = .022) and just missed

significance for reflexive (p = .055).

The general pattern of significance for response time comparisons between

experiments 1 and 2 based on visual field of presentation was fairly similar. In both

experiments 1 and 2, all comparisons between central and LVF presentation were

significant. Additionally, the pattern between the two experiments was the same for

LVF vs. RVF presentation with the exception of grammatical reflexive sentences: this comparison was not reliable in experiment 1, whereas in experiment 2, it just missed significance. For central vs. RVF presentation, the pattern is essentially the same between the two experiments with one exception: For ungrammatical subject/verb, the difference was reliable in experiment 1 but not experiment 2. Additionally, for grammatical reflexives, central is reliably faster than RVF presentation in experiment 1 ($p = .001$) but this difference just missed significance in experiment 2 ($p = .056$).

3.8. General Discussion: Experiments 1 and 2

We ran experiment 2 out of concern that the short critical word duration in experiment 1 (100 ms) was unduly influencing the accuracy data. Overall, as expected, the longer critical word duration (200 ms) in experiment 2 resulted in higher accuracy and faster response times, compared to experiment 1 (see Table 3.4 and Figure 3.2). Accuracy for ungrammatical conditions improved for both sentence types but dramatically so for subject/verb. This improvement in performance, however, did not produce any difference in the overall pattern of significant comparisons: the pattern seen in experiment 2 replicates the pattern of results seen in experiment 1 remarkably well. The only major differences in the results for accuracy was the comparison for the grammatical reflexive condition between LVF and RVF, as well as central and RVF: For LVF vs. RVF presentation, this comparison was not significant in experiment 1 (LVF: 88.5%; RVF: 90.9%); in contrast, in experiment 2, RVF (96.7%) was reliably more accurate than LVF (92.3%). For central vs. RVF presentation, the comparison was significant in

experiment 1 (central: 96.1%; RVF: 90.9%) but not in experiment 2 (central: 97.0%; RVF: 96.7%).

For response times, the general pattern of results replicated between the two experiments, but not as neatly as was the case for the accuracy data. As mentioned, comparisons across sentence type (keeping constant visual field and grammaticality) produced similar patterns of results between experiments 1 and 2, with the exception of grammatical sentences presented centrally and to LVF: both comparisons were reliable in experiment 1 but not experiment 2. For two-way comparisons between grammatical and ungrammatical (keeping constant sentence type and visual field), only comparisons for central presentation changed in significance: in experiment 1, they were not reliable for either sentence type, while in experiment 2, both comparisons were reliable.

For comparisons between visual fields (keeping constant sentence type and grammaticality), the general pattern of results was very similar for both experiments. Only two comparisons did not replicate. The comparison for subject/verb ungrammatical between central and RVF presentation was reliable in experiment 1 but not in experiment 2: Speed of response did not change between the two experiments for central presentation, while responses were faster by 88 ms for RVF presentation in experiment 2. Additionally, the comparison for grammatical reflexives between LVF and RVF presentation was not reliable in experiment 1 but was reliable in experiment 2: In experiment 1, response times were essentially the same for LVF (1,027 ms) and RVF (1,032 ms), while in experiment 2, responses for RVF (965 ms) were faster than for LVF (1,006 ms) presentation. In other words, the

longer critical word duration in experiment 2 produced greater performance gains for RVF than LVF grammatical reflexives.

3.8.1. Performance gains

As mentioned above, the increased critical word duration in experiment 2 resulted in overall faster response times and higher accuracy data, compared to experiment 1. Performance gains for experiment 2, however, differed as a function of sentence type. The subject/verb condition showed greater performance gains, both for accuracy and response times, in most comparisons, relative to gains in the reflexive condition (see Table 3.4 and Figure 3.2). This difference suggests that the shorter critical word duration in experiment 1 created greater processing difficulties for the subject/verb than the reflexive condition.[2]

There also was a difference across sentence types in terms of whether greater performance gains were seen for LVF or RVF presentation. For the reflexive condition, performance gains overall are greater for RVF than LVF presentation – in other words, in the reflexive condition, the left hemisphere gains more than the right from the longer critical word duration. In contrast, for the subject/verb condition, it is the right hemisphere which benefits more from the increased critical word duration: performance gains are greater for LVF than RVF

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[2] Interestingly, for central presentation, while response times to grammatical were faster with the longer critical word duration in experiment 2, for ungrammatical, response times were slightly slower in experiment 2 compared to experiment 1 (10 ms slower for subject/verb; 16 ms slower for reflexive). This could be an attentional effect: in experiment 1, the shorter critical word duration time made presentation to LVF and RVF particularly difficult, and thus, participants devoted more attention resources for this experiment than for experiment 2. However, the shorter critical word duration time likely did not increase the difficulty for central presentation of ungrammatical sentences to the extent that it did for lateralized presentation; this factor, plus the greater attentional resources participants likely devoted in experiment 1 (compared to experiment 2) may explain the shorter response times for central ungrammatical sentences in experiment 1.

presentation. In sum, we see the exact opposite pattern of gains between the two sentence types as a function of visual field. This difference in the pattern of results as a function of sentence type and visual field of presentation lends support to the claim that laterally presented stimuli are being processed primarily in the hemisphere to which the stimuli are initially presented. If the stimuli presented initially to the right hemisphere were somehow transferred to the left hemisphere for processing, as some have argued and as must follow from a view which claims syntactic processing is exclusively a left hemisphere function (Zaidel, 2001), one would not expect the performance gains in experiment 2 (compared to experiment 1) to differ as a function of sentence type and visual field of presentation.

Although the current experiment cannot determine how each hemisphere processes the critical word stimuli, our accuracy data from both experiments 1 and 2 suggest the way reflexive stimuli are processed is equally as effective, regardless of visual field of presentation[3] (response time data suggest that processing resulting from LVF presentation generally takes a little longer, relative to RVF presentation). One possible interpretation of our data could be that the right hemisphere differs from the left in its ability to process these stimuli at a high, language-specific level. Although we cannot rule out this possibility conclusively, our combined results from experiments 1 and 2 provide evidence in support of the view that the differences we observed are based in lower-level, perceptual differences between the two hemispheres.

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[3] For the reflexive condition, accuracy is very similar for LVF compared to RVF presentation, for both grammatical and ungrammatical conditions. Although in experiment 2, for grammatical reflexives, RVF (96.7%) presentation is reliably more accurate than LVF (92.3%), accuracy is nonetheless very high for both.

First, consider that the local/global view of hemispheric differences argues that it is the right hemisphere which is less adept at appreciating smaller, local perceptual differences while the left hemisphere is relatively better at such processing (Robertson & Lamb, 1991). One proposal is that these global/local differences emerge because of differences between the hemispheres at the perceptual level for processing spatial frequencies: the right hemisphere amplifies the relatively lower spatial frequencies of a visual stimulus– which tend to be more important for global aspects of stimuli, while the left hemisphere amplifies the relatively higher spatial frequencies – which tend to be more important for local aspects of stimuli (Ivry & Robertson, 1998; Robertson, Egly, Lamb, & Kerth, 1993; Robertson & Lamb, 1991; Sergent, 1982; Shulman, Sullivan, Gish, & Sakoda, 1986; Shulman & Wilson, 1987). Also, recall that the difference between grammatical and ungrammatical critical word stimuli in our subject/verb number agreement condition (the presence or absence of /s/ on the verb) was visually much less salient than was the case for reflexives (the difference between themselves and himself/herself). it may have been more difficult for the right hemisphere to differentiate between grammatical and ungrammatical items in the subject/verb condition (a difference of only one letter) due to the right hemispheres lesser ability to resolve relatively higher frequencies, compared to that of the left hemisphere. For the reflexive condition, differentiating grammatical from ungrammatical items did not require the finer resolution of higher frequencies; for this condition, the lower frequency resolution of the right hemisphere was adequate for differentiating between the two.

Additionally, there is evidence that decreasing exposure duration of visual stimuli has the effect of reducing the availability of higher frequencies relative to

lower (Christman, 1989). This implies that when differentiating between two stimuli is dependent more on higher frequencies, the right hemisphere will show a greater decrease in performance than does the left hemisphere for shorter exposure durations relative to longer. Under a view that the right hemisphere has more difficulty appreciating smaller, less salient differences between grammatical and ungrammatical stimuli, one would predict that increasing critical word duration in our experiment – in other words, making the violation more salient – would result in the greatest performance gains for subject/verb stimuli presented to the right hemisphere. This is precisely what we observed. Additionally, for the reflexive condition, we observed overall greater performance gains for RVF presentation (although these gains were relatively smaller than was the case for LVF presentation in the subject/verb condition). This result is also predicted by the global/local view, although the relatively smaller performance gains for the reflexive condition suggest the hemispheres differ less in their ability to appreciate the reflexive (more global) violations than the subject/verb (more local) violations.[4]

3.9. Introduction, Experiment 3

In experiment 3, we report an experiment using ERPs as an online measure of the brain's response to critical words. As ERPs provide a millisecond by

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[4] While the data we obtained in experiments 1 and 2 provide more support for a lower-level, perceptually-based explanation for the differences we observed between the sentence types as a function of visual field of presentation, one would like to obtain stronger evidence. One approach which may provide such evidence would be to manipulate levels of salience of both morphological and lexical markings within the same grammatical structure. The challenge in designing such an experiment is that English is morphologically, relatively impoverished and most morphological markings are not very salient. However, we were able design an stimuli which includes two levels of lexical marking and one level of morphological markings within the same grammatical construction. Experiments incorporating these stimuli will be reported in chapter 5 of this dissertation.

millisecond record of the brain's electrical activity, they can provide additional

information about the brain's response to complement the information from the end-

product measures (response times and accuracy data) used in experiments 1 and 2.

Stimuli across the three experiments were identical as were experimental

procedures with a few exceptions (as noted in Methods section for experiment 3).

3.10. Methods

3.10.1. Design

The design for experiment 3 was a 2 x 2 x 2 within-subject design. The

factors included sentence type (subject/verb grammatical number agreement,

reflexive/antecedent grammatical number agreement), grammaticality (grammatical,

ungrammatical), and visual field (left, right). The dependent variables were ERPs

and accuracy data.

3.10.2. Materials

Stimuli used in this ERP experiment were identical to the stimuli used in the

two previously-described behavioral experiments. Critical words were presented to

either LVF or RVF. Four stimulus lists were created, each consisting of 300

sentences in random order. Each list included 30 grammatical subject/verb for LVF

presentation, 30 grammatical subject/verb for RVF presentation, 30 violation

subject/verb for LVF presentation, 30 violation subject/verb for RVF presentation, 30

grammatical reflexive pronoun for LVF presentation, 30 grammatical reflexive

pronoun for RVF presentation, 30 violation reflexive pronoun for LVF presentation,

30 violation reflexive pronoun for RVF presentation, 15 grammatical fillers for LVF

presentation, 15 grammatical fillers for RVF presentation, 15 violation fillers for LVF

presentation, and 15 violation fillers for RVF presentation. A given list included for

each sentence either the number violation or its grammatical counterpart, never both. Violations in the filler sentences involved syntactic structures different from those in the experimental sentences. Each participant viewed only one list.

3.10.3. Participants

Thirty-six UCSD undergraduate students participated in the experiment for course credit or pay (18 female; ages ranged from 18 to 33; average age was 19.5 years). All subjects provided health and medical information, including history of psychiatric disorders, learning disorders, drug use, neurological disease, medications currently being taken, vision, and others; subjects were excluded from experiment participation as appropriate. All subjects were monolingual, right-handed (assessed using the Edinburgh Inventory, (Oldfield, 1971), and had normal or corrected-to-normal vision.

3.10.4. Experimental procedure

With the exception of the details noted here, the experimental procedure was identical to that for experiment 1, including procedures for familiarizing participants with stimulus presentation, the inclusion of comprehension sentences, and presentation of experimental sentences.

Participants were tested in a single experimental sessions lasting about 3.5 hours. Participants were seated 40 in. in front of a monitor in a sound-proof, electrically shielded recording chamber. Experimental and filler sentences were presented one word at a time every half second for a duration of 200 ms; all words of these sentences were presented in a black font. Before each sentence, a fixation cross appeared for 900 ms, followed by a random interval between 17 and 300 ms in duration. Additionally, a small central fixation dot, positioned approximately 0.25

degrees below the bottom edge of words, remained on the screen permanently, to

facilitate correct fixation. Participants were instructed to read each sentence for

comprehension, fixate the fixation point until after the sentence ended, and to

attempt not to blink or move during this period. Participants were also asked to

make an acceptability judgment at the end of the sentence: After the final word of a

sentence disappeared, participants were to indicate as quickly and as accurately as

possible whether or not the sentence was well formed.

3.10.5. Recording procedures

The electroencephalogram (EEG) was recorded from 26 tin electrodes,

embedded in an electrode cap, each referenced to the left mastoid. Right mastoid

was recorded as well; ERP averages were re-referenced offline to the average of

activity recorded at the right and left mastoids. Scalp recording sites included:

Prefrontal: left lateral (LLPf), left medial (LMPf), midline (MiPf), right medial (RMPf),

right lateral (RLPf); Frontal: left lateral (LLFr), left mediolateral (LDFr), left medial

(LMFr), right medial (RMFr), right mediolateral (RDFr), right lateral (RLFr); Central:

left mediolateral (LDCe), left medial (LMCe), midline (MiCe), right medial (RMCe),

right mediolateral (RDCe); Parietal: left mediolateral (LDPa), midline (MiPa), right

mediolateral (RDPa); Temporal: left lateral (LLTe), right lateral (RLTe); Occipital: left

lateral (LLOc), left medial (LMOc), midline (MiOc), right medial (RMOc), right lateral

(RLOc). Lateral eye movements were monitored via electrodes placed at the outer

canthus of each eye in a bipolar montage. An electrode was placed on the

infraorbital ridge of the right eye and referenced to the left mastoid to monitor blinks.

Electrical impedances were kept below 2.5 KΩ. The data were sampled at 250 Hz.

The EEG and EOG were amplified by Nicolet amplifiers set at a bandpass of 0.016 to 100 Hz.

3.10.6. ERP data analysis

Prior to analysis, data were examined for artifacts such as eye movements, blinks, amplifier blocking, and excessive muscle activity; 10.6% of the grammatical trials (10.4% for subject/verb /LVF; 11.8% for subject/verbs/RVF; 9.6% for reflexive/LVF;10.8% for reflexive/RVF) and 10.9% of the ungrammatical trials (10.9% for subject/verb /LVF; 11.5% for subject/verbs/RVF; 9.4% for reflexive/LVF;11.6% for reflexive/RVF) were rejected. ERP averages were re-referenced offline to the average of activity recorded at the right and left mastoids. ERPs were timelocked to the onset of the target words and a 200 ms prestimulus baseline was used for all analyses; artifact rejection tests were conducted out to 1,500 ms post-stimulus onset. Only sentences for which the participant made the correct grammaticality response were included in averages.

We examined mean amplitude of the waveforms for two latency windows synchronized to the onset of the critical word: 300 to 500 ms, and 600 to 900 ms. We first conducted an omnibus ANOVA for each time window with four within factors including Sentence Type (subject/verb vs. reflexive number agreement), Grammaticality (grammatical vs. ungrammatical), Visual Field (left vs. right), and Electrode (26 levels); this analysis is referred to as the "full analysis". When the full analysis revealed an interaction of Electrode with Sentence Type, Grammaticality, or Visual Field, a distributional analysis consisting of an ANOVA with six within-subject factors including Sentence Type, Grammaticality, Visual Field, Hemisphere (left vs. right), Laterality (lateral vs. medial electrodes), and Anteriority (five levels:

four prefrontal electrodes (LLPf, LMPf, RLPf, RMPf), four frontal electrodes (LLFr, LMFr, RLFr, RMFr), four central electrodes (LDTe, LMCe, RDTe, RMCe), four temporal or parietal electrodes (LLTe, LDPa, RLTe, RDPa), four occipital electrodes (LLOc, LMOc, RLOc, RMOc)) was conducted (see Figure 3.3).

In addition, we conducted planned omnibus ANOVAs for each sentence type separately with three within factors: Grammaticality, Visual Field, and Electrode, and followed these with distributional analyses as appropriate; these analyses consisted of an ANOVA with five within-subject factors including Grammaticality, Visual Field, Hemisphere, Laterality, and Anteriority as described previously. To better characterize effects which were distributed mainly over anterior or posterior sites, we also conducted modified distributional analyses by sentence type which were identical to the previously-described distributional analysis except they included fewer levels of the Anteriority factor. A "posterior-only distributional analysis" included three levels of Anteriority (four central electrodes (LDTe, LMCe, RDTe, RMCe), four temporal or parietal electrodes (LLTe, LDPa, RLTe, RDPa), four occipital electrodes (LLOc, LMOc, RLOc, RMOc)), while an "anterior-only distributional analysis" included two levels of Anteriority (four prefrontal electrodes (LLPf, LMPf, RLPf, RMPf), four frontal electrodes (LLFr, LMFr, RLFr, RMFr)). Our significance level was set at $p \leq .05$ and for all analyses involving more than one degree of freedom, the Geisser-Greenhouse (1959) correction for violations of sphericity was applied; uncorrected degrees of freedom but corrected p values are reported.

Early sensory components were measured as follows (collapsing across the conditions): the P1 as the average positive peak between 50 and 125 ms, the N1 as

the average negative peak between 75 and 175 ms, and the P2 as the average positive peak between 150 and 250 ms.

3.11. Results

3.11.1. Overt behavior

As expected, participants were reliably more accurate in classifying grammatical (mean=94%) than ungrammatical sentences (mean=71%); main effect of grammaticality, $F(1,35)=144.94$; $p = .000$. Grammaticality judgments were more accurate for RVF (87%) than LVF (77%) presentation; main effect of visual field, $F(1,35)=174.32$, $p = .000$. Additionally, responses were more accurate for reflexives (86%) than subject/verb (78%); main effect of sentence type, $F(1,35)=35.56$, $p = .000$. All interactions were significant (Type x Visual Field, $F(1,35)=140.73$, $p = .000$; Type x Grammaticality, $F(1,35)=28.85$, $p = .000$; Grammaticality x Visual Field, $F(1,35)=49.63$, $p = .000$; Type x Grammaticality x Visual Field, $F(1,35)=51.33$, $p = .000$.

Planned two-way comparisons showed that for the grammatical reflexive condition, there was no reliable difference in accuracy between LVF (93.3%) and RVF (94.5%) presentation, $F(1,35)=1.06$, $p = .311$. In contrast, for the ungrammatical reflexive condition, responses for RVF presentation (80.2%) were reliably more accurate than for LVF (76.7%); $F(1,35)=4.98$, $p = .032$. For the subject/verb condition, responses for RVF presentation were reliably more accurate than LVF for both grammatical (RVF, 97.1%, LVF, 90.8%; $F(1,35)=23.29$, $p = .000$) and ungrammatical (RVF, 78.3%, LVF, 46.8%; $F(1,35)=176.65$, $p = .000$) items. Response times are not reported for this experiment because participants made grammaticality at the end of the sentence rather than immediately after the critical

word (to avoid effects in the ERP data due to muscle activity related to button presses).

3.11.2. Comprehension probes

Responses to the comprehension probes were highly accurate (mean 88.9%), indicating participants were attending to and comprehending the experimental sentences they were reading.

3.11.3. ERPs

As is typical for ERPs to visually presented words, in all conditions we observed a P1 component peaking at around 90 ms, an N1 component peaking at around 120 ms (both anteriorly and posteriorly), and a P2 component peaking at around 167 ms. With visual half-field presentation, lateralized stimuli should produce a larger amplitude N1 over the hemisphere contralateral to visual field of presentation, particularly at temporal/parietal and occipital sites. To assess whether this was the case, we conducted a modified distributional analysis (including two levels in the anterior to posterior direction: temporal/parietal and occipital) for the mean amplitude in the 75 to 175 ms (N1) time window. This analysis revealed a significant Visual Field x Hemisphere interaction, $F(1,23)=45.02$, $p = .000$, with LVF presentation eliciting a larger amplitude N1 over right hemisphere (RH) sites and RVF presentation eliciting a larger N1 amplitude over left hemisphere (LH) sites. This result confirms that presentation of stimuli was successfully lateralized and initially went to only the contralateral hemisphere (see Figure 3.4.)

Grand average ERPs elicited by grammatical and ungrammatical critical words in the reflexive condition, for both RVF and LVF presentation, (N=36) are shown in Figure 3.5 for a representative subset of electrodes. Figure 3.6 shows the

corresponding grand average ERPs for the subject/verb condition. Figure 3.7

shows the difference ERPs (point-by-point subtraction of the ERP to the

grammatical condition from the ERP to the ungrammatical condition) for LVF and

RVF presentation for the reflexive condition; Figure 3.8 shows the same for the

subject/verb condition.

In the reflexive condition, following the early sensory components, the ERPs

elicited by ungrammatical compared to grammatical items, for both LVF and RVF

presentation, were characterized by a sustained centro-parietal late positivity (P600)

with an onset at about 600 ms (lasting about 400 ms at posterior sites). For LVF

presentation, the positivity was somewhat larger over the RH, whereas for RVF

presentation, the positivity was more bilaterally distributed, but slightly larger over

LH. Additionally, there was an early negativity which differed in its distribution and

duration as a function of visual field. For RVF presentation, the bilaterally

distributed negativity had an onset around 300 ms, lasted about 200 ms, was most

prominent at frontal and central electrodes (but extended to parietal and medial

occipital sites), and was larger at medial than lateral sites. For LVF presentation,

the anteriorly (prefrontal, frontal) distributed negativity was of longest duration and

largest amplitude over left electrodes, with an onset of about 400 ms and lasting

until 1,500 ms at two left frontal electrodes; over medial and right lateral electrodes,

the duration was only a few hundred milliseconds. Additionally, for RVF

presentation only, an N400-like effect was observed, most prominent at medial sites

and largest at frontal and central sites, but extending to more posterior sites as well.

In the subject/verb condition, following the early sensory components, for

RVF presentation, the ERPs in the ungrammatical compared to grammatical

condition were characterized by a sustained centro-parietal late positivity (P600), largest over midline and medial electrodes, with an onset at about 600 ms (lasting about 400 ms at central sites; 600 ms or longer at parietal and occipital sites). The ERPs for LVF presentation were markedly different from those for RVF. No P600 effect whatsoever was observed for LVF presentation: over temporal, parietal, and occipital sites, there was no difference in the response to grammatical vs. ungrammatical items. Rather, over anterior electrodes, a sustained negativity (grammatical items more positive than ungrammatical) was observed which was larger over LH than RH sites (particularly left lateral), and began roughly at 500 ms and lasted until the end of the epoch (1,500 ms post-stimulus). A less pronounced anterior negativity with an onset at about 1,000 ms was observed for RVF presentation as well.

The P600 observed for RVF presentation in the subject/verb condition was similar in onset latency, amplitude, and duration to those observed for the reflexive condition with both RVF and LVF presentation at central and temporal/parietal sites. For occipital sites only, however, the P600 observed in the subject/verb condition had a longer duration and slightly greater amplitude than those observed for the two reflexive conditions.

3.11.3.1. Analyses of mean amplitude: 300 to 500 ms

The distributional analysis showed that between 300 and 500 ms, ERPs in the reflexive condition were overall more positive than for the subject/verb condition, main effect of Sentence Type, $F(1,35)=41.02$, $p = .000$. Additionally, grammatical items (3.16 μV) were more positive than ungrammatical (2.80 μV), main effect of Grammaticality, $F(1,35)=9.85$, $p = .003$.

The four-way interaction of Sentence Type x Hemisphere x Laterality x Anteriority, $F(4,140)=8.32$, $p = .000$, $\varepsilon = .90$ modulated a number of lower-order interactions (Sentence Type x Laterality, $F(1,35)=40.54$, $p = .000$; Sentence Type x Anteriority, $F(4,140)=10.99$, $p = 002$, $\varepsilon = .37$; Sentence Type x Laterality x Anteriority, $F(4,140)=6.22$, $p = .001$, $\varepsilon = .68$; and Sentence Type x Hemisphere x Anteriority, $F(4,140)=4.75$, $p = .012$, $\varepsilon = .53$). This four-way interaction reflects greater positivity for the reflexive than subject/verb condition at all levels of anteriority, for both medial and lateral electrodes, and for both RH and LH sites. The difference between the two sentence types was larger over RH than LH sites, and was larger over medial than lateral sites. Additionally, the difference was larger for RH medial sites than LH medial sites. For lateral sites, the difference between the two sentence types was larger for RH lateral posterior (central, temporal/parietal, occipital), but over lateral anterior sites, the difference was larger for LH than RH sites.

A reliable Grammaticality x Anteriority interaction, $F(4,140)=4.30$, $p = .043$, $\varepsilon = .37$ was modulated by a three-way Grammaticality x Hemisphere x Anteriority, $F(4,140)=3.10$, $p = .050$, $\varepsilon = .60$, interaction, reflecting greater positivity for RH than LH sites at each level of anteriority for both grammatical and ungrammatical items, and greater positivity for grammatical than ungrammatical items for both LH and RH sites at each level of anteriority with the exception of LH and RH occipital sites (where grammatical and ungrammatical had approximately the same mean amplitude). The grammaticality effect was a "negativity" (ungrammatical less positive than grammatical) and was slightly larger over RH than LH sites, due mainly to the negativity being larger for RH

temporal/parietal sites; the negativity was approximately the same size for prefrontal, frontal, central, and occipital sites.

The Sentence Type x Grammaticality x Hemisphere x Laterality interaction was reliable, $F(1,35)=4.16$, $p = .049$. ERPs to reflexives were more positive than to the subject/verb condition at each level of laterality and hemisphere for both grammatical and ungrammatical items. For each sentence type, the grammaticality effect was a negativity at each level of laterality and hemisphere. However, the distribution of the negativity differed as a function of sentence type. For the subject/verb condition, the negativity was about equal over lateral and medial sites, as well as over LH and RH sites (grammaticality effect: LH: lateral, 0.32 μV; medial, 0.27 μV; RH: lateral, 0.22 μV; medial, 0.27 μV). In contrast, for the reflexive condition, the grammaticality effect was larger over medial than lateral sites and larger over RH than LH sites (grammaticality effect: LH: lateral, 0.23 μV; medial, 0.53 μV; RH: lateral, 0.48 μV; medial, 0.63 μV). Overall, the negativity was larger for the reflexive than the subject/verb condition.

The four-way Visual Field x Hemisphere x Laterality x Anteriority interaction, $F(4,140)=14.78$, $p = .000$, $\varepsilon = .55$ was reliable (and modulated two lower order interactions: Visual Field x Hemisphere x Laterality, $F(1,35)=11.28$, $p = .002$; Visual Field x Hemisphere, $F(1,35)=20.61$, $p = .000$). For both LVF and RVF presentation, medial electrodes were more positive than lateral over LH and RH at all levels of anteriority. However, for LVF presentation, RH lateral sites were more positive than LH lateral sites (exception: occipital), while for LH medial sites were more positive than RH medial sites (exception: prefrontal). In contrast, for RVF, both RH lateral and RH medial sites were more positive than the corresponding LH sites.

3.11.3.2. Analyses of mean amplitude: 600 to 900 ms

The distributional analysis between 600 and 900 ms showed no reliable main effects, but multiple interactions, reflecting a different pattern across the scalp in the ERP response for LVF presentation of subject/verb sentences, compared to RVF presentation of subject/verb and both LVF and RVF presentation of reflexives. The pattern for each sentence type will be discussed in greater detail in the analyses in the sections below. In the higher-order interactions, the factors of sentence type and grammaticality never reliably interacted with one another.

The significant five-way interaction of Grammaticality x Visual Field x Hemisphere x Laterality X Anteriority, $F(4,140)=2.71$, p = .049, ε = .74 (which modulated numerous lower-order interactions (Grammaticality x Visual Field x Hemisphere, $F(1,35)=7.66$, p = .009; Grammaticality x Laterality, $F(1,35)=11.76$, p = .002; Grammaticality x Hemisphere x Laterality, $F(1,35)=4.60$, p = .039; Grammaticality x Visual Field x Hemisphere x Laterality, $F(1,35)=6.69$, p = .014; Grammaticality x Anteriority, $F(4,140)=13.39$, p = .000, ε = .39; Grammaticality x Hemisphere x Anteriority, $F(4,140)=2.97$, p = .035, ε = .72; and Grammaticality x Laterality x Anteriority, $F(4,140)=5.38$, p = .002, ε = .79) reflected a different distribution in the grammaticality effect primarily over anterior and posterior lateral and medial electrodes as a function of visual field of presentation. In general, over anterior sites (prefrontal, frontal), grammatical items were more positive than ungrammatical (exception: medial anterior sites, both RH and LH, for RVF presentation; medial frontal RH with LVF presentation) – in other words, the grammaticality effect (ungrammatical – grammatical) over anterior sites was a negativity. In contrast,

over posterior sites (central, temporal/parietal, occipital), ungrammatical items were generally more positive than grammatical (exception: lateral central and temporal/parietal LH sites with LVF presentation), in other words, the grammaticality effect was a positivity. Additionally, this posterior positivity was larger for RVF than LVF presentation and larger for medial than lateral sites. For RVF presentation, the positivity was about the same amplitude over RH and LH sites, whereas for LVF presentation, it was larger over RH sites, both medial and lateral. For RVF presentation, the anterior negativity was seen only at lateral sites, where it was small but slightly larger over the RH. For LVF presentation, the negativity was seen for both medial and lateral sites, but was largest at left lateral sites; for RH sites, the negativity was smaller than for LH sites but was also larger at lateral than medial sites.

The four-way interaction of Sentence Type x Hemisphere x Laterality x Anteriority, $F(4,140)=9.54$, $p = .000$, $\varepsilon = .71$, was significant (and modulated the lower order interactions of Sentence Type x Hemisphere x Anteriority, $F(4,140)=10.29$, $p = .000$, $\varepsilon = .58$, and Sentence Type x Laterality x Anteriority, $F(4,140)=3.57$, $p = .032$, $\varepsilon = .61$). Over RH lateral and medial sites, as well as LH medial sites, mean amplitude for the reflexive condition was overall more positive than for the subject/verb condition, although at occipital sites and lateral frontal RH sites, the subject/verb condition showed the larger mean amplitude. For LH lateral sites, overall, the two sentence types had about the same mean amplitude, although it was larger for reflexives at prefrontal and temporal/parietal sites, and larger for subject/verb at frontal and central sites (occipital showed no difference).

The Visual Field x Hemisphere x Anteriority interaction,

$F(4,140)=82.84$, p = .000, ε = .41, primarily reflected a greater asymmetry between LH and RH for RVF compared to LVF presentation. For RVF presentation, RH sites were more positive than LH at all levels of anteriority, whereas for LVF presentation, LH sites were overall more positive than LH (exception: frontal sites). The difference between the hemispheres was much larger for RVF than LVF presentation for frontal, central, temporal/parietal, and occipital sites.

3.11.3.3. ERPs for the reflexive condition

3.11.3.3.1. Analyses of mean amplitude: 300 to 500 ms, RVF presentation only (N400-like effect)

For RVF presentation only, we observed an N400-like effect, most prominent at medial sites and largest at frontal and central sites, but extending to more posterior sites as well prefrontal. This visual observation was confirmed by a distributional analysis including data from the reflexive condition with RVF presentation only. Grammatical items were more positive (3.80 μV) compared to ungrammatical (3.17 μV), main effect of Grammaticality, $F(1,35)=7.84$, p = .008. Mean amplitude measures were larger at medial than lateral sites, Grammaticality x Laterality, $F(1,35)=6.95$, p = .012, and there was a trend towards significance for the interaction of Grammaticality x Laterality x Anteriority, $F(4,140)=2.47$, p = .091, ε = .57), reflecting the fact that the difference between grammatical and ungrammatical was largest at medial frontal and central sites.

3.11.3.3.2. Post-hoc analyses of mean amplitude, 400 to 800 ms, anterior

electrodes only, LVF presentation only

For LVF presentation, we observed a large anterior negativity beginning at

about 400 ms and extending to at least 800 ms at most LH sites, but of shorter

duration and smaller amplitude at RH sites. We quantified it by running a anterior-

only distributional analysis on the mean amplitude for the 400 to 800 ms time

window. Grammatical items were more positive (3.71 μV) compared to

ungrammatical (3.04 μV), (marginal) main effect of Grammaticality,

$F(1,35)=2.76$, $p = .106$. Medial sites were overall more positive than lateral and the

grammaticality effect (negativity) was larger at lateral sites, Grammaticality x

Laterality, $F(1,35)=4.40$, $p = .043$. Furthermore, overall, RH sites were slightly more

positive than LH; the grammaticality effect was larger over LH sites, Grammaticality

x Hemisphere, $F(1,35)=5.71$, $p = .022$. Finally, there was a trend for the

grammaticality effect to be larger at prefrontal than frontal sites, Grammaticality x

Anteriority, $F(1,35)=3.39$, $p = .074$.

3.11.3.3.3. Analyses of mean amplitude: 600 to 900 ms, posterior electrodes

only

As described above under the analyses for the 300 – 500 ms window, for

LVF presentation, over left lateral prefrontal and frontal electrodes, there was a

sustained negativity beginning at about 400 ms and lasting into the 600 to 900 ms

time window. Therefore, in order to examine just the P600 effect, we ran a modified

distributional analysis for the 600 to 900 ms window which included only posterior

electrodes, with three levels of electrodes in the anterior-posterior direction (central,

temporal/parietal, and occipital). The ungrammatical condition (4.35 μV) was more

positive than the grammatical (3.49 μV), main effect of Grammaticality,

$F(1,35)=11.55$, $p = .002$.

There was a trend for the P600 effect to be slightly larger at occipital

electrodes (grammaticality effect: 1.06 μV: grammatical: 3.17 μV; ungrammatical:

4.23 μV) compared to central (0.76 μV: grammatical: 4.74 μV; ungrammatical: 5.50

μV) or temporal/parietal (0.76 μV: grammatical: 2.57 μV; ungrammatical: 3.33 μV);

Grammaticality x Anteriority, $F(2,70)=2.67$, $p = .108$, $\varepsilon = .74$. Overall, medial

electrodes were more positive than lateral and the P600 effect was larger over

medial than lateral sites, Grammaticality x Laterality, $F(1,35)=11.56$, $p = .002$.

Additionally, the Grammaticality x Visual Field x Hemisphere,

$F(1,35)=5.17$, $p = .029$, interaction was reliable and showed a similar pattern to that

seen in the (full) distributional analysis: For LVF presentation, the P600 was

asymmetrically distributed, larger over RH (1.21 μV: grammatical: 3.10 μV;

ungrammatical: 4.31 μV) than LH (0.70 μV: grammatical: 3.89 μV; ungrammatical:

4.59 μV), whereas for RVF presentation, the grammaticality effect was more

bilaterally symmetrical and only slightly larger for LH (0.87 μV grammatical: 2.65 μV;

ungrammatical: 3.52 μV) than RH (0.66 μV: grammatical: 4.33 μV; ungrammatical:

4.99 μV).

The four-way interaction of Visual Field x Hemisphere x Laterality x

Anteriority, $F(2,70)=47.78$, $p = .000$, $\varepsilon = .94$ (which modulated several lower-order

interactions: Visual Field x Hemisphere x Anteriority,

$F(2,70)=57.46$, $p = .000$, $\varepsilon = .79$; Visual Field x Hemisphere,

$F(1,35)=77.10$, $p = .000$) reflected medial sites being more positive for both LVF and

RVF presentation; however, there was a difference in distribution across the hemispheres based on visual field of presentation. For RVF presentation, RH sites were more positive than LH, while for LVF presentation, LH sites were more positive than RH (exception: lateral central).

3.11.3.4. ERPs for the subject/verb condition

3.11.3.4.1. Analyses of mean amplitude: 600 to 900 ms, posterior electrodes only

As the effect observed in the 600 to 900 ms time window differed as a function of visual field of presentation, we will conduct separate analysis for LVF and RVF.

3.11.3.4.1.1. Analyses of mean amplitude: 600 to 900 ms, posterior electrodes only, RVF presentation

For RVF presentation, the ERPs in the ungrammatical compared to grammatical condition were characterized by a sustained centro-parietal late positivity (P600). Ungrammatical items (4.28 μV) were more positive than grammatical (3.44 μV). Medial sites were more positive than lateral and the grammaticality effect (positivity) was larger at lateral than medial sites, Grammaticality x Laterality, $F(1,35)=4.98$, $p = .032$. This interaction was modulated by the three-way Grammaticality x Laterality x Anteriority interaction, $F(2,70)=3.70$, $p = .030$, $\varepsilon = .91$: reflecting the fact that the grammaticality effect was much larger over occipital sites compared to central and temporal/parietal.

3.11.3.4.1.2. Analyses of mean amplitude: 600 to 900 ms, posterior electrodes only, LVF presentation

As already mentioned, no P600 effect was observed for the 600 to 900 ms time window for LVF presentation. There was no reliable main effect of grammaticality. There was a significant Grammaticality x Laterality x Anteriority interaction, $F(2,70)=3.48$, $p = .036$, $\varepsilon = .99$. This interaction was due to the grammaticality effect being a negativity (grammatical more positive than ungrammatical) in this time window for central and temporal/parietal sites, larger over medial than lateral sites. For occipital sites, there was a positivity, larger at lateral than medial sites. This positivity does not have the expected distribution to be considered a P600 effect, which is typically characterized as larger at medial than lateral sites.

Over anterior sites, a sustained negativity was observed, but for LVF presentation, the onset was much earlier (about 500 ms) than for RVF presentation (onset about 1,000 ms). Both negativities were sustained until at least 1,500 ms (end of epoch).

3.11.3.4.2. Post-hoc analyses of mean amplitude: 500 to 1,500 ms, LVF presentation only

For LVF presentation, we observed a sustained negativity over anterior sites, beginning at about 500 ms and lasting until the end of the epoch (1,500 ms). We quantified this effect as the mean amplitude in the 500 to 1,500 ms time window and ran an anterior-only distributional analysis. Grammatical items (4.10 μV) were more positive than ungrammatical (2.75 μV), main effect of Grammaticality, $F(1,35)=9.35$, $p = .004$. Medial sites were more positive than lateral and LH sites

more positive than RH. Furthermore, the grammaticality effect (negativity) was larger over lateral than medial sites, but was bisymmetric across the hemispheres, Grammaticality x Hemisphere x Laterality, $F(1,35)=8.06$, $p = .008$. Additionally, there was a marginal Grammaticality x Laterality x Anteriority interaction, $F(1,35)=3.76$, $p = .061$, reflecting a larger grammaticality effect at medial sites for prefrontal electrodes, while for frontal electrodes, the grammaticality effect was larger at lateral sites.

3.11.3.4.3. Post-hoc analyses of mean amplitude: 1,000 to 1,500 ms, RVF presentation only

For RVF presentation, we observed a sustained negativity over anterior sites which began much later (about 1,000 ms) than was the case for LVF presentation; this negativity lasted until the end of the epoch. We measured this effect as the mean amplitude in the 1,000 to 1,500 ms time window and ran an anterior-only distributional analysis. Grammatical items (4.18 μV) were more positive than ungrammatical (3.07 μV), main effect of Grammaticality, $F(1,35)=7.96$, $p = .008$. The Grammaticality x Hemisphere x Laterality x Anteriority interaction, $F(1,35)=6.64$, $p = .014$, reflected that the grammaticality effect was overall, somewhat larger for frontal than prefrontal sites; slightly larger overall for medial than lateral sites, and slightly larger over RH than LH sites. For frontal sites, the grammaticality effect was largest at left lateral sites, whereas for prefrontal sites, the grammaticality effect was largest over medial sites.

3.12. Discussion, Experiment 3

The aim of experiment 3 was to investigate the capabilities of each hemisphere for processing grammatical number marked in two different ways:

lexically (reflexive condition) and morphologically (subject/verb condition). To that end, we recorded ERP and behavioral responses as participants read sentences with laterally presented grammatical and ungrammatical critical words.

For the lexically marked number violations, LVF and RVF presentations yielded similar patterns in that presentation of violations in either visual field elicited a P600 of similar amplitude and latency. At the same time, however, LVF presentation also elicited a frontally distributed, left lateralized negativity (beginning at about 400 ms and of longer duration, at least several hundred milliseconds, at left lateral sites) for violations relative to controls, suggesting a difference in how each hemisphere processes lexically marked number violations. In contrast, RVF presentation elicited an N400-like response, of much shorter duration, between approximately 350 and 550 ms, with a different distribution, being most prominent at frontal and central midline and medial sites but extending to parietal and occipital sites as well[5]. The similar P600 response to violations relative to controls for both LVF and RVF presentation suggests similarities between the hemispheres in

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[5] It is not clear what cognitive function(s) this N400-like response for RVF presentation in the reflexive condition reflects. On the basis of the results from only the current experiment, one might speculate that the violation in the reflexive condition is not just syntactic but has some semantic aspects as well, and that the left hemisphere picks up on this. However, in another experiment (presented in chapter 5 of this dissertation), we observe a similar N400-like effect for RVF presentation with high, but not low, salience irregular participle forms of verbs. In the sentence stimuli for this experiment, the control form was the correct participle form of the verb while for the violation, the verb's infinitive was presented. Had we observed this N400-like effect for RVF presentation of both the high and low salience irregular verb conditions (but not the regular verb condition), as well as for the reflexive (but not the subject/verb) condition, the common denominator would be that none of these conditions involved morphological constructions. Such a finding could suggest that the left hemisphere, but not the right hemisphere, differentiates between morphological and lexical constructions. However, the lack of an N400-like effect in the low salience irregular verb condition makes it difficult to make such an argument.

appreciating lexically marked grammatical number agreement in terms of the processes reflected in the P600 response. However, the differences in the negativity as a function of visual field suggest that processing is not identical between the two hemispheres.

For morphologically marked number agreement violations, LVF and RVF presentations yielded significant differences in the ERP response to critical words. Only violations in RVF yielded a reliable P600. Violations presented to the LVF instead elicited an enhanced frontal negativity, larger over LH than RH sites, beginning at about 500 ms and sustained until at least 1,500 ms. The presence of the P600 for RVF presentation compared to the absence of it for LVF presentation suggests a qualitative difference in the brain response as a function of visual field[6]. A less pronounced anterior negativity (slightly larger over LH than RH sites) with an onset at about 1,000 ms was observed for RVF presentation as well.

Results for central presentation of these stimuli were previously reported in Kemmer et al. (2004) which included results for both younger (college-aged) and older adults; the results for the younger adults only will be discussed here. For both morphologically and lexically marked grammatical number, the ERP response to violations relative to controls was a centro-parietally distributed P600 of similar onset (about 400 ms), amplitude, and duration (lasting until at least 1,300 ms at

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[6] For the subject/verb condition, the presence of the third person singular "s" on the end of the verb is what creates the violation. Note that with LVF presentation, this means that the "s" which indicates the violation is closer to the fixation point. In contrast, with RVF presentation, the "s" is farthest from the point of fixation. Since acuity decreases slightly outside the fovea as distance from fixation increases, acuity should be highest for LVF. However, behavioral performance was superior for RVF than LVF presentation. Additionally, the P600 was observed only for RVF presentation. Both of these patterns are in a direction opposite to what one would expect if acuity influence the results, suggesting differences in acuity did not drive the pattern we observed.

posterior sites). The P600s we observed in experiment 3 for both RVF and LVF

presentation of lexically marked and RVF presentation of morphologically marked

number were similar in distribution to the P600 observed in Kemmer et al. (2004) for

central presentation, although all lateralized presentations resulted in P600s with

somewhat later onset latencies (about 550 ms), shorter durations, and smaller

amplitudes. Moreover, the P600 observed for RVF presentation in the subject/verb

condition was generally similar in onset latency, amplitude, and duration to those

observed for the reflexive condition with both RVF and LVF presentation, although

at occipital sites, duration was longer for the subject/verb condition. It remains

unclear exactly what processes the frontal negativities we observed reflect.

3.13. General Discussion

The purpose of the experiments presented here was to investigate in

neurologically normal individuals the capabilities of each hemisphere for processing

grammatical number agreement. Stimuli included grammatical number marked in

two different ways, lexically (reflexive) and morphologically (subject/verb), as

previous research with split brain patients (Zaidel, 1983b; 1990) had suggested that

the right hemisphere finds it more difficult to deal with morphological than lexical

constructions.

3.13.1. Anterior negativities

In no condition did we observe the effect referred to as the LAN which is

usually elicited by a syntactic violation and generally is measured between 300 and

500 ms. We did, however, observe later anterior negativities (more pronounced at

left than right anterior sites) with LVF presentation in the reflexive condition

(between about 400 and 800 ms) as well as for the subject/verb condition, with both

LVF (onset about 500 ms) and RVF (onset about 1,000 ms) presentation. The negativities for the subject/verb condition were sustained, extending until the end of the epoch (1,500 ms), whereas LVF presentation of reflexives resulted in a negativity which generally lasted just a few hundred milliseconds. However, a relatively large number of studies with morphosyntactic violations have not observed LANs (Coulson et al., 1998 (LAN observed for pronoun case but not subject/verb agreement); Gunter et al., 1997 (exp. 1); Hagoort & Brown, 2000a (exp. 1, visual); Hagoort et al., 1993; Kemmer et al., 2004; Kutas & Hillyard, 1983; Munte, Szentkuti, Wieringa, Matzke, & Johannes, 1997; Osterhout et al., 1996; Osterhout & Mobley, 1995 (LAN reported for exp. 1 but not exp. 3); Osterhout & Nicol, 1999), and there are a number of studies in which LANs have been elicited by stimuli which do not involve morphosyntactic violations (Hagoort & Brown, 2000a (exp. 2); Osterhout & Holcomb, 1992; 1993 (exp. 1)). Additionally, some of the reported "LANs" have been bilaterally symmetric and some have extended into (or even been most prominent at) posterior electrode sites. In sum, there is a great deal of variability in the literature in terms of what has been labeled a LAN and identifying the necessary and sufficient conditions for the elicitation of the LAN, as well as identifying what cognitive function(s) it reflects remains a task for future research.

We do not make a strong claim that the negativities we have observed either are or are not of the same family with the LAN which has been associated with morphosyntactic violations. There is much still to be worked out about the conditions necessary to elicit this effect. If we assumed that the negativities we observed in our subject/verb condition were elicited by processes related to the morphosyntactic nature of the violation (or that the verb is regular), we would still have to account for

why the onset of the negativity is so much later with RVF (left hemisphere-initial) than LVF (right hemisphere-initial). Under such an assumption, one possible interpretation of the earlier onset latency for LVF presentation would be that the right hemisphere is dominant for morphosyntactic processing – a position we do not take.

3.13.2. P600

As mentioned above, the similar brain response – a P600 – for both LVF and RVF presentation of lexically-marked number agreement, and its similarity to the response observed with central presentation of stimuli (as reported in Kemmer et al., 2004) suggests engagement of similar neural generators and processing mechanisms for this condition. Furthermore, the behavioral results we observed in experiment 1 of similar response times and (high) accuracy for both lateralized presentation conditions suggest that both hemispheres appreciate lexically marked grammatical number agreement to an equal degree. In contrast, for morphologically marked number agreement, in experiments 1 and 2, we observed significantly slower and less accurate behavioral responses for LVF presentation compared to RVF. These behavioral data suggest that the right hemisphere experiences greater difficulty than the left hemisphere in processing morphologically marked number agreement. The ERP data from experiment 3 – the presence of the P600 for RVF presentation versus its complete absence for LVF presentation – suggests a qualitative difference in terms of how our critical word stimuli were processed as a function of which hemisphere initially received the stimuli. With left hemisphere initial (RVF) presentation, the stimuli seem to be processed in a way which is similar to that seen for central presentation, whereas the brain's response for LVF

presentation suggests that the right hemisphere is less able than the left

hemisphere to appreciate grammatical number agreement.[7]

Of import is whether the left hemisphere advantage for the morphological

marking (subject/verb condition) reflects a language-specific difference between the

two hemispheres for syntactic processing, or whether it reflects some more general

difference (e.g., perceptual) between the two different ways of marking grammatical

number. One possibility is that the left hemisphere advantage for morphologically

marked agreement errors reflects a high-level difference between the hemispheres

in their processing capabilities for language stimuli, consistent with Zaidel's proposal

based on his findings with commissurotomy patients (Zaidel, 1983b; 1985). Another

explanation, however, could be based on hemispheric differences in lower level

perception. A possible design confound in the experiments presented here involves

the visual salience difference in the way grammatical number is marked across the

two sentence types. Grammatical number marking is perceptually relatively more

salient for reflexive pronouns (*himself/herself/themselves*), whereas it is quite subtle

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[7] For the subject/verb condition, the third plural present tense verb form (e.g., Industrial scientists develop …) was always used in the grammatical condition, while the third singular present tense form (*Industrial scientists develops …) was always used in the ungrammatical condition. This was done because the form of the verb with the "s" on it is unique and can only represent the third present singular form. Thus, when the sentence subject is plural, there is a clear number violation. In contrast, the third plural form of the verb – without the "s" – is homonymous with other verb forms (e.g., the infinitive). The concern was that participants may not necessarily interpret this form as a number violation and thus, the lack of counterbalancing in the grammatical and violation forms. For lateralized presentation, it is possible that one hemisphere may have been less sensitive to the unexpected "s" and thus would have been less likely to notice the ungrammaticality, which could present a confound since all our violations were of one type. However, a priori, there was not strong evidence this was the case. Manipulating salience of a fully counterbalanced violation, as is done in chapter 5, is one way to address this concern. In the reflexive condition, number was counterbalanced across violations and controls.

for subject/verb agreement where number is marked on the verb by the presence or absence of a word-final /–s/.

One asymmetry which is supported by converging evidence from many fields and methodologies suggests that the hemispheres are differentially dominant at processing local as opposed to global information: the right hemisphere is biased for global processing whereas the left hemisphere is biased for processing on a local level (Banich & Noll, 1993; Delis et al., 1986; Heinze, Hinrichs, Scholz, Burchert, & Mangun, 1998; Heinze & Munte, 1993; Lamb & Robertson, 1989; Martin, 1979; Martinez et al., 1997; Robertson & Delis, 1986; Robertson & Lamb, 1991; Robertson et al., 1988; Robertson, Lamb et al., 1993; Sergent, 1982; Yovel, Levy, & Yovel, 2001). In a review, Robertson and Lamb (1991) argue that their evidence (e.g., Robertson, Egly et al., 1993) suggests there are two separate lateralized neural subsystems involved in processing global and local aspects of stimuli. They also point out that the question of what type of information each mechanism processes remains unanswered, and put forth the hypothesis that the differential response of the hemispheres to spatial frequencies (e.g., Kitterle, Christman, & Conesa, 1993; Sergent, 1982) may contribute to the global/local difference.

Ivry and Robertson's (1998) double filtering by frequency (DFF) theory further develops the idea that global and local differences can be explained based on (post-sensory) hemispheric differences at the perceptual level in processing visual or auditory frequencies. The first filtering stage occurs on the sensory representation where selective attention acts as a "filter" in that it determines what aspects of the entire sensory scene are selected for further processing.

Hemispheric asymmetries emerge at the perceptual level due to differential filtering in each hemisphere. Specifically, processing in the right hemisphere functions like a low-pass filter, while processing in the left hemisphere functions like a high pass filter. Each of these "filters" amplifies and attenuates different (relative) frequencies in a particular stimulus, resulting in a processing advantage for the amplified frequencies. The filtering effect of selective attention, which selects some frequency range of information for further processing, is important in that it provides an account as to why global and local asymmetries are based on relative frequency differences, rather than absolute. The link between the differential filtering of frequencies by the hemispheres and the observed hemispheric asymmetries for global and local information is that global information about a stimulus pattern is usually conveyed by lower frequencies, while local information is usually conveyed by higher frequencies (Kitterle et al., 1993; Shulman et al., 1986). In other words, in this account, the global/local asymmetry is an emergent property, resulting from asymmetric representations created by the different filtering properties of each hemisphere.

3.13.3. Conclusion

The ERP and two behavioral experiments reported here provide evidence that the right hemisphere is better at processing lexically marked grammatical number (reflexive pronoun condition) than morphologically marked (subject/verb condition). Of interest is whether these results reflect a high level, language-specific difference between the two hemispheres for syntactic processing or whether the difference we observed may be due to hemispheric differences in low-level perception.

Given the possible confound in salience of our stimuli, our results from these experiments do not allow us to determine whether the pattern of results we observed is due to high-level processing differences between the two hemispheres or low-level. The right hemisphere may have been less likely to pick up on grammatical number marking in the subject/verb relative to the reflexive condition because the presence or absence of the /-s/ is a perceptually less salient feature, the discrimination of which requires higher frequencies. If this is the case, the present results do not provide evidence of language specific hemispheric differences in processing grammatical markings which are lexical as opposed to morphological, but rather evidence that the hemispheres are differentially able to process global as opposed to local information.

However, the results from experiments 1 and 2 lend support to the view that the differences observed are based in lower-level, perceptual differences between the two hemispheres. As discussed earlier, under a view that the right hemisphere has more difficulty appreciating smaller, less salient differences between grammatical and ungrammatical stimuli, one would predict that increasing critical word duration in experiment 2 – in other words, making the violation more salient – would result in the greatest performance gains for subject/verb stimuli presented to the right hemisphere. This is what we observed. Furthermore, the results we observed for the reflexive condition were in accord with what would be predicted by the global/local view: we observed overall greater performance gains for RVF presentation with the increased critical word duration in experiment 2. The greater performance gains for the subject/verb compared to the reflexive condition suggests that the hemispheres differ less in their ability to appreciate the reflexive (more

global) marking than the subject/verb (more local) marking. Whatever the reason

for the difference in the pattern of results we observed, we did obtain evidence for a

right hemisphere ability to appreciate grammatical number agreement, at least when

it is marked lexically.

Table 3.1. Sample sentences from each condition.

Subject/verb agreement

Grammatical:	Industrial scientists _develop_ many new consumer products.
Ungrammatical:	*Industrial scientists _develops_ many new consumer products.

Reflexive pronoun-antecedent number agreement

Grammatical:	The grateful niece asked _herself_ how she could repay her aunt.
Ungrammatical:	*The grateful niece asked _themselves_ how she could repay her aunt.

An asterisk preceding a sentence conventionally indicates it is ungrammatical; asterisks were not included in experimental stimuli.

Table 3.2. Statistical results for analyses of accuracy and response time data from experiment 1 (statistically significant results are shown in a bolded font).

Accuracy data.

Grammaticality	F(1,23) = 33.93, *p*=**.000**	Grammatical 91.7%	Ungrammatical 77.5%	
Sentence Type	F(1,23) = 15.03, *p*=**.001**	Reflexive 88.7%	Subject/verb 82.7%	
Visual Field	F(2,46) = 37.86, *p*=**.000**	Central 90.3%	RVF 85.8%	LVF 78.1%
	LVF vs. RVF F(1,23) = 20.55, *p*=**.000**	LVF vs. Central F(1,23) = 79.87, *p*=**.000**	RVF vs. Central F(1,23) = 15.78, *p*=**.001**	

Two-way comparisons for accuracy data: *p* values.

RVF:	S/V Gr vs. Ungr *p*=**.000**	Refl Gr vs. Ungr *p*=**.011**		
Central:	S/V Gr vs. Ungr *p*=**.003**	Refl Gr vs. Ungr *p*=**.000**		
LVF:	S/V Gr vs. Ungr *p*=**.000**	Refl Gr vs. Ungr *p*=.072		
SubjVerb Grammatical:	Central vs. RVF *p*=**.011**	Central vs. LVF *p*=**.000**	LVF vs. RVF *p*=**.001**	
SubjVerb Ungrammatical:	Central vs. RVF *p*=**.025**	Central vs. LVF *p*=**.000**	LVF vs. RVF *p*=**.000**	
Reflexive Grammatical:	Central vs. RVF *p*=**.002**	Central vs. LVF *p*=**.001**	LVF vs. RVF *p*=.322	
Reflexive Ungrammatical:	Central vs. RVF *p*=.987	Central vs. LVF *p*=.474	LVF vs. RVF *p*=.498	
RVF	Gr: S/V vs. Refl *p*=.140	Ungr: S/V vs. Refl *p*=.344		
Central	Gr: S/V vs. Refl *p*=.188	Ungr: S/V vs. Refl *p*=.172		
LVF	Gr: S/V vs. Refl *p*=.104	Ungr: S/V vs. Refl *p*=**.000**		

Table 3.2 (continued). Statistical results for analyses of accuracy and response time data from experiment 1 (statistically significant results are shown in a bolded font).

Response time data.

Grammaticality	$F_{(1,23)} = 6.47$, $p=.018$	Grammatical 1,055 ms	Ungrammatical 1,191 ms	
Sentence Type	$F_{(1,23)} = 26.80$, $p=.000$	Reflexive 1,048 ms	Subject/Verb 1,199 ms	
Visual Field	$F_{(2,46)} = 23.68$, $p=.000$	Central 1,035 ms	RVF 1,121 ms	LVF 1,211 ms
	LVF vs. RVF	LVF vs. Central	RVF vs. Central	
	$F_{(1,23)} = 13.90$, $p=.001$	$F_{(1,23)} = 33.30$, $p=.000$	$F_{(1,23)} = 16.48$, $p=.000$	

Two-way comparisons for response time data: p values.

RVF	S/V Gr vs. Ungr $p=.002$	Refl Gr vs. Ungr $p=.258$	
Central	S/V Gr vs. Ungr $p=.197$	Refl Gr vs. Ungr $p=.111$	
LVF	S/V Gr vs. Ungr $p=.002$	Refl Gr vs. Ungr $p=.047$	
Subj/Verb Grammatical:	Central vs. RVF $p=.117$	Central vs. LVF $p=.000$	LVF vs. RVF $p=.002$
Subj/Verb Ungrammatical:	Central vs. RVF $p=.002$	Central vs. LVF $p=.002$	LVF vs. RVF $p=.003$
Reflexive Grammatical:	Central vs. RVF $p=.001$	Central vs. LVF $p=.011$	LVF vs. RVF $p=.864$
Reflexive Ungrammatical:	Central vs. RVF $p=.226$	Central vs. LVF $p=.226$	LVF vs. RVF $p=.049$
RVF	Gr: S/V vs. Refl $p=.174$	Ungr: S/V vs. Refl $p=.000$	
Central	Gr: S/V vs. Refl $p=.024$	Ungr: S/V vs. Refl $p=.019$	
LVF	Gr: S/V vs. Refl $p=.003$	Ungr: S/V vs. Refl $p=.000$	

Table 3.3. Statistical results for analyses of accuracy and response time data from experiment 2 (statistically significant results are shown in a bolded font).

Accuracy data.

Grammaticality	F(1,11) = 17.69, p=.002	Grammatical 95.7%	Ungrammatical 87.7%	
Sentence Type	F(1,11) = .19, p=.668	Reflexive 91.3%	Subject/verb 92.1%	
Visual Field	F(2,22) = 13.92, p=.000	Central 94.3%	RVF 93.6%	LVF 87.3%
	LVF vs. RVF F(1,11) = 15.19, p=.003	LVF vs. Central F(1,11) = 19.64, p=.001	RVF vs. Central F(1,11) = .38, p=.552	

Two-way comparisons for accuracy data: p values.

RVF:	S/V Gr vs. Ungr p=.061	Refl Gr vs. Ungr p=.033	
Central:	S/V Gr vs. Ungr p=.006	Refl Gr vs. Ungr p=.028	
LVF:	S/V Gr vs. Ungr p=.054	Refl Gr vs. Ungr p=.190	
Subj/verb Grammatical:	Central vs. RVF p=.074	Central vs. LVF p=.003	LVF vs. RVF p=.020
Subj/verb Ungrammatical:	Central vs. RVF p=.795	Central vs. LVF p=.012	LVF vs. RVF p=.018
Reflexive Grammatical:	Central vs. RVF p=.802	Central vs. LVF p=.013	LVF vs. RVF p=.015
Reflexive Ungrammatical:	Central vs. RVF p=.927	Central vs. LVF p=.467	LVF vs. RVF p=.469
RVF	Gr: S/V vs. Refl p=.830	Ungr: S/V vs. Refl p=.085	
Central	Gr: S/V vs. Refl p=.097	Ungr: S/V vs. Refl p=.090	
LVF	Gr: S/V vs. Refl p=.798	Ungr: S/V vs. Refl p=.075	

Table 3.3 (continued). Statistical results for analyses of accuracy and response time data from experiment 2 (statistically significant results are shown in a bolded font).

Response time data.

Grammaticality	F(1,11) = 41.81, *p*=.000	Grammatical 881 ms	Ungrammatical 1,161 ms	
Sentence Type	F(1,11) = 19.13, *p*=.001	Reflexive 1,123 ms	Subject/verb 1,019 ms	
Visual Field	F(2,22) = 45.42, *p*=.000	Central 1,010 ms	RVF 1,046 ms	LVF 1,157 ms
	LVF vs. RVF F(1,11) = 50.43, *p*=.000	LVF vs. Central F(1,11) = 59.01, *p*=.000	RVF vs. Central F(1,11) = 8.16, *p*=.016	

Two-way comparisons for response time data: *p* values.

RVF	S/V Gr vs. Ungr *p*=.000	Refl Gr vs. Ungr *p*=.103		
Central	S/V Gr vs. Ungr *p*=.000	Refl Gr vs. Ungr *p*=.005		
LVF	S/V Gr vs. Ungr *p*=.002	Refl Gr vs. Ungr *p*=.001		
Subj/verb Grammatical:	Central vs. RVF *p*=.058	Central vs. LVF *p*=.005	LVF vs. RVF *p*=.022	
Subj/verb Ungrammatical:	Central vs. RVF *p*=.151	Central vs. LVF *p*=.001	LVF vs. RVF *p*=.013	
Reflexive Grammatical:	Central vs. RVF *p*=.058	Central vs. LVF *p*=.024	LVF vs. RVF *p*=.055	
Reflexive Ungrammatical:	Central vs. RVF *p*=.415	Central vs. LVF *p*=.028	LVF vs. RVF *p*=.023	
RVF	Gr: S/V vs. Refl *p*=.818	Ungr: S/V vs. Refl *p*=.025		
Central	Gr: S/V vs. Refl *p*=.871	Ungr: S/V vs. Refl *p*=.054		
LVF	Gr: S/V vs. Refl *p*=.122	Ungr: S/V vs. Refl *p*=.010		

Table 3.4. Performance gains for response times and accuracy for Experiment 2 compared to Experiment 1.

Difference in response times between Exp. 1 and Exp. 2 (Exp. 2 response times minus Exp. 1 response times)

	RVF			LVF			Central	
	Gram	**Ungram**		**Gram**	**Ungram**		**Gram**	**Ungram**
Subject/verb	103 ms	88 ms		125 ms	94 ms		80 ms	-10 ms
Reflexive	67 ms	39 ms		21 ms	-22 ms		49 ms	-16 ms

Difference in accuracy between Exp. 1 and Exp. 2 (Exp. 2 accuracy minus Exp. 1 accuracy)

	RVF			LVF			Central	
	Gram	**Ungram**		**Gram**	**Ungram**		**Gram**	**Ungram**
Subject/verb	4.1%	15.6%		8.2%	18.8%		1.1%	8%
Reflexive	5.8%	5.6%		3.8%	6.0%		-1.1%	5.9%

Figure 3.1.A.

	RVF(LH)	Central	LVF(RH)
S/V Gram	93.5%	98.1%	83.6%
Refl Gram	90.9%	96.1%	88.5%
S/V Ungram	78.0%	86.1%	57.4%
Refl Ungram	80.8%	80.9%	82.9%

Figure 3.1.B.

	RVF(LH)	Central	LVF(RH)
S/V Gram	1074	1024	1232
Refl Gram	1032	941	1027
S/V Ungram	1290	1130	1442
Refl Ungram	1086	1046	1142
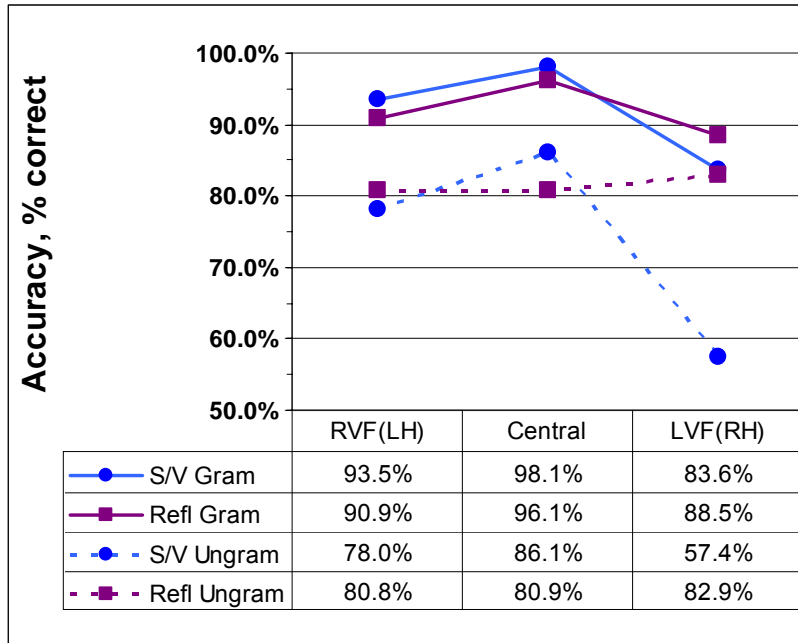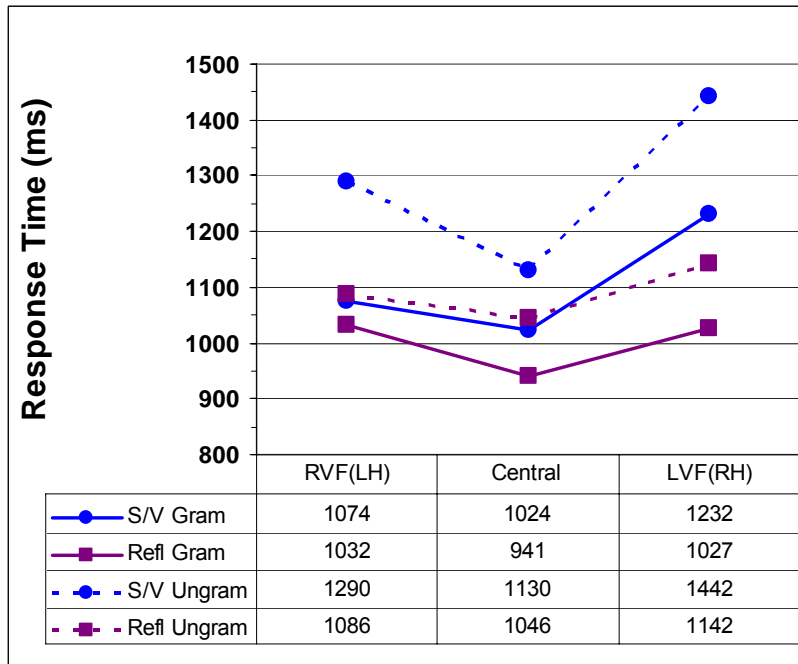
Figure 3.1.
Figure 3.1.A and 3.1.B. Accuracy and response time data for experiment 1. Data for the subject/verb condition are shown in blue; data for the reflexive condition are shown in purple. Grammatical conditions are shown with solid lines; ungrammatical with dashed lines. Figure 3.1.A shows the accuracy data; Figure 3.1.B shows response time data.

Figure 3.1.C.

	RVF(LH)	Central	LVF(RH)
SV Gram	97.6%	99.2%	91.8%
Refl Gram	96.7%	97.0%	92.3%
SV Ungram	93.6%	94.1%	76.2%
Refl Ungram	86.4%	86.8%	88.9%

Figure 3.1.D.

	RVF(LH)	Central	LVF(RH)
SV Gram	971	943	1107
Refl Gram	965	892	1006
S/V Ungram	1202	1140	1349
Refl Ungram	1047	1062	1165
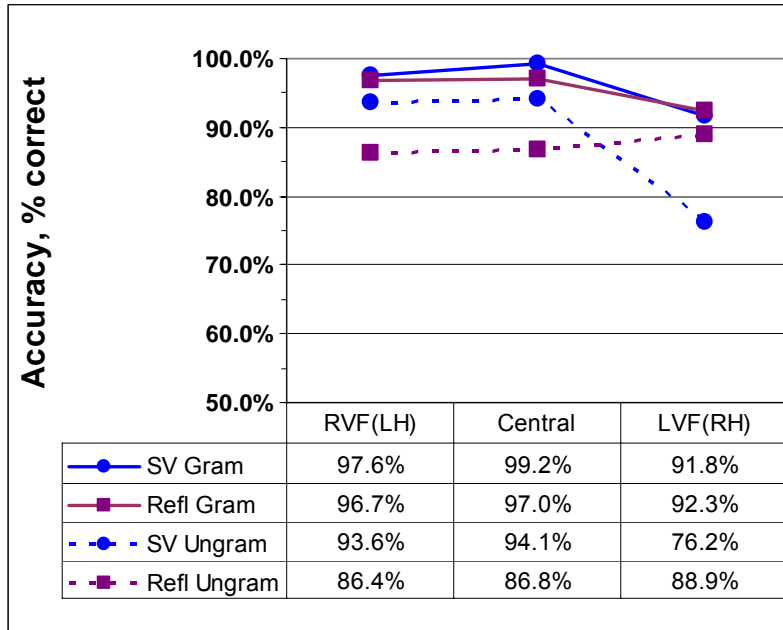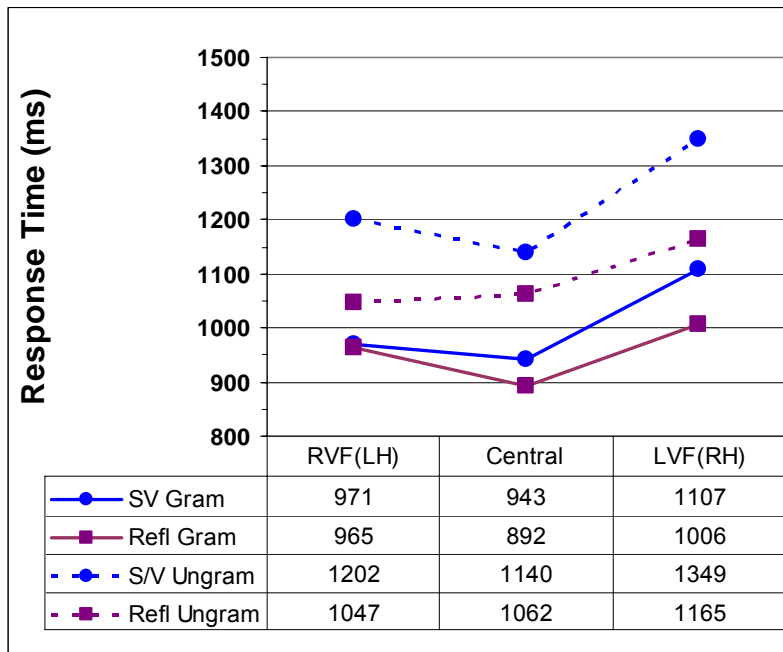
Figure 3.1. (continued)
Figure 3.1.C. and 3.1.D. Accuracy and response time data for experiment 2. Data for the subject/verb condition are shown in blue; data for the reflexive condition are shown in purple. Grammatical conditions are shown with solid lines; ungrammatical with dashed lines. Figure 3.2.A shows the accuracy data; Figure 3.2.B shows response time data.

Figure 3.2.A.

Performance Gains for Accuracy

	Grammatical	Ungrammatical
☐ SV RVF	4.1	15.6
■ SV LVF	8.2	18.8
☐ Refl RVF	5.8	5.6
■ Refl LVF	3.8	6.0

Figure 3.2.B.

Performance Gains

	Grammatical	Ungrammatical
☐ SV RVF	103	88
■ SV LVF	125	94
☐ Refl RVF	67	39
■ Refl LVF	21	-22
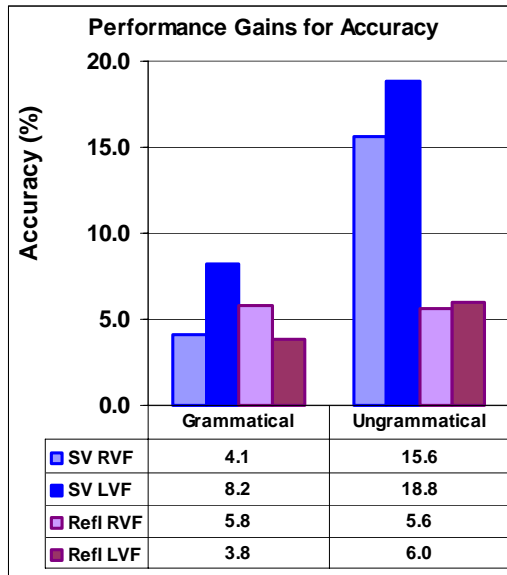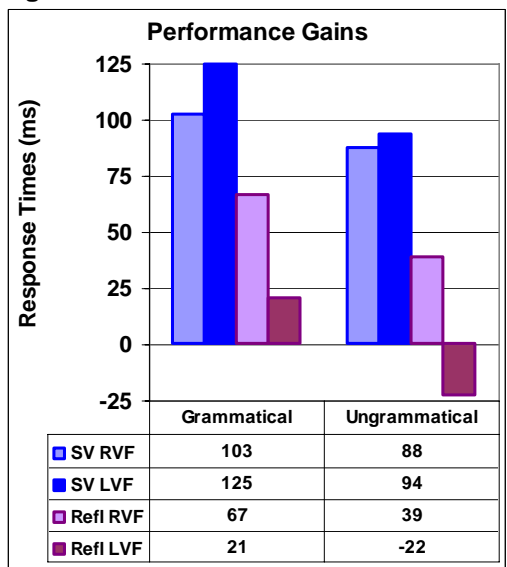
Figure 3.2.A. and 3.2.B. Performance gain data for accuracy (Figure 3.2.A.) and response time (Figure 3.2.B.) data. Performance gain represents the difference in performance between experiments 1 and 2, created by subtracting the data from experiment 1 from that for experiment 2. A positive value means that performance was better (more accurate or faster) in experiment 2. The data for the subject/verb condition is shown in the blue shades while the data for the reflexive condition is shown in the purple shades. For each, the lighter shade represents data for RVF presentation; the darker shade represents data for LVF presentation. Data for grammatical conditions are shown in the left column; ungrammatical in the right column.
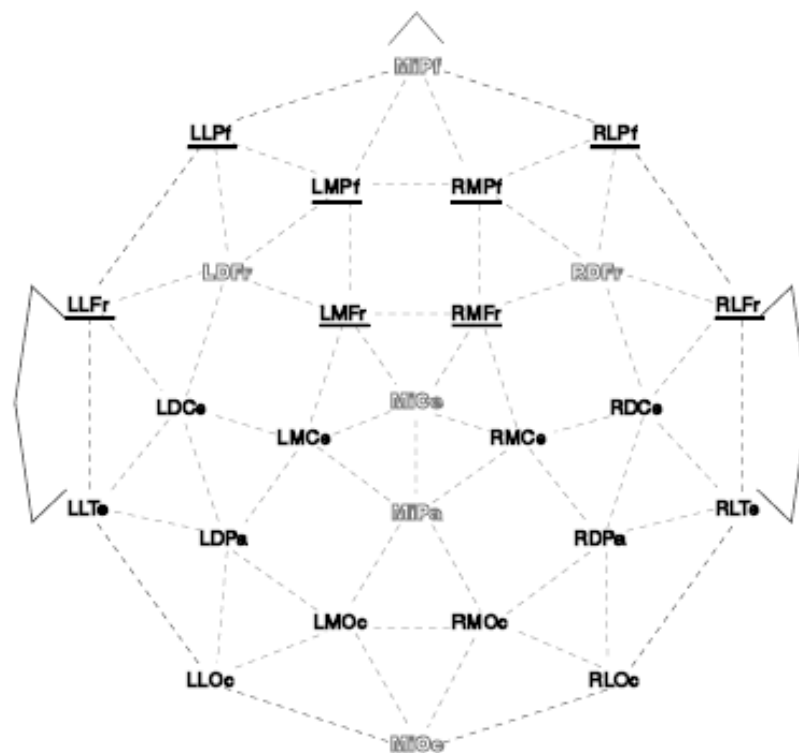
Figure 3.3. Schematic diagram of the locations of the 26 scalp electrodes, all of which were used for the full statistical analysis. The distributional analysis was restricted to the 20 electrodes with labels shown in bold print. The 8 electrodes with underlined labels were included in the "anterior only" distributional analyses; the remaining 12 electrodes with labels shown in bold print were included in the "posterior only" distributional analysis.
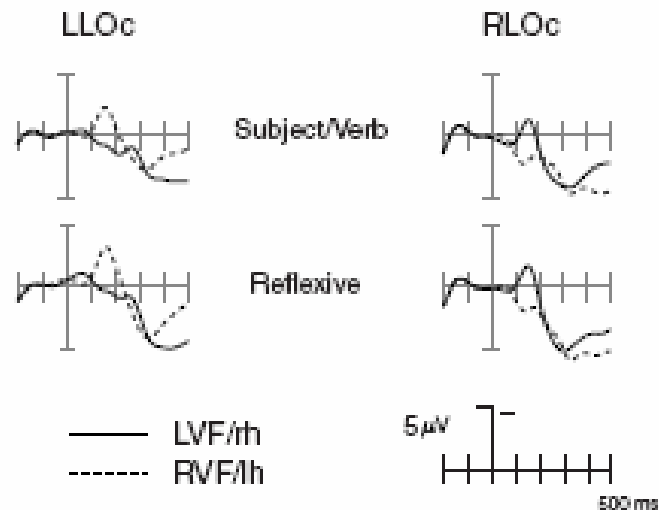
Figure 3.4. Early visual potentials elicited by presentation to the left visual field (LVF/rh; solid line) and the right visual field (RVF/lh; dashed line) for the subject/verb (top) and reflexive (bottom) conditions at electrodes LLOc and RLOc. The first negative deflection is the N1. Stimuli presented to RVF/lh elicit an N1 which is larger over left hemisphere sites; stimuli presented to LVF/rh elicit an N1 which is larger over right hemisphere sites.
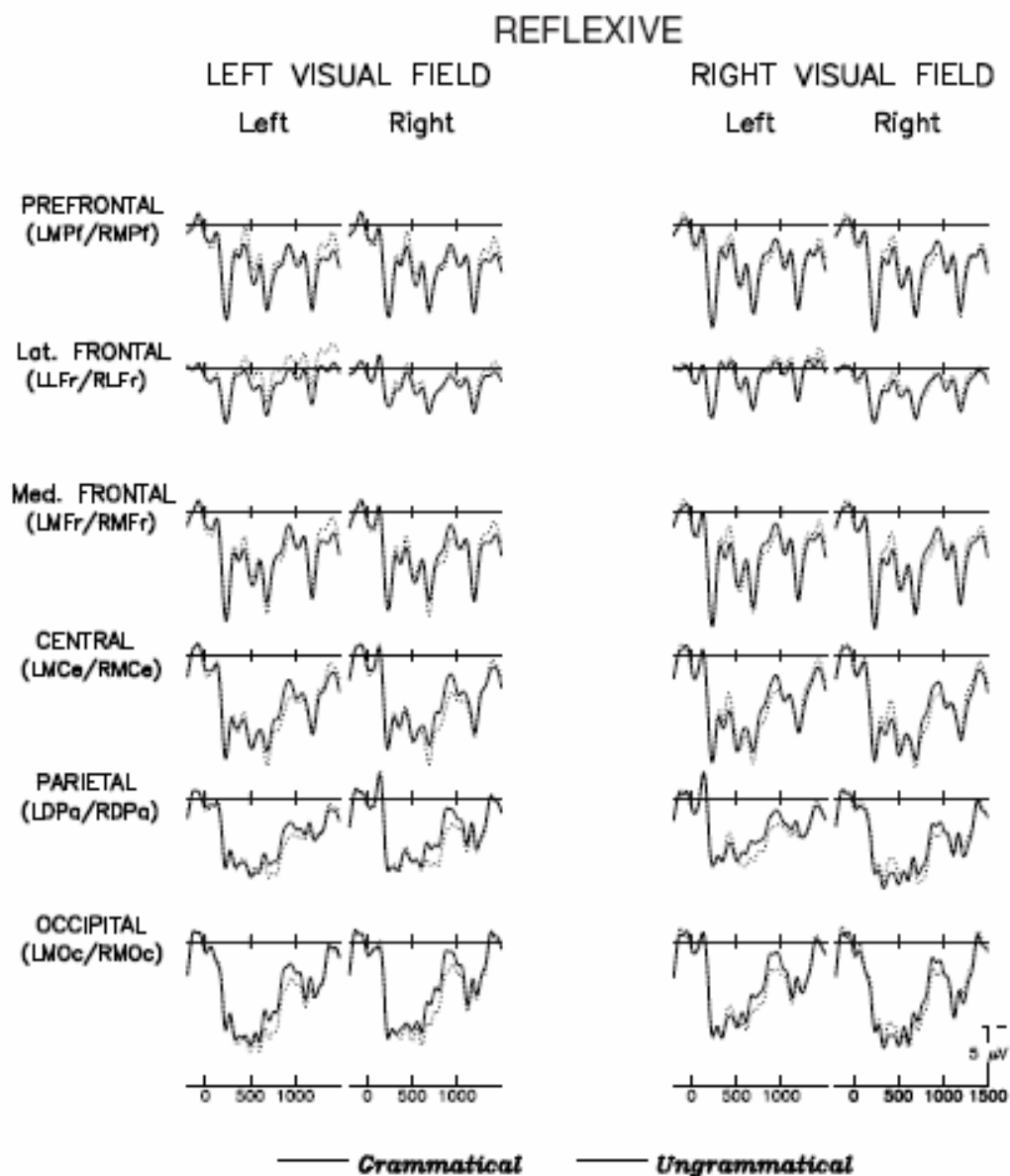
Figure 3.5. Grand average (N = 36) ERP waveforms elicited by grammatical number violations (solid line) and corresponding control sentences (dotted line) for reflexive sentences for LVF and RVF presentation. Electrodes shown are a representative subset, including left and right medial prefrontal electrodes (LMPf, RMPf), lateral frontal (LLFr, RLFr), medial frontal (LMFr, RMFr), mediolateral central (LDCe, RDCe), mediolateral parietal (LDPa, RDPa), and medial occipital (LMOC, RMOc).
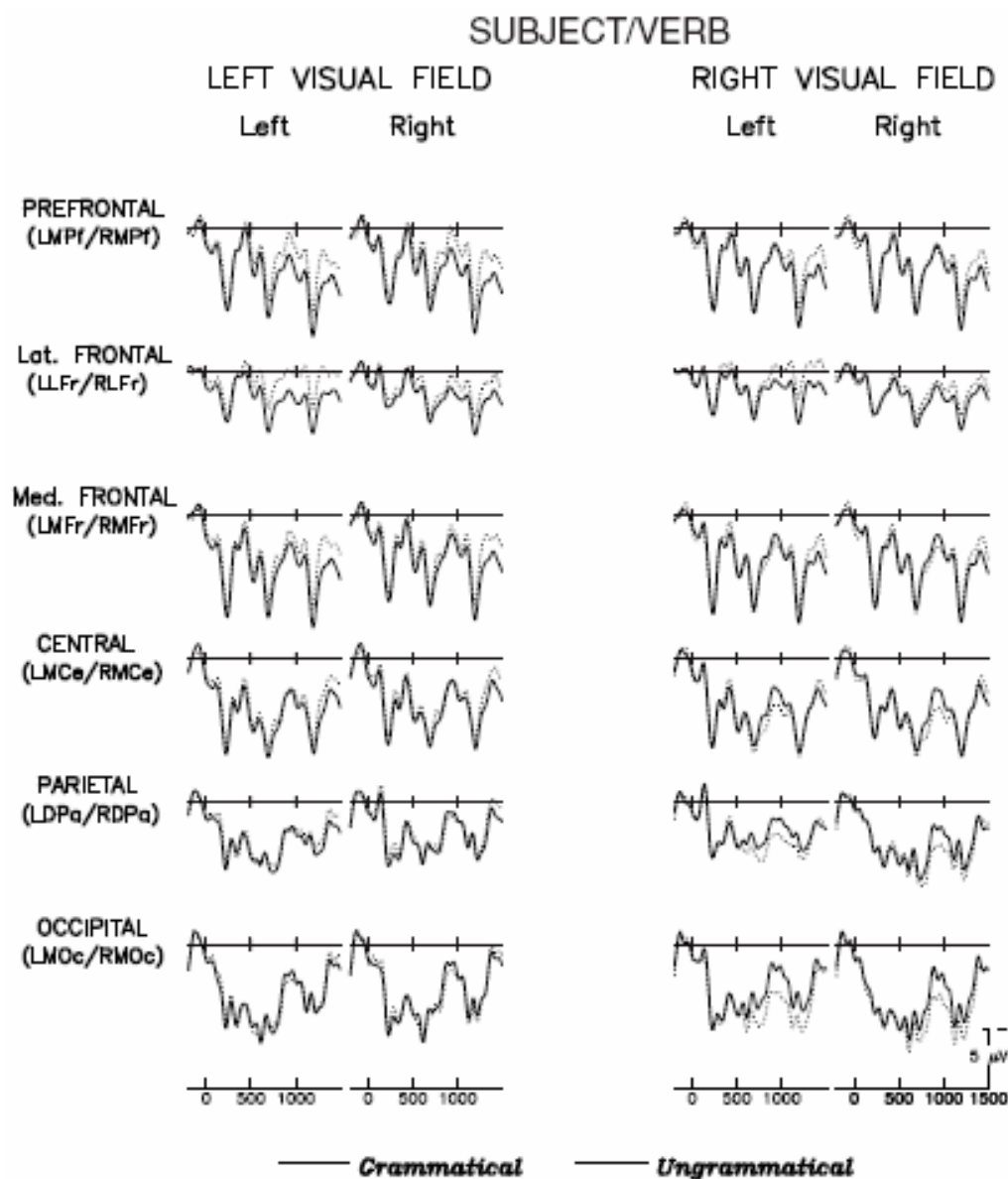
Figure 3.6. Grand average (N = 36) ERP waveforms elicited by grammatical number violations (solid line) and corresponding control sentences (dotted line) for subject/verb sentences for LVF and RVF presentation. Electrodes shown are a representative subset, including left and right medial prefrontal electrodes (LMPf, RMPf), lateral frontal (LLFr, RLFr), medial frontal (LMFr, RMFr), mediolateral central (LDCe, RDCe), mediolateral parietal (LDPa, RDPa), and medial occipital (LMOC, RMOc).

REFLEXIVE
GRAMMATICALITY EFFECT
(Ungrammatical–Grammatical ERP)

3 μV

0 500 1000 1500 ms

HE

——— *Left Visual Field*   ——— *Right Visual Field*
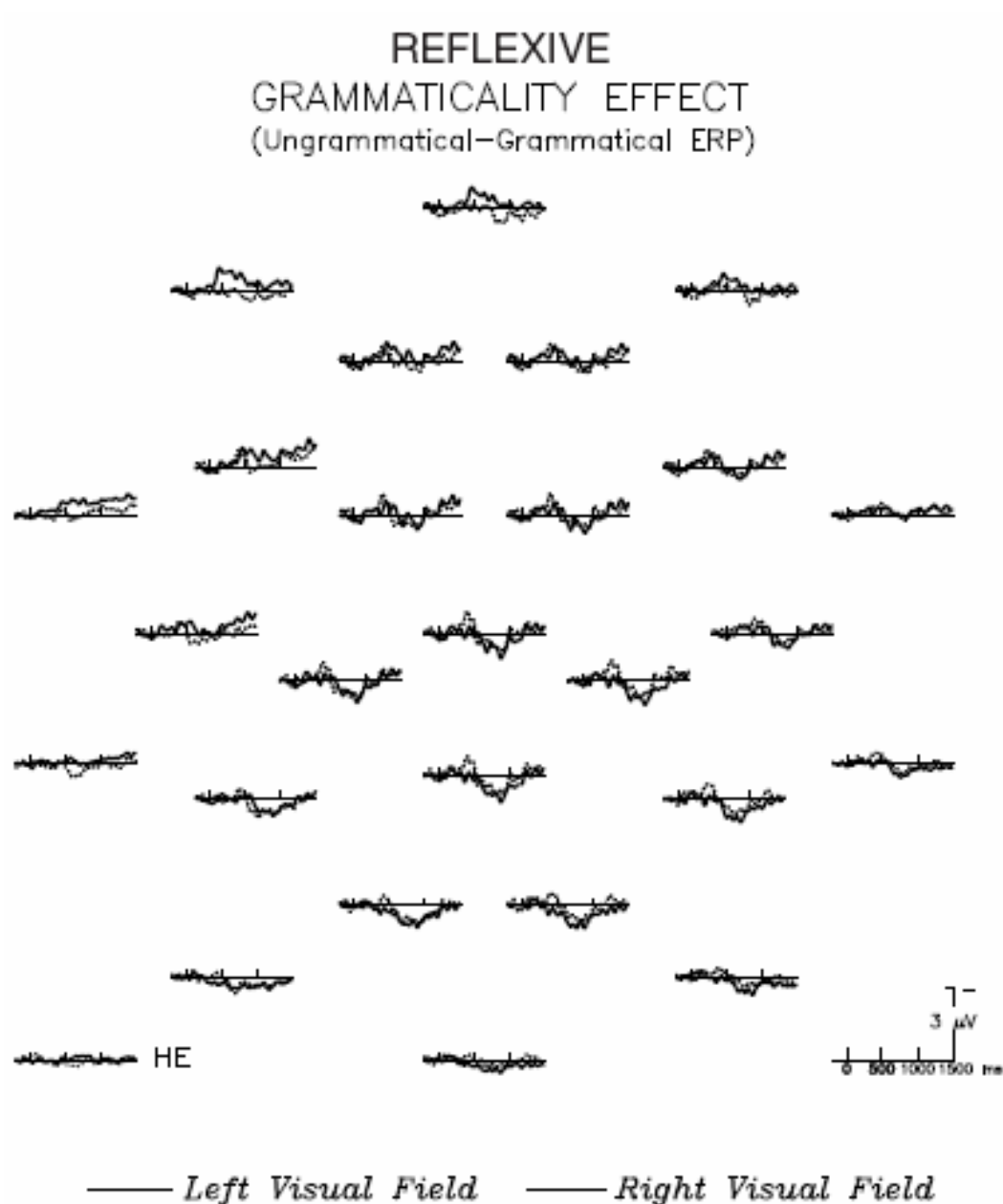
Figure 3.7. Difference ERPs for the reflexive condition, formed by subtracting grammatical from ungrammatical ERPs, showing the P600 effect for LVF (N = 36; solid line) and RVF (N = 36; dotted line) presentation.
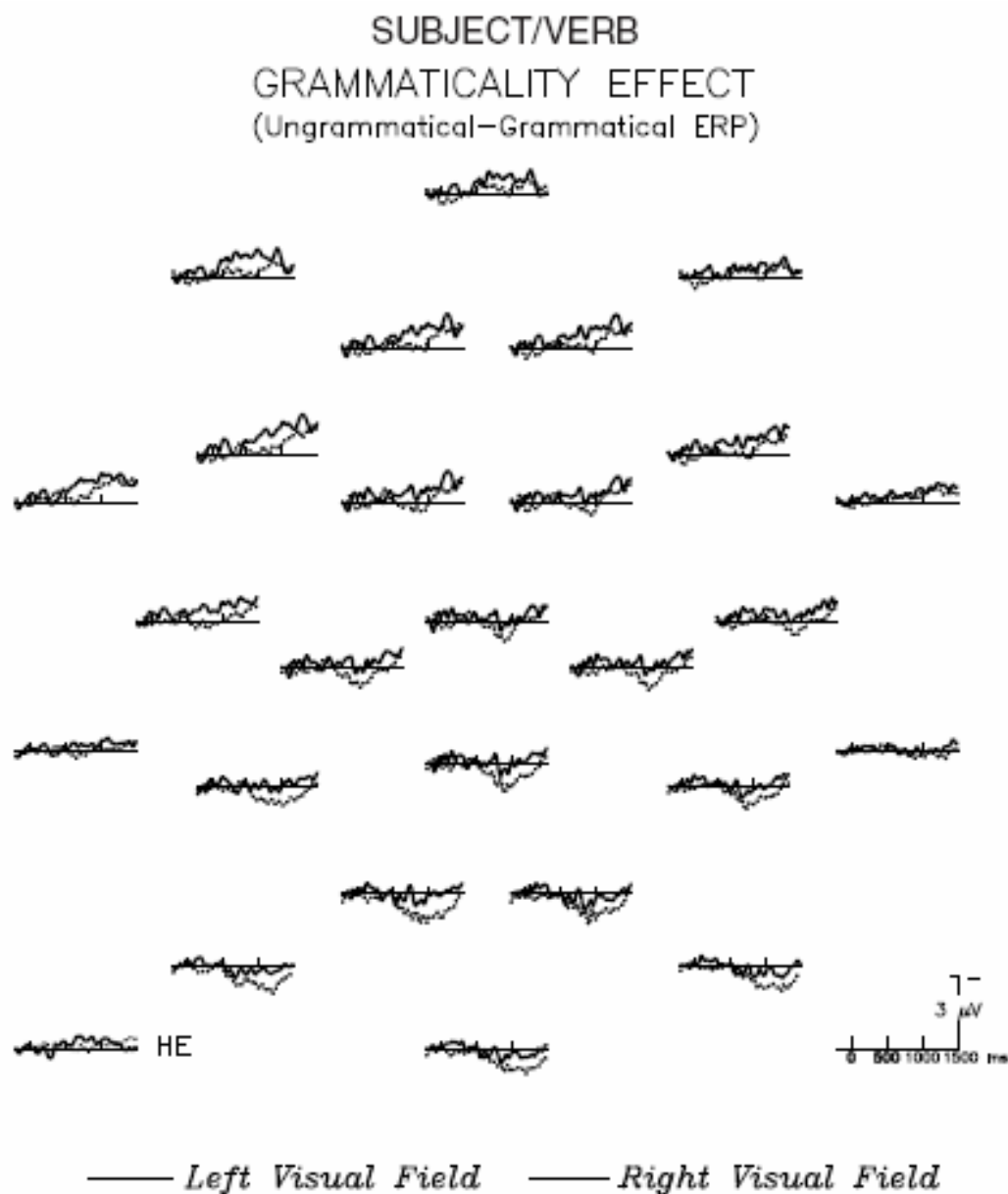
Figure 3.8. Difference ERPs for the subject/verb condition, formed by subtracting grammatical from ungrammatical ERPs, showing the P600 effect for LVF (N = 36; solid line) and RVF (N = 36; dotted line) presentation.

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Chapter 4

Salience of grammatical violations, but not verb (ir)regularity, affects the P600: an event-related brain potential study

4.1. Abstract

In a study of English sentence processing, event-related brain potential (ERP) responses to grammatical (past participle) vs. violation (infinitival) verb forms were examined in three conditions. In the regular condition, the participle form ends in -ed (e.g., "The modern art museum has exhibited/ *exhibit these paintings before."). For the irregular conditions, verbs are "high salience" if their grammatical and ungrammatical forms differ by two or more letters (e.g., "His new theory has caught/ *catch the attention of many scholars.") and "low salience" if their grammatical and ungrammatical forms differ by only one letter (e.g., "That small monkey has flung/ *fling many things at the zookeepers.). All violations elicited a P600 component, although that in the low salience/irregular verb condition was slightly smaller and later relative to the other conditions. In contrast to proposals that invoke different neural mechanisms for regular and irregular verbs, the ERPs to violations of regular and high salience/irregular verbs in this experiment were quantitatively and qualitatively indistinguishable. Moreover, none of these violations, including those of the regular verb (a morphosyntactic violation), elicited a left anterior negativity (LAN), thereby inconsistent with the proposal that the LAN is a direct reflection of a morphosyntactic violation.

4.2. Introduction

Over the past few decades, a number of investigators have looked to the event-related brain potential (ERP) technique to provide invaluable data for the

development of theories regarding the cognitive and neural architectures supporting language comprehension. In the realm of syntactic processing, ERP researchers have identified three main components of interest: the P600, an early left anterior negativity (ELAN), and a later left anterior negativity (LAN), all described in greater detail below. Although each of these components is not without some controversy, of particular interest here is the LAN which Friederici and her colleagues have offered as an index of the processing of morphosyntactic violations, with an onset latency putatively determined by when the relevant morphosyntactic information becomes available to the language processor (Friederici, 2002). By contrast, others have linked both phasic and more prolonged LAN activity to some aspects of working memory (King & Kutas, 1995; Kluender & Kutas, 1993). In the present study, we examine the hypothesized link between the phasic LAN and morphosyntactic violations using clear cases in English sentences. In particular we focus on the brain's response to morphosyntactic violations created by manipulating past participle forms as these have not been previously investigated in English with ERPs. In English, the regular participle is formed by adding -ed to the verb's stem (e.g., exhibit, exhibit-ed); violation trials can be created by presenting the infinitive instead (e.g., He had exhibited/*exhibit the …). In addition, we examined violations of irregular participles (e.g., He had flung/*fling … , He had caught/*catch …).

4.2.1. Syntax-related ERP components

4.2.1.1. P600

The most reliable ERP component elicited by virtually all types of syntactic violations is the P600 component, a late centro-parietal positivity (generally beginning at around 500 ms) relative to syntactically correct control items (Hagoort,

Brown, & Groothusen, 1993; Osterhout & Holcomb, 1992; , 1993). P600s are

elicited by outright syntactic violations (Coulson, King, & Kutas, 1998; Friederici,

Pfeifer, & Hahne, 1993; Gunter, Stowe, & Mulder, 1997; Hagoort & Brown, 2000;

Hagoort et al., 1993; Osterhout, Allen, McLaughlin, & Inoue, 2002; Osterhout,

McKinnon, Bersick, & Corey, 1996; Osterhout & Mobley, 1995), and to syntactically

correct but non-preferred structures such as garden path sentences (Osterhout &

Holcomb, 1992; , 1993; Osterhout, Holcomb, & Swinney, 1994). The P600 has

been linked with reprocessing costs (Osterhout et al., 1994) and to repair and

reanalysis processes (Friederici, 1995; Friederici & Mecklinger, 1996; Friederici et

al., 1993; Gunter et al., 1997; Hagoort & Brown, 2000; Munte, Matzke, & Johannes,

1997) pursuant to the appearance of a syntactic violation or temporary syntactic

ambiguity, as well as to syntactic integration difficulties (Hagoort & Brown, 2000;

Kaan, Harris, Gibson, & Holcomb, 2000). Additionally, some researchers have

argued that it may reflect a more general-purpose response (e.g., the P3b

component) that is not specific to syntax (Coulson et al., 1998). Whatever its

functional role, the P600 is observed in response to many different types of

grammatical violations and is relatively easy to identify and thus readily subject to

experimental manipulation.

By contrast, both the LAN and the ELAN components not only seem to be

elicited by a more restricted set of syntactic violations but also are more difficult to

identify in a ERP waveform. Indeed, these two negativities can often be difficult to

distinguish from each other.

4.2.1.2. Early left anterior negativity (ELAN)

The ELAN is a small negativity occurring most prominently over frontal electrode sites between 100 and 300 ms post-violation onset. It is typically left-lateralized (auditory: Friederici, Gunter, Hahne, & Mauth, 2004; Friederici, Hahne, & Mecklinger, 1996; Friederici et al., 1993; Hahne & Friederici, 1999; visual: Friederici et al., 1996; Neville, Nicol, Barss, Forster, & Garrett, 1991) but a bilateral distribution has also been reported (auditory: (Hahne & Friederici, 2002; Hahne & Jescheniak, 2001; visual: Friederici, Steinhauer, & Frisch, 1999; Gunter, Friederici, & Hahne, 1999). Friederici (2002) argues that the ELAN is correlated with word-category (and not morphosyntactic) errors and that elicitation of the ELAN requires an outright syntactic violation. Friederici (2002) further claims that the ELAN is functionally separate from the LAN and that their generators are located in different brain areas.

The ELAN has been elicited in both visual and auditory modalities, generally by word category (phrase structure) violations. To date, most studies reporting the ELAN have been conducted in German (although see Neville et al., 1991, in English). With few exceptions (for example, Neville et al., 1991), the comparison for ELAN elicitation has involved a control condition in which critical stimuli are past participle forms of German verbs (all forms begin with ge-) and a violation condition, in which a preposition is inserted before the past participle, e.g., Das Baby wurde <u>gefuttert</u> (The baby was <u>fed</u>) vs. *Die Gans wurde im <u>gefuttert</u> (The goose was in the <u>fed</u>; visual: Friederici et al., 1993; Friederici et al., 1999; Gunter et al., 1999; auditory: Friederici et al., 1993; Hahne & Friederici, 1999; Hahne & Friederici, 2002; Hahne & Jescheniak, 2001). In the violation sentences, the past participle is

ungrammatical because the preposition requires that a noun phrase follow – thus a word category violation occurs.

Nonetheless, some investigations have not been able to identify an ELAN in response to word category violations. Gunter and Friederici (1999), for instance, using stimuli similar to those which have generally elicited ELANs, observed only N400-like activity (i.e., posterior negativity). Friederici and Meyer (2004) observed a later (380-450 ms) frontal but not left-lateralized negativity to the omission of an obligatory complementizer. Additionally, Hagoort and Brown (2000) did not observe an ELAN (or LAN) in response to phrase structure violations for either visual or auditory presentation of Dutch sentences, nor did Hagoort, Wassenaar, and Brown (2003) for word category violations in visually-presented Dutch sentences.

Some have proposed that unequivocally identifying an anterior negativity as an ELAN (as opposed to a LAN, for instance) may be exacerbated by the possibility that the onset of the ELAN may vary as a function of when the relevant information needed to appreciate that there is a word class violation becomes available (Friederici et al., 2004; Friederici et al., 1996). For example, Friederici et al. (1996) compared the ERP response to grammatically correct spoken sentences such as "Das Metall wurde veredelt von dem …" to ungrammatical spoken sentences such as "Das Metall wurde zur veredelt von dem …". In their ungrammatical sentences, a noun form such as "*Veredelung"* could be grammatical, thus it is only later in the critical word (*"veredelt"*) that participants can appreciate that the word category is incorrect. Indeed in this study, only the suffix differentiated nouns (e.g., -ung) from verbs (e.g., -t), which were identical up to that point. When the ERP was time-locked to the onset of the critical word, the frontal negativity to ungrammatical stimuli

began at about 370 ms, late for a typical ELAN component. However, the authors

argued that when the ERP was time-locked to the average word-category

uniqueness point of all critical words (about 330 ms post-stimulus onset on

average), the negativity elicited by the violation falls within the typical early ELAN

time window.

Alternatively, Hagoort et al. (2003) proposed that the "early" nature of most

reported ELANs might be a function of when word class could be determined. They

point out that if word class assignment can be determined from a prefix or word-

initial consonants, the component may occur earlier than when it is determined by

the suffix. In this study, they observed a bilaterally distributed anterior negativity

between 300 and 500 ms, not an ELAN; importantly, the word class in their critical

words was determined by the suffix. Clearly, additional studies are needed to

elucidate exactly when word-category violations elicit this early anterior activity and

under what circumstances, as well as to resolve conflicting opinions regarding

whether the LAN and the ELAN are or are not separate components.

4.2.1.3. Left anterior negativity (LAN)

While the extant literature ties the ELAN to word category violations, the

antecedent conditions requisite for LAN elicitation are more poorly specified. Most

identified LANs fall between 300 and 500 ms, although they can occur at other times

and, like the ELAN, are not always left lateralized. Anterior negativities with a left-

lateralization have been observed in response to a number of stimuli across a

number of languages, including violations of case marking (Coulson et al., 1998 (for

English pronouns)), subject-verb agreement (Angrilli et al., 2002 (Italian); Rossi,

Gugler, Hahne, & Friederici, 2005 (German)); and verb inflections (Gunter et al.,

1997 (exp. 3, Dutch); Newman, Ullman, Pancheva, Waligura, & Neville, 2007; Osterhout & Mobley, 1995 (exp. 1 but not exp. 3, English); Palolahti, Leino, Jokela, Kopra, & Paavilainen, 2005 (Finnish)). Additionally, Hagoort and Brown (2000, Dutch) reported a bilaterally-distributed anterior negativity within the LAN time window to violations of subject-verb number agreement in an auditory experiment (exp. 2) but no LAN was reported for the corresponding visual experiment (exp. 1).

Friederici (2002) hypothesized that the LAN reflects morphosyntactic processing and correlates with morphosyntactic errors. Not all data support this proposal, however, as LANs have not been reported in numerous experiments using morphosyntactic violations, indeed, in a few cases, LANs were not reported in experiments using the same or very similar stimuli as those which have elicited LANs. For example, LANs were not elicited by violations of subject-verb agreement (English: Coulson et al., 1998; Kemmer, Coulson, De Ochoa, & Kutas, 2004; Osterhout et al., 1996; Osterhout & Mobley, 1995 (LAN reported for exp. 1 but not exp. 3); Dutch: Hagoort & Brown, 2000 (exp. 1, visual); Hagoort et al., 1993; German: Munte, Szentkuti, Wieringa, Matzke, & Johannes, 1997) or to violations of verb inflections (Gunter et al., 1997 (exp. 1, Dutch); Newman et al., 2007 (English); Osterhout & Nicol, 1999 (English)). The LAN was also not reported by Osterhout et al. (2002) in one morphosyntactic violation condition which included stimuli with either noun agreement or verb tense errors in English. Additionally, the LAN has at times failed to be elicited by the same researchers using (nearly identical) stimuli as that which elicited the LAN in another experiment (e.g.,Gunter et al., 1997; Osterhout & Mobley, 1995).

Further complicating the picture, LANs have also been observed in studies to syntactic violations or temporary syntactic ambiguities that were not morphosyntactic in nature. For example, LANs have been described in association with English garden-path sentences (Osterhout & Holcomb, 1992; , 1993) and to subcategorization violations in Dutch (Hagoort & Brown, 2000 (only for exp. 2, auditory)). Additionally, LANs have been seen in syntactically complex sentences without violations, presumably varying with working memory demands of storing a filler or retrieving it for filler-gap assignment (Kluender & Kutas, 1993). Finally, a number of the studies that have reported LAN-like anterior negativities used word pair stimuli (Munte, Heinze, & Mangun, 1993) or sentence fragments (Rosler, Putz, Friederici, & Hahne, 1993). LANs also have been described in response to morphologically decomposable pseudowords (Rodriguez-Fornells, Clahsen, Lleo, Zaake, & Munte, 2001, Catalan) and to pseudowords but not real words (Munte, Matzke et al., 1997, German). Although these data are important in the big picture, processing words in isolation or within sentence fragments, as well as the processing of pseudowords, may be substantively different than the processing of real words in sentence contexts.

Thus, the necessary and sufficient conditions for LAN elicitation, as well as what cognitive function(s) the LAN(s) reflect(s), remain to be specified. Of particular interest to us in this report are the specific conditions which lead to elicitation of LANs when morphosyntactic violations in English are present. At minimum it would be essential to know if morphosyntactic violations within natural sentence contexts reliably elicit LAN activity – left lateralized between 300 and 500 ms – for conditions that are similar to those identified by Friederici as classic cases. It was to that end

we chose to examine violations of past participle forms in English. Specifically, in our regular verb condition, we compared the ERP response elicited by the (grammatical) past participle form of a regular verb to the response elicited by the (ungrammatical) infinitival form of the same verb (e.g., He had exhibited/*exhibit the…). The violations in this condition are morphosyntactic in nature, thus if the LAN reflects morphosyntactic processing, we would expect violations to elicit a LAN. Additionally, we had two conditions involving irregular verbs (see Methods for greater detail). As with the regular verb condition, we compared responses elicited by ungrammatical infinitives with those elicited by grammatical past participle forms. For the irregulars, the violations were not morphosyntactic in nature and thus, should not elicit a LAN, according to theories which regard the LAN as a reflection of morphosyntactic processing. If, however, they did elicit a LAN, this would also provide information as to what cognitive functions LAN reflects. Furthermore, given that our stimulus materials included both regular and irregular verb forms, we could also look at our ERP data with an eye towards hypotheses about the processing of regular versus irregular verb forms.

4.2.2. The neural representation of regular and irregular word forms

Regular and irregular verbs are often used as test cases in discussions of how morphologically complex word forms exist in the lexicon: whether they are represented as stems and affixes which are combined as needed via rules, or whether they are represented as whole word forms. For example, some word forms have very straightforward relationships to their stem form: to form the progressive of a verb, the affix -ing is added to the verb stem: e.g., walking. At issue is whether the overt word form (e.g., "walking") is directly stored in the lexicon, or whether only the

stem ("walk") is stored, with the overt form computed via the application of an add
-*ing* rule.

While progressive forms in English are all regular (the progressive is always
formed by adding the suffix -*ing* to the stem), some word forms in English are
"irregular" in form. For example, the regular English past tense affix is [-(e)d] (e.g.,
exhibit-ed) but plenty of verbs have irregular past tense forms (e.g., sing/sang,
bring/brought). While all models agree that irregular forms are simply "listed" in the
lexicon, they differ in their treatment of regular forms. On the connectionist
approach, morphology is not explicitly represented in the lexicon. In fact, there is no
qualitative difference in how regular vs. irregular word forms are represented and
accessed; a single mechanism is presumed to account for both (Rumelhart &
McClelland, 1986). Other accounts (e.g., Pinker & Ullman, 2002; Ullman, 2001),
however, invoke two different mechanisms to deal with regular and irregular word
forms with only the latter being stored in the lexicon. Regular word forms by contrast
are presumed to be computed via the application of some rule to a stored word stem
(e.g., "follow" (stem) + "(e)d" (past tense morpheme) combine to produce the regular
past tense form "followed"). With the aim of better understanding how regulars and
irregulars are represented in the lexicon, we can look at the ERPs elicited by the two
types to see the extent to which they elicit similar waveforms and behave similarly
when they are syntactically incorrect.

4.2.3. The present study

The current study examines ERP responses to various verb forms in
English. Specifically, we compare and contrast the processing of grammatical and
ungrammatical verb forms: in grammatical sentences, the correct verb form is the

past participle; in ungrammatical sentences, an (incorrect) infinitival form appears

instead. Verbs occur in one three conditions: regular, high salience/irregular, and

low salience/irregular (see Table 4.1). For verbs in the regular condition, the correct

participle form ends in -ed. For the irregular conditions, verbs are either "high

salience" if their grammatical and ungrammatical forms differ noticeably, that is, by

two or more letters (e.g., caught vs. *catch) or "low salience" if their grammatical and

ungrammatical forms are visually quite similar, i.e., differ by only one letter (e.g.,

flung vs. *fling).

In one study involving past participle forms, Gunter et al. (1997) examined

their processing of within sentence contexts; their stimuli were all regular verb

forms. In two visual experiments conducted in Dutch, syntactically correct

sentences required a past participle form of a verb, while in violation sentences, the

infinitive was used (e.g., De vuile matten werden door de hulp geklopt/*kloppen; The

dirty doormats were by the housekeeper beaten/*beat). In experiment 1, these

morphosyntactic violations elicited a P600 response; no LAN was reported. In

experiment 3, however, they reported a LAN prior to the P600[1] using similar stimuli.

Based on the findings of Gunter et al. (1997) and more generally on the

literature, we anticipated that our (morphosyntactic) violations also would elicit a

P600 At issue was whether or not they would also elicit a preceding LAN. Based

on the hypothesis that LAN elicitation is a marker of morphosyntactic processing, we

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[1] The results of Gunter et al.'s (1997) MANOVA analysis indicated that this early negative effect in experiment 3 was reliable over mainly left frontotemporal electrodes (F3, Fz, FC5, FC1, T7, and C3). The ERP data they show, however, suggests that this early negativity was more widely distributed and may have differed as a function of probability. For their high probability condition, the negativity appears fairly left anterior, although it may be present over right medial electrodes. In their low probability condition, the negativity appears to be bilaterally distributed over medial (but not lateral) electrodes; additionally, it appears larger over central and posterior electrodes than over frontal.

would expect to see a LAN. The clear absence of a LAN would constitute evidence against this hypothesis. Complicating this prediction were the experiments reported in Gunter et al. (1997): a LAN was elicited in one experiment, while in another experiment, no LAN was elicited, despite about 75% overlap of the stimuli in the two experiments. Additionally, we plan to examine whether the responses to regular and irregular verbs would differ systematically and if so, in what way(s).

4.3. Methods

4.3.1. Materials

There were 360 experimental sentences (average number of words: 10.7; range: 7 to 17) and 186 filler sentences, including 120 sentences (half grammatical) for another experiment in which subject/verb agreement was manipulated, and 66 filler sentences (half grammatical) which included syntactic manipulations other the those being manipulated for the current experiment or the subject/verb agreement manipulation.

There were three experimental conditions (120 sentences per condition): regular verbs, high salience/irregular verbs ("high salience"), and low salience/irregular verbs ("low salience"); see Table 4.1 for sample experimental sentences. For each condition, half of the sentences were grammatical and the critical word was the past participle form of a verb. For syntactic violations, the (ungrammatical) critical word was the infinitival form of the verb. Regular verbs are those verbs for which the past participle form adds -ed to the infinitive (e.g., exhibited). The irregular verbs were divided into high and low salience conditions for the purposes of another experiment. The high salience condition included those verbs for which the past participle form and infinitival form (e.g., caught vs. catch)

differed by 2 or more letters, whereas for the low salience condition, the difference was one letter (e.g., flung vs. fling). For each experimental condition, 30 verbs were used; each verb occurred in four different sentences frames, twice grammatical and twice ungrammatical (two had singular subjects; two had plural subjects), randomly distributed throughout the 546 total sentences. A given list included for each sentence either the violation, or its grammatical counterpart, never both.

For each pair of participants, we created two stimulus lists, each consisting of 546 sentences in random order. A given list included for each sentence either the violation or its grammatical counterpart, never both. Each participant viewed only one list. Each list included 60 grammatical regular verbs, 60 violation regular verbs; 60 grammatical high salience verbs, 60 violation high salience verbs; 60 grammatical low salience verbs, 60 violation low salience verbs; 60 grammatical subject-verb agreement (filler), 60 violation subject-verb agreement (filler); 33 grammatical filler, and 33 violation filler sentences. For the experimental verbs (participles), a pair of stimulus lists was created as follows: in one list, for each verb, a computer routine randomly determined which two of the four sentence frames for that verb would be grammatical and which two – ungrammatical. The second list of the pair would have the grammaticality reversed. Each list was then combined with filler sentences; then each list was randomly shuffled with a computer algorithm. Additional pairs of lists were generated in the same way.

Verbs were matched for frequency using the Francis and Kučera (1982) norms. For the regular condition, verbs had an average frequency of 174 occurrences per million (SD = 141; range = 28 to 625); in the high salience condition, average frequency was 188 (SD = 199; range = 7 to 487); and for the low

salience condition, average frequency was 159 (SD = 166; range = 6 to 583). In the

grammatical condition, regular verbs averaged 7.9 letters in length (SD = 1.2;

range = 6 to 10 letters); for ungrammatical, 5.9 letters (SD = 1.2; range = 4 to 8).

High salience verbs averaged 5.5 letters (SD = 1.6; range = 3 to 10 letters) for

grammatical; for ungrammatical, 4.9 letters (SD = 1.4, range = 3 to 10 letters). For

low salience, grammatical verbs averaged 4.4 letters (SD = 1.1; range = 3 to 8

letters) and ungrammatical - 4.5 letters (SD = 1.0; range = 3 to 8 letters). Critical

words always occurred in sentence-medial position and across all sentences, were

preceded by 3.8 words on average (range: 3 to 6) and followed by 5.8 words on

average (range: 3 to 10 words). Overall sentence length and the average number of

words preceding and following the critical word were balanced across experimental

conditions.

4.3.2. Participants

Twenty University of California, San Diego (UCSD) undergraduate students

participated in the experiment for course credit or pay (10 women; ages ranged from

18 to 25; average was 20.4 years). All participants provided health and medical

information, including history of psychiatric disorders, drug use, neurological

disease, medications currently being taken, vision, and others; subjects were

excluded from experiment participation as appropriate. All participants were

monolingual, right-handed (assessed using the Edinburgh Inventory, Oldfield, 1971),

and had normal or corrected-to-normal vision.

4.3.3. Norming studies

Prior to collecting data for this experiment, a number of norming studies

were conducted to verify the actual usage of the participial verb forms, to establish

the cloze expectancy for the verbs, and to verify the visual salience classifications

for irregular verbs.

4.3.3.1. Norming study: verifying actual usage of verb forms

Certain irregular verb participle forms are currently undergoing change in

American English and thus, we conducted a norming study to ensure that only those

verbs were included for which there was a high degree of agreement within our

participant population (UCSD undergraduates) as to what the correct form is. For

this study, we first created a list of potential irregular verbs for our study and then

created sentences in which these verbs could be used. We then gave 65

participants these sentences with blanks where the participle form should be; in

parentheses next to the blank we provided the infinitive of the target verb which they

were to use. Participants were instructed to fill in the blank with the form of the verb

which "sounded right" to them. As we expected, there was variability across

subjects for a handful of verbs; those verbs were not used in the experimental

stimuli.

4.3.3.2. Norming study: Establishing cloze expectancy for verbs

Additionally, to ensure that sentence context did not lead participants to

expect certain verbs in our sentences, in another norming study we determined the

cloze expectancy of the verb for our experimental sentences. Participants were

given sentence preambles (the sentence up through the word preceding the verb)

and were instructed to fill in a verb which could reasonably follow the initial

sentence preamble, given the prior context (participants were told that the verb

alone would probably not complete the sentence and that they should think of a

full sentence completion, but were required to write only the verb). Any sentence

for which cloze probability was greater than 10% was rewritten and re-normed. For each of the three conditions, average cloze probability was <3%. For the final stimuli, average sentence cloze probabilities were equal across the conditions.

4.3.3.3. Norming study: Verifying visual salience classifications for irregular verbs

Finally, once our sentence stimuli were finalized, we verified our visual salience classifications for the high and low salience conditions by recording response times and accuracy data to grammaticality decisions. In an experimental session lasting approximately 3 hours, sentence stimuli were presented exactly as described below for the ERP experiment (word-by-word), with the following exceptions. Non-critical words were presented in a blue font, while the critical word of a sentence was presented in a black font. Participants were instructed to indicate with a button press whether the sentence, up to and including the word in black, was "well-formed" or not as soon as they saw the word in black. Twenty participants were included; mean age was 18.9 years (range: 18 to 20; 14 were women).

A 2 x 2 within-subjects ANOVA with factors of Grammaticality (grammatical, ungrammatical) and Verb Type (high salience, low salience) was conducted for the response time and accuracy data. Responses for the high salience condition (1,005 ms) were reliably faster than those for the low salience condition (1,038 ms), $F(1,19)=8.94$, $p = .008$. Additionally, there was a marginally reliable Grammaticality x Verb Type interaction, $F(1,19)=2.92$, $p = .104$: while the differences in response times for grammatical items was fairly small between the high (1,016 ms) and low (1,033 ms) salience conditions, for ungrammatical items, the difference was larger (high salience, 994 ms; low salience, 1,043 ms). For the accuracy data, there was a

marginally reliable main effect of verb type, $F(1,19)=3.82$, $p = .066$, reflecting higher

accuracy for the high (96.3%) than low (95.2%) salience condition. Furthermore,

the Grammaticality x Verb Type interaction was reliable, $F(1,19)=6.54$, $p = .019$. For

grammatical critical words, there was essentially no difference in accuracy between

high salience (95.9%) and low salience (96.2%) conditions, whereas for

ungrammatical critical words, responses in the high salience (96.8%) were more

accurate than for the low salience (94.3%) condition.

The reliably faster response times for the high salience conditions, combined

with the trend for greater accuracy in the high salience condition and the significant

interaction showing greater accuracy for high salience with ungrammatical items,

confirmed our salience classifications: ungrammatical items were more salient in

the high salience than low salience condition.

4.3.4. Experimental procedure

Participants were tested in a single experimental session lasting about 3.5

hrs. Participants were seated 40 inches in front of a monitor in a sound-proof,

electrically shielded recording chamber. Experimental and filler sentences were

presented one word at a time every half second for a duration of 200 ms; critical

words subtended from 1.2 - 4.9 degrees of horizontal visual angle (vertical angle

subtended was approximately one-half degree). Before each sentence a fixation

cross appeared for 900 ms, followed by a random interval between 617 and 1017

ms in duration. Additionally, a small central fixation dot, positioned approximately

0.25 degrees below the bottom edge of words, remained on the screen permanently

to facilitate correct fixation. Participants were instructed to read each sentence for

comprehension, fixating the fixation point until after the sentence ended, and to

attempt not to blink or move during this period. Participants also were required to make an acceptability judgment at the end of every sentence: after the final word of a sentence disappeared, participants were to indicate as quickly and as accurately as possible whether or not the sentence was well-formed.

In addition, to ensure that participants read the entire sentence for comprehension and to discourage them from engaging in any strategies due to the presence of grammatical violations, a random one-third of the sentences were followed by a comprehension probe sentence that appeared in its entirety in a red font. Participants were asked to indicate whether this comprehension probe had approximately the "same content" as its associated experimental sentence. As response times were not of interest here, participants were instructed to strive for accuracy at the expense of speed.

First, participants were familiarized with the stimulus presentation parameters and the task via a practice block of 30 sentences. Experimental sentences were then presented in 18 blocks of 30 or 31 trials each with short breaks between blocks and a longer break halfway through the experiment. The same hand, counterbalanced across participants, was used to indicate a "good sentence" and "same content" and was switched halfway through the experiment. The practice block was presented again after the mid-break until participants were accustomed to the hand mapping switch.

4.3.5. Recording procedures

The electroencephalogram (EEG) was recorded from 26 tin electrodes, embedded in an electrode cap, each referenced to the left mastoid. Right mastoid was recorded as well; ERP averages were re-referenced offline to the average of

activity recorded at the right and left mastoids. Scalp recording sites included:

Prefrontal: left lateral (LLPf), left medial (LMPf), midline (MiPf), right medial (RMPf),

right lateral (RLPf); Frontal: left lateral (LLFr), left mediolateral (LDFr), left medial

(LMFr), right medial (RMFr), right mediolateral (RDFr), right lateral (RLFr); Central:

left mediolateral (LDCe), left medial (LMCe), midline (MiCe), right medial (RMCe),

right mediolateral (RDCe); Parietal: left mediolateral (LDPa), midline (MiPa), right

mediolateral (RDPa); Temporal: left lateral (LLTe), right lateral (RLTe); Occipital: left

lateral (LLOc), left medial (LMOc), midline (MiOc), right medial (RMOc), right lateral

(RLOc). Lateral eye movements were monitored via electrodes placed at the outer

canthus of each eye in a bipolar montage. An electrode was placed on the

infraorbital ridge of the right eye and referenced to the left mastoid to monitor blinks.

Electrical impedances were kept below 2.5 KΩ. The data were sampled at 250 Hz.

The EEG and electrooculogram (EOG) were amplified by Nicolet amplifiers set at a

bandpass of 0.016 to 100 Hz.

4.3.6. ERP data analysis

Prior to analysis, data were examined for artifacts such as eye movements,

blinks, amplifier blocking, and excessive muscle activity; 3.1% of the grammatical

trials (3.5% for regular verbs; 3.1% for high salience; 2.8% for low salience) and

3.3% of the ungrammatical trials (4.0% for regular verbs; 3.3% for high salience;

and 2.8% for low salience) were rejected. ERP averages were re-referenced offline

to the average of activity recorded at the right and left mastoids. ERPs were

timelocked to the onset of the target words and a 200 ms prestimulus baseline was

used for all analyses; artifact rejection was conducted out to 1,500 ms post-stimulus

onset. Only sentences for which the participant made the correct grammaticality response were included in averages.

We examined mean amplitude of the waveforms for two latency windows synchronized to the onset of the critical word: 300 to 500 ms, and 500 to 1100 ms. We first conducted an omnibus ANOVA for each time window with three within-subject factors including Verb Type (regular, high salience, low salience), Grammaticality (grammatical vs. ungrammatical), and Electrode (26 levels); this analysis is referred to as the "full analysis". When the full analysis revealed an interaction of Electrode with Verb Type or Grammaticality, a distributional analysis consisting of an ANOVA with five within-subject factors including Verb Type, Grammaticality, Hemisphere (left vs. right), Laterality (lateral vs. medial electrodes), and Anteriority (five levels: four prefrontal electrodes [LLPf, LMPf, RLPf, RMPf], four frontal electrodes [LLFr, LMFr, RLFr, RMFr], four central electrodes [LDTe, LMCe, RDTe, RMCe], four temporal or parietal electrodes [LLTe, LDPa, RLTe, RDPa], four occipital electrodes [LLOc, LMOc, RLOc, RMOc]) was conducted (see Figure 4.1).

To better characterize effects in the 500 to 1,100 ms window which were distributed mainly over posterior sites, we also conducted a modified distributional analysis by verb type which was identical to the distributional analysis except it included fewer levels of the Anteriority factor: this "posterior-only" distributional analysis included three levels of Anteriority (four central electrodes [LDTe, LMCe, RDTe, RMCe], four temporal or parietal electrodes [LLTe, LDPa, RLTe, RDPa], four occipital electrodes [LLOc, LMOc, RLOc, RMOc]). For the LAN time window (300 to 500 ms), we conducted a hemispheric analysis over anterior electrodes which included factors of Verb Type, Grammaticality, and Hemisphere (Left vs. Right); ten

electrodes (LLPf, LMPf, LLFr, LDFr, LMFr, RLPf, RMPf, RLFr, RDFr, RMFr) were used in this analysis which included all but midline anterior electrodes.

Finally, in order to determine the onsets and offsets of components, for each verb type, we conducted a "moving window analysis" at each electrode site. For this analysis, we compared the mean amplitude voltage for grammatical and ungrammatical critical words in each verb condition, from 300 to 1500 ms in 50-ms non-overlapping increments. An interval was considered significant only when at least one adjacent interval was also significant; when significant effects within a range are referred to, all intervals in that range were significant.

Our significance level was set at $p \le .05$ and for all analyses involving more than one degree of freedom, the Geisser-Greenhouse (1959) correction for violations of sphericity was applied; uncorrected degrees of freedom but corrected p values are reported.

Early sensory components were measured as follows (collapsing across the conditions): the P1 as the average positive peak between 50 and 125 ms, the N1 as the average negative peak between 75 and 175 ms, the P2 as the average positive peak between 150 and 250 ms, and the N2 as the average negative peak between 250 and 350 ms.

4.4. Results

4.4.1. Overt behavior

As expected, participants were reliably more accurate in classifying grammatical (mean = 96.7%; range = 87.5 to 100%) than ungrammatical sentences (mean = 94.2%; range = 84.5 to 100%); main effect of Grammaticality, $F(1,19)=9.22$; $p = .001$. There was also a main effect of Verb Type,

*F(*1,19)=5.11, *p* = .011, with participants responses being most accurate for the high

salience sentences, followed by regular; responses were least accurate for the low

salience condition. Finally, there was a significant Type x Grammaticality

interaction, *F(*2,38)=4.26, *p* = .021, due to responses in the high

salience/ungrammatical condition being as accurate as responses to all three

grammatical conditions, whereas responses in the regular/ungrammatical and low

salience/ungrammatical conditions were less accurate (see Table 4.2 for means in

each condition). The greater accuracy in the high salience/ungrammatical condition

is likely due to the greater visual salience of those violations.

4.4.2. Comprehension probes

The overall high accuracy rate (95.3%) on comprehension probes indicated

that participants were attending to and comprehending the sentences they were

reading.

4.4.3. ERPs

Grand average ERPs elicited by verb type for grammatical vs.

ungrammatical critical words are shown in Figure 4.2 for a representative subset of

electrodes. Figure 4.3 shows the difference ERPs (point-by-point subtraction of the

ERP to the grammatical condition from the ERP to the ungrammatical condition) for

each verb type. As is typical for ERPs to visually presented words, for all conditions

we observed a P1 component peaking at around 89 ms, an N1 component peaking

at around 117 ms posteriorly and about 100 ms at anterior sites, a P2 component

peaking at around 194 ms, and an N2 component peaking at around 313 ms.

The omnibus ANOVA showed that for the peak latency of the P2, there was

a main effect of Grammaticality, *F*(1,19) = 4.77, *p* = .042, with the P2 peaking later

for grammatical (196 ms) than ungrammatical (193 ms). For the peak latency of the

N2, there was a main effect of Verb Type, $F(1,19) = 4.63$, $p = .016$, $\varepsilon = .97$. the N2

in the regular condition had slightly earlier peak (309 ms) than did the high salience

(315 ms) and low salience (315 ms) conditions. Unplanned two-way comparisons

showed for the difference between the regular and high salience conditions:

$F(1,19) = 7.42$, $p = .014$; for the difference between the regular and low salience

conditions: $F(1,19) = 5.74$, $p = .027$; and for the difference between high and low

salience conditions: $F(1,19) = .01$, $p = .932$ (p values shown are *uncorrected* for

post-hoc comparison; none of the comparisons would be significant after

correction).

For all three conditions, following the early sensory components, verbs

rendering the sentence ungrammatical were more positive-going over centro-

parietal sites than were equivalent words in the grammatical sentences, beginning

at about 500 ms and lasting until about 1,500 ms at posterior sites. Due to the long

duration of this positivity, we analyzed it in a longer time window (500 to1,100 ms)

than is typical (other analyses run in shorter time windows showed that overall

results were largely unaffected by the time window used). Prefrontal sites showed a

positivity with an earlier onset and shorter duration, beginning at about 400 ms and

lasting only a few hundred milliseconds.

4.4.3.1. P600

4.4.3.1.1. Analyses of mean amplitude: 500 to 1,100 ms

Between 500 and 1,100 ms, ungrammatical items (2.61 μV) were

significantly more positive than grammatical items (0.94 μV), main effect of

Grammaticality, $F(1,19)=30.91$, $p = .000$, across all verb types. Grammaticality

effects (ungrammatical – grammatical) were larger at medial than lateral sites, especially over posterior sites, although even at frontal medial sites, the effect was fairly large, Grammaticality x Laterality, $F(1,19)=39.14$, $p = .000$; Grammaticality x Anteriority, $F(4,76)=27.41$, $p = .000$, $\varepsilon = .43$; Grammaticality x Laterality x Anteriority, $F(4,76)=25.93$, $p = .000$, $\varepsilon = .62$. Furthermore, grammaticality effects were slightly larger over right than left hemisphere sites and the difference between the hemispheres was more pronounced at medial than lateral sites, Grammaticality x Hemisphere, $F(1,19)=19.09$, $p = .000$; Grammaticality x Hemisphere x Laterality, $F(1,19)=49.77$, $p = .000$.

For the low salience condition, mean amplitude over RH sites (1.93 μV) was more positive than over LH sites (1.76 μV); this was also true for the regular verbs although the difference between the hemisphere was smaller (RH: 1.79 μV, LH: 1.71 μV). In contrast, the opposite was true for the high salience condition (RH: 1.66 μV, LH: 1.81 μV), Verb Type x Hemisphere, $F(1,19)=4.92$, $p = .014$. ERPs were generally more positive at medial than lateral sites; the exception was at prefrontal sites where lateral sites were more positive than medial. Furthermore, over medial occipital and parietal sites, mean amplitude in the regular condition was the most positive of the three verb types, over frontal and central sites, mean amplitude in the low salience condition was the most positive; mean amplitude in the high salience condition was the least positive over central, parietal, and occipital sites, Verb Type x Laterality x Anteriority, $F(4,76)=2.61$, $p = .043$, $\varepsilon = .46$.

4.4.3.1.2. Analyses of mean amplitude, 500 to 1,100 ms, posterior electrodes only

Because of the late negativity which develops over prefrontal and frontal electrodes, in order to examine just the P600 effect, we ran a modified distributional analysis for the 500 to 1,100 ms window which included only posterior electrodes, with three levels of electrode in the anterior-posterior direction (central, temporal/parietal, and occipital). This modified "posterior-only" distributional analysis showed that the ungrammatical condition was more positive than the grammatical, main effect of Grammaticality, $F(2,38)=50.20$, $p = .000$. Grammaticality effects were larger over RH than LH overall, but medial sites (both LH and RH) showed larger grammaticality effects than did lateral sites (lateral: LH, 0.81 μV; RH: 1.80 μV; medial: LH, 3.20 μV; RH, 3.42 μV), Grammaticality x Hemisphere x Laterality, $F(2,38)=57.15$, $p = .000$. The difference between RH and LH sites was particularly large for the temporal/parietal level (LH, 1.21 μV; RH, 2.15 μV; central: LH, 2.30 μV; RH, 2.80 μV; occipital: LH, 2.51 μV; RH, 2.88 μV), Grammaticality x Hemisphere x Anteriority, $F(2,38)=8.00$, $p = .002$, $\varepsilon = .85$; Grammaticality x Hemisphere, $F(2,38)=13.07$, $p = .002$; Grammaticality x Anteriority, $F(2,38)=15.99$, $p = .000$, $\varepsilon = .82$. Furthermore, the difference between lateral and medial sites was particularly large for the temporal/parietal level (LH: 0.62 μV; RH: 2.74 μV; central: LH, 1.80 μV; RH, 3.30 μV; occipital: LH, 1.49 μV; RH, 3.90 μV), Grammaticality x Laterality x Anteriority, $F(2,38)=17.35$, $p = .000$, $\varepsilon = .98$; Grammaticality x Laterality, $F(2,38)=81.08$, $p = .000$. The main effect of Verb Type was not reliable, nor did any reliable interactions involve verb type.

We also ran this modified "posterior-only" distributional analysis for the 500 to 1,100 ms window for each verb type individually to examine the distribution and size of the P600 effect. For each, the main effect of grammaticality was reliable, as were all possible interactions with grammaticality (see Table 4.3 for F and *p* values). In general, the regular verb and high salience verb conditions patterned together in terms of size of the grammaticality effect, while for the low salience condition, the P600 effect was generally slightly smaller than that for the other two conditions. However, the overall distribution of the P600 effect was very similar for each of the verb types: mean amplitudes were larger for medial than lateral electrodes; larger over RH than LH sites, and larger at occipital and central sites, with temporal-parietal sites showing a somewhat smaller amplitude (to a large degree because no P600 effect is seen at all at LLTe and only a small effect is seen at RLTe).

4.4.3.1.3. P600 onset and offset latencies

Visual inspection of the ERP waveforms suggested that there may be differences between the onset of the P600s across the different verb type conditions: specifically, it appears that the onset of the P600 for low salience verbs may be slightly delayed, relative to the regular and high salience verbs. To explore this possibility, for each electrode site, we compared mean amplitude voltage elicited by grammatical and ungrammatical critical words for each verb condition, from 300 to 1,500 ms in 50-ms non-overlapping increments. These results are shown in Figure 4.4; effects are shown only when at least two adjacent 50 ms windows are significant. Although this is a somewhat inexact measure of onset and offset latencies, over posterior sites (excluding LLTe), our results showed that the regular and high salience conditions have similar onset latencies (average onset to

offset: regular: 561-1,250 ms; high salience: 539-1,279 ms), whereas low salience

has a later onset (646 ms-1,304 ms). The average duration of the effect over

posterior electrodes was shortest for low salience (658 ms), followed by regular (689

ms); high salience had the longest average duration (740 ms).

4.4.3.2. LAN: Analyses of mean amplitude, 300 to 500 ms

Visual inspection of the raw ERPs revealed no suggestion of an early

negativity (ungrammatical more negative than grammatical) such as a LAN effect in

the 300-500 ms time window for any condition. We confirmed our visual impression

for the regular condition (where a LAN would be expected according to one current

hypothesis) with statistical analyses using a hemispheric analysis of anterior

electrodes only (LLPf, LMPf, LLFr, LDFr, LMFr, RLPf, RMPf, RLFr, RDFr, RMFr) for

the 300 to 500 ms time window. This analysis showed no significant main effects

(Grammaticality, $F(1,19) = 2.33$, $p = .144$; Hemisphere, $F(1,19) = 1.45$, $p = .243$) or

interaction (Grammaticality x Hemisphere, $F(1,19) = 1.29$, $p = .186$).

4.4.3.3. Late negativity

We did observe a late negativity (ERPs for ungrammatical more negative

than grammatical) in all three verb conditions, visible primarily at left frontal and

prefrontal electrodes sites and beginning as early as 800 ms post-stimulus in one

case (see Figure 4.2 for raw ERPs for each verb condition and Figure 4.5 for spline-

interpolated voltage maps for the 1,100-1,500 ms time window for each verb

condition). As can be seen in Figure 4.4 showing analyses of 50 ms intervals, for

the low salience condition, this late negativity was significant only at LLFr, beginning

at 800 ms and lasting until the end of the epoch (= 1,500 ms). In contrast, the

negativity in this time window was somewhat more broadly distributed for the regular

and high salience conditions. For the regular condition, the negativity was most prominent at LLFr, beginning at 900 ms and lasting until the end of the epoch, but was also significant at LDCe (1,400 to 1,500 ms) and LLTe (1,350 to 1,500 ms). For the high salience condition, the negativity again has its earliest onset at LLFr (1,000 to 1,500 ms) but is also present at LMFr (1,200 to 1,500 ms), LDCe (1,350 to 1,500 ms), and LMPf (1,350 to 1,450 ms).

4.5. Discussion

The current study examined the processing of verbs in English sentences that set up an expectation for participle forms of verbs (e.g., exhibited, caught, flung); when this expectation was violated, the infinitival form appeared instead (e.g., exhibit, catch, fling). Both regular and irregular verbs were used. Irregular verbs were either high salience (e.g., catch, caught) or low salience (e.g., fling, flung), allowing us to examine whether the degree to which the ungrammatical infinitive differed from the correct participle form would affect the nature or size of the ERP effects observed. In all cases, these grammatical violations elicited only a late positivity (P600) and no prior negativity, LAN or otherwise. We also observed a negativity beginning late in the epoch (800 ms or later) at some electrodes (predominantly left prefrontal and frontal sites) which varied in terms of onset and location (electrode site) as a function of verb condition.

4.5.1. LAN

Of particular interest in this study was whether or not a LAN, an anterior negativity typically observed between 300 and 500 ms, would be elicited by violations in the regular (morphological) condition. Friederici and colleagues (e.g., Friederici, 2002; Gunter, Friederici, & Schriefers, 2000; Munte, Matzke et al., 1997)

have proposed that the LAN is elicited by morphosyntactic violations; if so true, we would expect a LAN to be elicited to violations in our morphological condition as the violations are morphosyntactic in nature. Additionally, Newman et al. (2007) reported a LAN for violations of regular past tense, but not irregular past tense; on the basis of this study we would also expect to observe a LAN to violations of our regular verbs. We did not observe a LAN in this condition.

Given the proposed link between the LAN and morphosyntactic violations, our data are important in that they reveal not even a hint of an anterior negativity between 300 and 500 ms (LAN or otherwise), not even for the regular verb condition. Although some studies have reported the presence of LANs in response to morphosyntactic violations (Angrilli et al., 2002 (Italian); Newman et al., 2007 (English); Osterhout & Mobley, 1995 (exp. 1 but not exp. 3, English); Palolahti et al., 2005 (Finnish)), as detailed in the Introduction, a number of studies in various languages have failed to find a LAN to morphosyntactic violations (English: Coulson et al., 1998 (subject/verb agreement); Kemmer et al., 2004; Kutas & Hillyard, 1983, (N300-400, central); Osterhout et al., 1996; Osterhout & Mobley, 1995, (LAN reported for exp. 1 but not exp. 3); Osterhout & Nicol, 1999; Dutch: Gunter et al., 1997, exp. 1; Hagoort & Brown, 2000 (exp. 1, visual); Hagoort et al., 1993; German: Munte, Szentkuti et al., 1997). Furthermore, still other studies have reported a LAN in the absence of any morphosyntactic violation (English: Osterhout & Holcomb, 1992; 1993; Dutch: Hagoort & Brown, 2000 (exp. 2)). Clearly, the mixed results across studies suggest that a morphosyntactic violation is neither sufficient nor necessary to elicit LAN activity. At the very least, then, these results overall suggest

that an account of the LAN which appeals only to morphosyntactic processing in general is incomplete.

The variability across studies as to when and whether a LAN is reported is further underlined by the findings of Newman et al. (2007), which is perhaps the most similar study to ours in the literature. Its reported findings stand at odds with our present findings. Exactly what factor(s) explain(s) the discrepancy between Newman et al. and our current study is unclear at present: across the two studies, stimulus presentation parameters were similar and sentence-final acceptability judgments were required; additionally, both were conducted in English. Similar to the present study, the Newman et al. study included a regular verb condition in which the simple past tense form was grammatical, and for violation conditions, the infinitival (stem) form was used. In contrast to our findings, Newman et al. reported a LAN (between 300-500 ms and prominent over left and midline anterior electrodes but extending back to central and posterior midline electrodes) for violations. Newman et al. also included an irregular verb condition, for which a LAN was not found, although a focal negativity in the 300-500 ms window over left posterior electrodes was reported. The finding by Newman et al. of a LAN elicited in the regular condition stands in contrast with the current study in which we found no comparable negativity for either our regular or irregular conditions.

One possible explanation for the difference in results reported in this study and by Newman et al. (2007) might be related to the degree to which the sentence position of the critical word in the Newman et al. study was predictable: the critical word in the regular and irregular conditions always occurred in third position in a sentence frame which began with "*Yesterday",* followed by a pronoun (*I, he,* or *she*),

then the critical verb, then a postverbal argument (i.e., *Yesterday I frowned/*frown at Billy*). In contrast, in the current study, the critical word (verb) position was highly variable although always sentence-medial, occurring in the fourth to seventh position in the sentence (with at least three words following the verb). However, in the current study, because we used the participle verb form, the verb was always preceded by some form of "have", which likely served as a predictor of the (experimental) verb. Thus, an explanation based on predictability is unlikely to account for the very different findings of these two studies. [2] Additionally, all the verbs used in the Newman et al. study were monosyllabic in both their stem and past tense forms. This was not the case in the current study; in fact, in the regular condition, most verb stems were at least two syllables; furthermore, the addition of the –ed to form the regular participle added a syllable for about half the verbs. However, the literature provides no evidence that LANs should be expected for mono- but not multisyllabic verbs.

Another difference between the two studies is the relative frequency of regular vs. irregular verb conditions. In Newman et al. (2007), sentences in the regular and irregular verb conditions occurred with equal frequency (25% each; 25% phrase structure condition; 25% lexical semantics conditions). In contrast, in our study, 22% of total sentences (546) involved the regular verb condition (120 sentences) and 44% involved an irregular verb (either high or low salience

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[2] Newman et al. state that about half of the sentences in the phrase structure and lexical semantics conditions began with either "*Yesterday"* or some other past tense frame such as "*Last week she* …" and thus, subjects could not predict the sentence condition based on the initial sentence words. However, all sentences in their regular and irregular conditions began with "*Yesterday"*, therefore, this word would be highly predictive that a past tense form of either a regular or irregular verb would be the correct third word of the sentence (for violation conditions, a verb stem would occur in this position).

conditions). Given that the regular verb condition was represented in only 1/3 of

experimental sentences (22% of total sentences), whereas 2/3 of the experimental

sentences (44% of total sentences) were irregular (either high or low salience),

there may have been a difference across studies in terms of strategies participants

engaged in. For example, once a participant encountered the word "*Yesterday*" in

the Newman et al. study, s/he knew that either a regular or irregular verb would

likely occur as the third word of the sentence. One strategy a participant might

engage in would be to pay more attention to the letters at the end of the third word:

if –ed occurred (25% likelihood), the sentence would be grammatical. In the current

study, such a strategy is less likely because for the experimental sentences, 2/3 of

the words following some form of "have" would be irregular verbs, as –ed would

occur at the end of only 1/6 (17% likelihood) of these sentences.

However, other studies argue against the hypothesis that the predictability of

a morphological violation is related to the elicitation of the LAN. In Osterhout and

Mobley (1995) and Kemmer et al. (2004), subject/verb agreement (morphological)

errors were also highly predictable: in both studies, the critical word was always

third in the sentence. Additionally, for both studies, all sentence subjects were

plural in the subject/verb condition, so strategizing would pay off: if there was an –s

at the end of the third word of the sentence, the sentence was more likely to be

ungrammatical (the strategy wouldn't be absolute: for other conditions, it could be

grammatical). Osterhout and Mobley reported a LAN for exp. 1, in which

subject/verb agreement violations totaled 29% (60/210) of all sentences, but not for

exp. 3, in which sentences in the subject/verb agreement condition totaled 25%

(60/240) of all sentences. In Kemmer et al., sentences in the subject/verb

agreement totaled 40% (120/300) of all sentences but no LAN was seen. A

difference between Osterhout and Mobley's experiment 1 and experiment 3 is that

participants made explicit grammaticality judgments in experiment 1 but not

experiment 3, which might suggest that the LAN is more likely when participants'

attention is drawn to errors by these judgments. However, the results reported by

Kemmer et al. make this possibility unlikely, as explicit judgments were required but

no LAN was reported.

The presence of comprehension sentences (as in the current study and

Kemmer et al. (2004)), which might discourage strategizing as participants are more

motivated to read for comprehension, also does not seem related to the LAN's

elicitation as Osterhout and Mobley (1995) did not include them in either experiment

1 or experiment 3, yet reported a LAN in experiment 1 but not experiment 3.

4.5.2. P600

In all three violation conditions in this study, grammatical violations elicited a

centro-parietally distributed positivity beginning at approximately 500 ms and

extending at least to 1,100 ms – a P600 component. The P600 effects in the

regular and irregular/high salience conditions did not reliably differ from each other.

These P600 effects did, however, reliably differ from the P600 observed in the low

salience/irregular condition, for which the onset of the P600 effect was later, and its

amplitude smaller. The scalp distribution (see Figure 4.6 for voltage map) of the

positivity was remarkably similar across the three conditions; additionally, current

source density maps (Figure 4.7) were strikingly similar across all three conditions.

Taken together, these suggest that the generators of the P600 in each condition are

similar, which argues against theories which propose qualitative differences in

processing of regular vs. irregular verbs. Our finding of a P600 to morphosyntactic

violations is in agreement with a large number of studies spanning a number of

languages, including Dutch, English, Finnish, German, Italian, and Spanish, and

including both visual and auditory modalities (Angrilli et al., 2002; Coulson et al.,

1998; Gunter et al., 1997; Hagoort & Brown, 2000; Hagoort et al., 1993; Hinojosa,

Martín-Loeches, Casado, Muñoz, & Rubia, 2003; Kemmer et al., 2004; Munte,

Heinze, Matzke, Wieringa, & Johannes, 1998; Munte, Szentkuti et al., 1997;

Osterhout et al., 2002; Osterhout et al., 1996; Osterhout & Mobley, 1995; Osterhout

& Nicol, 1999; Palolahti et al., 2005; Rossi et al., 2005).

4.5.2.1. What processes does the P600 reflect?

The P600 has been elicited in a number of situations, including outright

violations of syntax which require syntactic repair (Friederici & Mecklinger, 1996;

Friederici et al., 1993; Hagoort et al., 1993; Osterhout & Mobley, 1995) as well as by

syntactic ambiguities, where a critical word is temporarily perceived as a violation

until a later word disambiguates the correct sentence structure (e.g., garden-path

sentences: Osterhout & Holcomb, 1992; 1993; Osterhout et al., 1994). Additionally,

Kaan et al. (2000) have shown that a P600 can be elicited by grammatical, non-

garden-path sentences. They propose that in these cases, increasing P600

amplitude reflects increasing difficulty of integrating (into the ongoing sentence) the

critical word relative to a control (due to taxing of processing resources).

A number of hypotheses (not necessarily mutually exclusive) have been

proposed as to what processes the P600 reflects. Some have proposed the P600

reflects the cost of reprocessing/reanalysis when a structural ambiguity (i.e., garden-

path sentences) leads to an incorrect parse based on a preferred structure which

later must be revised when subsequent words clarify that the dispreferred structure

is the correct one (Osterhout et al., 1994). In contrast, Kaan et al. (2000) proposed

that the P600 reflects syntactic integration difficulties, rather than processes specific

to reprocessing (in their account, outright syntactic violations can cause a great deal

of integration difficulty). Most pertinent to the current study, some have suggested

the P600 reflects processes related to repair of outright syntactic violations or the

failure of a parse resulting from the violation (Friederici, 1998; Friederici, Hahne, &

Saddy, 2002; Hagoort & Brown, 2000; see for example Coulson et al., 1998;

Friederici et al., 1996; Gunter et al., 1997; Hagoort et al., 1993; Hagoort et al., 2003;

Kemmer et al., 2004; Osterhout & Mobley, 1995)[3]

4.5.2.2. What factors affect P600 amplitude and latency?

For the low salience/irregular condition, we observed a P600 reduced in

amplitude and delayed in latency, relative to the P600 observed in the irregular/high

salience and regular verb conditions. It is unlikely that latency jitter can explain the

lower amplitude P600 obtained in the low salience/irregular condition. If this were

the case, one would expect P600 duration to be correspondingly longer; this was

not observed. Thus, of interest is what the delayed onset latency and reduced

amplitude may reflect in our low salience/irregular condition. Kaan et al. (2000)

suggest that increasing P600 amplitude reflects increasing integration difficulty. Our

results, however, cannot be accounted for under this explanation, because there is

no difference in "integration difficulty" (as defined in Kaan et al., 2000) across our

conditions.

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[3] Additionally, some have claimed that the P600 belongs to the P300 family (Coulson et al., 1998; Gunter et al., 1997) although others have argued against this view (Frisch, Kotz, von Cramon, & Friederici, 2003; Osterhout & Hagoort, 1999; Osterhout et al., 1996; Wassenaar, Brown, & Hagoort, 2004).

In the case of syntactic ambiguity, Friederici and Mecklinger (1996)

proposed that P600 latency[4] may increase as the complexity of syntactic reanalysis

(necessary to recover from initially making the wrong analysis) increases. While the

current study has outright violations, rather than temporary ambiguities, reanalysis

likely takes place in both cases. Additionally, In a study which used outright

violations, Munte, Szenkuti et al. (1997) reported that P600 latency to be earlier in

their lowest complexity condition ("simple") compared to two other conditions with

more complex sentence structure. The current study did not manipulate syntactic

complexity, however, and it is unlikely that violations in the low salience/irregular

condition were any more difficult for subject to reanalyze or repair, compared to the

other two conditions. Additionally, it is important to emphasize that participants

were aware of the violations, as reflected in the high accuracy of their acceptability

judgments (see Table 4.2). Accuracy was high in all conditions, slightly higher for

grammatical (96.7%) than ungrammatical (94.2%). For grammatical sentences,

there was essentially no difference as a function of condition in accuracy. For

ungrammatical, accuracy was lower for the regular verb condition (93.1%) and the

low salience/irregular condition (93.1%), compared with the high salience/irregular

condition (96.4%). Thus, the likely explanation for our finding of a delayed onset of

the P600 in the low salience/irregular condition is that it took participants slightly

longer to notice the less salient violation.

Several studies have shown that P600 amplitude is affected by a number of

experimental factors, including probability of syntactic violations, salience, task, and

nature of the manipulation. Gunter et al. (1997) observed that P600 amplitude was

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[4] Friederici and Mecklinger (1996) are not explicit as to whether they mean "peak latency" or "onset latency"; it is likely, however, that they mean "peak latency".

modulated by the probability of syntactic violations: in their 75% violation condition, P600 amplitude was smaller than in their 25% violation condition. Additionally, Coulson et al. (1998) reported a similar result: P600 amplitude was smaller in their 80% violation condition compared to their 20% violation condition. However, others have failed to find an effect of probability on P600 amplitude in cases where the difference in probability was not so extreme across conditions. For example, Osterhout et al. (1996) failed to find a reliable effect of violation probability when they compared P600 amplitude elicited in a condition with 20% agreement violations vs. 60%.

Coulson et al. (1998) also reported an effect of salience on P600 amplitude: their more salient English pronoun case violations elicited a larger amplitude P600 than did their less salient number agreement (subject/verb) violations. Moreover, P600 amplitude has been reported to vary as a function of whether participants make explicit sentence acceptability judgments. For example, Osterhout et al. (2002) observed a quantitative difference in P600 as a function of task: a larger P600 was elicited when participants made acceptability judgments as opposed to when they did not. Osterhout et al.(1996) report a similar finding; in both studies, this observation was based on between-groups comparisons: the participants who made acceptability judgments were different from those who did not). It may be that sentence acceptability judgments draw attention to violations – in effect, make them more salient. In this regard, the findings of Osterhout et al. (2002) agree with our study's finding that the P600 is reduced in amplitude for the low salience/irregular condition. Furthermore, although Osterhout et al. (2002) do not discuss P600 onset for their data, visual examination of their ERP traces (their Figure 2) suggests that in

the "no judgment" condition, onset of the late positivity is delayed at frontal and central electrodes (although not at more posterior electrodes). Thus, the current study, together with Osterhout et al. (2002) and Coulson et al. (1998) provide evidence that P600 amplitude can be modulated by salience of grammatical violations.

Additionally, Osterhout et al. (1994) reported a larger-amplitude P600 for outright grammatical violations and smaller for less preferred (but grammatical) constructions. On the basis of this finding, the authors proposed that P600 amplitude may reflect the "cost of reprocessing" (constructing an alternative analysis) or it may reflect the "syntactic fit" between the eliciting word and the preceding syntactic structure. Such a "syntactic fit" explanation cannot account for our finding of a smaller P600 amplitude for the low salience/irregular condition: across our three conditions, the syntactic fit of the critical word with the preceding syntactic structure was identical. However, Osterhout et al.'s (1994) cost of reprocessing account is compatible with our findings: one might expect that repair in the low salience/irregular condition (where the critical word (verbal infinitive) in the violation condition differed from the correct participle form by one letter) would be less difficult than repair in the other two conditions. Thus, our finding of a smaller-amplitude P600 in our low salience/irregular condition could be due to the effect of salience, a smaller cost of reprocessing, or both.

4.5.2.3. Regular/Irregular debate

Our data also speak indirectly to the debate about the representation and processing of regular versus irregular word forms. Across our three violation conditions, one used regular verb forms and two used irregular word forms (high

and low salience). To the extent that for any particular measure, the regular and both irregular conditions systematically differ, we could entertain some dual mechanism account. Our data, however, are at odds with any such view. Overall, the data from the regular and high salience/irregular conditions pattern together and are reliably distinct from the data for the low salience/irregular condition. In other words, in these data, it is visual salience -- not regularity -- that seems to determine the pattern of effects observed. Whatever processes the P600 are presumed to reflect, our pattern of P600 results fail to support any dual mechanism account whereby all regular word forms are processed in one way and irregular word forms in another. As noted in the Introduction, the dual mechanism account argues that while irregular word forms are stored in the lexicon, regular word forms are not, and instead are computed via the application of a rule to a stored stem (Pinker & Ullman, 2002; Ullman, 2001). In contrast, the connectionist account holds that both regular and irregular word forms are represented in the lexicon and accessed in qualitatively similar ways.

Our finding of a later onset latency and smaller amplitude of the P600 effect for the low salience/irregular condition compared to the high salience/irregular and regular conditions, in the absence of any significant differences between the high salience/irregular and regular conditions, suggests that at least for the current study, the critical dimension was the degree to which the ungrammatical critical word differs from the grammatical control word (in this case, the critical dimension was along visual perception lines), rather than verb regularity.

Our findings are somewhat at odds with electrophysiological investigations that have reported differences between the processing of regular and irregular word

forms. Several methodological factors may account for this inconsistency,

especially given that the studies themselves show different patterns of ERPs

depending on the nature of the stimuli and task conditions, none of which observed

large P600s of the types elicited by the participle violations described herein. First

of all, in several cases the contrast involved regular versus irregular word forms

appearing in isolation rather than within sentences either in a (delayed) priming

paradigm (Munte, Say, Clahsen, Schiltz, & Kutas, 1999 (English); Rodriguez-

Fornells, Munte, & Clahsen, 2002 (Spanish); Weyerts, Munte, Smid, & Heinze, 1996

(German)) or within lists (Gross, Say, Kleingers, Clahsen, & Munte, 1998 (Italian)).

All three of the priming studies showed a modulation of the N400 for regular verb

forms when primed by a different form of the verb (e.g., prime: tanzen; target:

getanzt), whereas priming with irregulars (e.g., prime: schreiben; target:

geschriebt) elicited either no effect or a later (different) effect. The dissociation in

response to regulars compared to irregulars was interpreted as support for the dual

mechanism model: priming (as evidenced by N400 modulation for the target) for the

regular targets occurs because both the prime and the target access the same

lexical entry, whereas for the irregulars, the lack of an N400 priming effect is due to

the prime and target accessing different lexical entries (Rodriguez-Fornells et al.,

2002).

In a study of regular and irregular Italian verbs presented in lists, Gross et al.

(1998) also observed a dissociation in ERP responses (the verbs were interspersed

with nouns; participants' task was to press a button whenever a noun appeared).

The Italian verbs included correctly and incorrectly formed participles for regular

verbs (decomposable into root + theme vowel + participial ending + gender/number

(e.g., parl + a + t + o, dorm + i + t + o)) and irregulars which involve phonologically modified stems and cannot be similarly decomposed (e.g., preso, rotto; infinitival forms: prendere, rompere). Violations for regular verbs were formed by using the incorrect theme vowel (e.g., *parlito, *dormato), whereas violations for irregular verbs were formed by "regularization" – adding a theme vowel ("a") plus participial ending ("t") to the stem of the irregular verb (e.g., *prendato). No effect was seen for the regular violations, whereas the irregular violations produced a widespread negativity, beginning at about 250 ms and lasting until at least 750 ms, largest over anterior regions but extending to posterior regions as well. The observed qualitative dissociation in ERP responses was taken as support for the existence of processing differences between regular and irregular words as predicted by dual mechanism models.

Three studies have examined regular and irregular word forms processing within sentence contexts, with variable results: two of these were in German (Penke et al., 1997; Weyerts, Penke, Dohrn, Clahsen, & Munte, 1997) and one was in Catalan (Rodriguez-Fornells et al., 2001).

Weyerts et al. (1997) examined different classes of noun plurals in German (1) masculine or neuter nouns whose plural is –(e)n (e.g., Insekten "insects"; (2) feminine nouns with stem ending in an unstressed vowel (schwa) whose plural is –n (e.g., Fassaden "fronts"); (3) (regular) loan nouns whose plural is –s (e.g., Steaks "steaks"); (4) (regular) names whose plural is –s (e.g., Holgers "Holgers"); violations were formed by applying the wrong plural ending (-s instead of –n, and vice versa). The authors reported a LAN for conditions 1 and 2 (= "regularizations") although the onset was somewhat later for condition 2. In contrast, for conditions 3 and 4

("irregularizations"), a negativity was observed with a maximum at about 380 ms (Weyerts et al. state that this negativity resembles the N400 effect). Weyerts et al. interpret this LAN as a marker of regularization processes (that their "regularizations" are decomposed into stem + affix combinations) based on their findings combined with other findings in the literature. In contrast, they argue that irregularizations cannot be similarly decomposed because the –n affix is not a "regular" affix and thus, these violations may be treated as pseudowords; evidence for this conclusion is drawn from the negativity observed, which they argue may be similar to the N400 observed for pseudowords.

In a series of experiments, Penke et al. (1997) examined German participle forms for both regular (participle ends in –t, e.g., durchgetanzt "danced through") and irregular verbs (participle ends in –n, e.g., aufgeladen "loaded on"); violations were formed by applying the wrong participle ending to the verb stem). The authors examined processing of participle forms in word lists, sentences, and stories. For the irregular participles, violations ("regularizations", e.g., *aufgeladet) elicited a widespread negativity (LAN), beginning at about 200 ms, generally largest over left anterior sites. In contrast, for the regular participle violations ("irregularizations", e.g., *durchgetanzen), no consistent results across all three experiments were observed: in the sentence experiment, violations were associated with a slightly greater positivity beginning at about 200 ms, whereas in the story experiment, violations were associated with a greater negativity at electrode T3 (no effect was reported for the list experiment). The authors noted that the results for German participles were similar to those they reported for German plurals (Weyerts et al., 1997): in the case of both verbs and nouns, regularizations elicited a LAN, and

interpreted their results as providing additional support for the dual mechanism model.

Rodriguez-Fornells et al. (2001) embedded correct and incorrect forms of past participles within short stories in Catalan. There were three regular verb conditions representing first, second, and third conjugation verbs (which differ in terms of which theme vowel is used) for which violations were formed by inserting the incorrect theme vowel (e.g., infinitive: cantar/temer/dormir; correct participle form: cantat/temut/dormit; violations: *cantit/ *temat/ *dormat). For the irregulars, the violation is a "regularization" formed from the infinitival stem plus –a- as a theme vowel, plus –t, the past participle ending, is added (e.g., infinitive: admetre; correct participle form: admes; violation: *admetat). For all four conditions, violations involved an incorrect theme vowel; violations for the irregular verbs (*admetat) included an additional inflectional error. The authors predicted they would observe a LAN to violations of the irregular verbs due to the overapplication of the –t participle affixation (=regularization); they also expected that violations in the second and third conjugation (regular) verbs should elicit a LAN, due to overapplication of the –a- theme vowel of first conjugation verbs. Finally, they stated a LAN may be observed for violations of first conjugation verbs; if so, that would signify that third conjugation stem formation is rule based as well.[5] The authors' prediction with respect to the irregular verb violations was not borne out: no LAN was reported for that condition. Additionally, no LAN was reported for violations in the first conjugation (regular) condition (*cantit). For violations in the second (*temat) and third (*dormat) conjugation (regular verb) conditions, a left-

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[5] The first conjugation verbs are considered "regulars" whereas as the authors discuss, the status of the second and third conjugation with respect to "regularity" is unclear.

lateralized negativity was observed with an onset at about 300 ms which they termed a LAN, although its distribution was more posterior (maximal over temporal sites; based on visual inspection of their Figure 2, the negativity was smaller at left frontal and occipital sites) than is usually reported for LAN effects. Additionally, in all conditions, a P600 (onset about 600 ms) was observed, although it was not significant for the second regular condition.

Although there is some degree of similarity in the results across the Weyerts et al. (1997) and Penke et al. (1997) studies in that regularizations elicited LAN, in the Rodriguez-Fornells et al. (2001) study, regularizations failed to elicit a LAN. Additionally, the irregularizations show inconsistent results across the three studies: Weyerts et al. reported a N400 effect, whereas Penke et al. reported different effects (none being an N400) for the story vs. sentence experiments. In contrast, Rodriguez-Fornells et al. reported no effect for the first conjugation/regulars and reported a LAN for the second and third conjugation regulars. Overall, although there may be differences in how regular and irregular word forms are processed, ERP data to date do not support any consistent distinction between the two classes. Additionally, Rodriguez-Fornells et al.'s failure to find a LAN for their "regularization" condition suggests that the presence of the LAN in the Weyerts et al. study cannot simply be due to violations being decomposed into stem + affix combinations: if this were the case, one would expect Rodriguez-Fornell et al.'s irregular violations to elicit a LAN, as they could be broken down into stem + -a- + -t (e.g., *admet-a-t)in the same manner that the Weyerts et al.'s irregular violations could be broken down into stem + -s (e.g., *Insekt-s).

One possible explanation for the difference between the present study's finding of no difference in processing along regular/irregular lines compared with the three studies discussed above (Penke et al., 1997; Rodriguez-Fornells et al., 2001; Weyerts et al., 1997) may be related to the fact that in all three of the previous studies, the violation forms of the regular and irregular words were pseudowords: either an incorrect ending and/or theme vowel was applied to word stems. This contrasts with the present study in which violations were always words. It is not unlikely that using pseudowords in this way changes the nature of processing at the verbs, and may contribute to the different ERP effects seen in these studies relative to ours. Additional research will be necessary (1) to account for the differences observed across these studies using pseudowords, and (2) to account for the difference between their findings of differences between processing of irregular and regular forms (which provide support the dual mechanism model), and the current study's finding of no difference in processing of regulars and irregulars (which provides evidence against the dual mechanism model).

4.5.3. Late negativity

As mentioned above, we also observed a negativity beginning late in the epoch (800 ms or later) at some electrodes (predominantly left prefrontal and frontal sites) which varied in terms of onset and location (electrode site) as a function of verb condition. At present time, it is unclear what mental processes this late negativity may reflect. Late negativities have been previously reported in the literature. Mecklinger, Schriefers, Steinhauer, & Friederici (1995) reported a late negativity between 700 and 1,100 ms (widely distributed but largest frontocentrally) which they associated with memory load. Furthermore, Sabourin and Stowe (2004)

reported a late frontal negativity to sentence-medial violations of subject-verb agreement (ERPs for only one electrode (Pz) are shown for this condition; visual inspection shows the onset is roughly 1,300 ms post-stimulus). In contrast, no such late negativity was observed for their finiteness condition, in which violations were sentence-final. Participants made grammatical decisions at the end of the sentence and the authors hypothesized that the late negativity was due to memory load effects related to participants' maintenance of the grammatical decision.

In the current study, participants did make grammaticality decisions after sentences in which violations were in sentence-medial position. Thus, it is possible that the late negativity we observed is due to maintenance of the grammatical decision in memory until the end of the sentence[6]. However, as there was no condition in which grammaticality judgments were not made (or were made sentence-medially, immediately after the critical word), we cannot claim the negativity is due to maintaining the decision in memory. Even if true, such an account cannot explain why for the low salience/irregular condition, the negativity began earlier (about 800 ms) but was reliable at only one electrode (LLFr). In contrast, for the regular verbs, the negativity begins at about 900 ms and is present only at LLFr (although LDCe and LLTe show a much later negativity), while for the high salience/irregular verbs, the negativity begins even later at LLFr (1,000 ms) but also appears at LDFr (onset: 1,200 ms) and LDCe and LMPf (onset for both: 1,350 ms). Further investigation is necessary to determine what this late negativity reflects.

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[6] In a previous study (Kemmer et al., 2004), we also observed a late frontal negativity, earlier and larger at left prefrontal and frontal sites, although it was not discussed. In that study, participants also were required to make grammaticality judgments after the end of the sentence for violations which occurred in sentence medial position.

4.5.4. Conclusion

Given the proposed link between the LAN and morphosyntactic violations, our data are important in that they reveal no hint of anterior negativity between 300 and 500 ms (LAN or otherwise), even for the regular verbs. Although some studies have reported the presence of LANs in response to morphosyntactic violations (Angrilli et al., 2002 (Italian); Osterhout & Mobley, 1995 (exp. 1 but not exp. 3, English); Palolahti et al., 2005 (Finnish); Rossi et al., 2005 (German)), as detailed in the Introduction, a number of studies in various languages have failed to find a LAN to morphosyntactic violations (English: Coulson et al., 1998; Gunter et al., 1997 (exp. 1); Hagoort et al., 1993 (Dutch); Kemmer et al., 2004; Kutas & Hillyard, 1983 (N300-400, central); Osterhout et al., 1996; Osterhout & Mobley, 1995 (LAN reported for exp. 1 but not exp. 3); Osterhout & Nicol, 1999; Dutch: Gunter et al., 1997 (exp. 1); Hagoort & Brown, 2000 (exp. 1, visual); Hagoort et al., 1993, German: Munte, Szentkuti et al., 1997). Clearly, a morphosyntactic violation is neither sufficient nor necessary to elicit LAN activity. At the very least, then, these results overall suggest that an account of the LAN which appeals only to morphosyntactic processing in general is incomplete.

Table 4.1. Sample sentences from each condition.

Regular verbs

Grammatical: The modern art museum has _exhibited_ these paintings before.

Ungrammatical: *The modern art museum has _exhibit_ these paintings before.

High Salience/Irregular verbs

Grammatical: His new theory has _caught_ the attention of many scholars.

Ungrammatical: *His new theory has _catch_ the attention of many scholars.

Low Salience/Irregular verbs

Grammatical: That small monkey has _flung_ many things at the zookeepers.

Ungrammatical: *That small monkey has _fling_ many things at the zookeepers.

Critical words are indicated in the table in italics; in the experiment, they were not italicized. An asterisk preceding a sentence conventionally indicates it is ungrammatical; asterisks were not included in experimental stimuli.

Table 4.2. Accuracy data

	Grammatical Mean (SEM)	Ungrammatical Mean (SEM)
Regular	0.97 (.007)	0.931 (.010)
High Salience (Irregular)	0.968 (.006)	0.964 (.006)
Low Salience (Irregular)	0.963 (.006)	0.931 (.008)

Note. Accuracy; standard error of the mean in parentheses. Main effects of Verb Type, $F(1,19) = 5.11$, $p = .011$, $\varepsilon = .99$, and Grammaticality, $F(1,19) = 9.22$, $p = .007$, are significant, as was the Type x Grammaticality interaction, $F(1,19) = 4.26$, $p = .022$, $\varepsilon = .92$.

Table 4.3. P600: Posterior-only analysis for each verb type separately: statistical results

	Regular	High Salience	Low Salience
Main effect of grammaticality	F=52.31, *p*=.000	F=39.82, *p*=.000	F=21.68, *p*=.000
Grammaticality effect (ungrammatical – grammatical)	2.51 μV	2.47 μV	1.95 μV
Mean amplitude values (in μV) given show the grammaticality effect			
Grammaticality x Hemisphere x Laterality	F=14.23, *p*=.001	F=33.64, *p*=.000	F=34.93, *p*=.000
LH/lateral	1.02 μV	0.82 μV	0.60 μV
LH/medial	3.54 μV	3.43 μV	2.64 μV
RH/medial	3.67 μV	3.70 μV	2.90 μV
RH/lateral	1.82 μV	1.91 μV	1.67 μV
Grammaticality x Hemisphere x Anteriority	F=4.75, *p*=.016	F=3.02, *p*=.061	F=5.45, *p*=.009
LH/central	2.51 μV	2.54 μV	1.87 μV
LH/temporal-parietal	1.34 μV	1.26 μV	1.03 μV
LH/occipital	3.00 μV	2.58 μV	1.96 μV
RH/central	2.90 μV	3.07 μV	2.42 μV
RH/temporal-parietal	2.17 μV	2.23 μV	2.06 μV
RH/occipital	3.17 μV	3.11 μV	2.36 μV
Grammaticality x Laterality x Anteriority	F=7.76, *p*=.002	F=13.02, *p*=.001	F=13.99, *p*=.000
Lateral/central	1.86 μV	1.95 μV	1.60 μV
Lateral/temporal-parietal	0.60 μV	0.61 μV	0.65 μV
Lateral/occipital	1.79 μV	1.55 μV	1.14 μV
Medial/central	3.55 μV	3.66 μV	2.69 μV
Medial/temporal-parietal	2.90 μV	2.88 μV	2.44 μV
Medial/occipital	4.38 μV	4.15 μV	3.18 μV
Grammaticality x Hemisphere	F=8.28, *p*=.000	F=5.88, *p*=.025	F=7.32, *p*=.014
Grammaticality x Laterality	F=54.27, *p*=.000	F=77.96, *p*=.000	F=31.21, *p*=.000
Grammaticality x Anteriority	F=15.66, *p*=.001	F=11.90, *p*=.000	F=4.97, *p*=.013
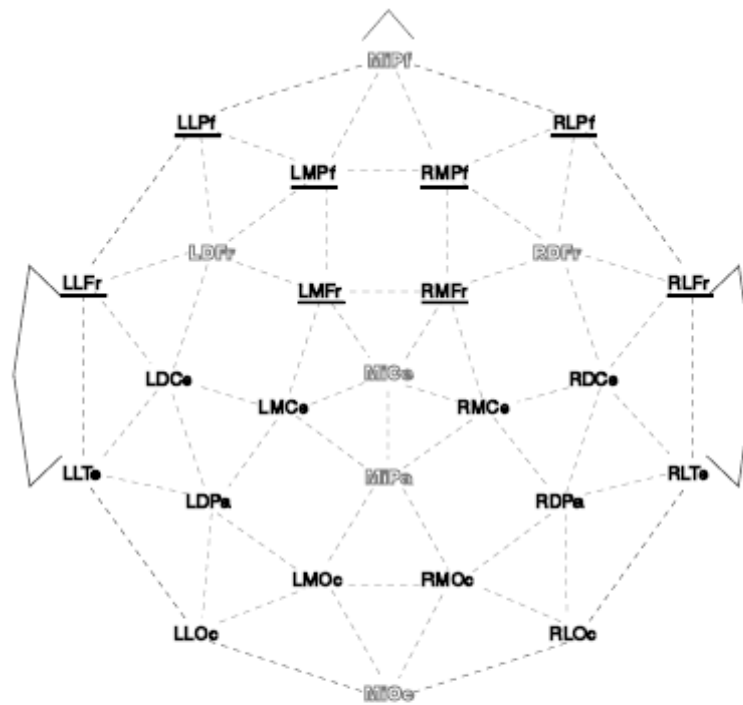
Figure 4.1. Schematic diagram of the locations of the 26 scalp electrodes, all of which were used for the full statistical analysis. The distributional analysis was restricted to the 20 electrodes with labels shown in bold print. The 8 electrodes with underlined labels were included in the "anterior only" distributional analyses; the remaining 12 electrodes with labels shown in bold print were included in the "posterior only" distributional analysis.
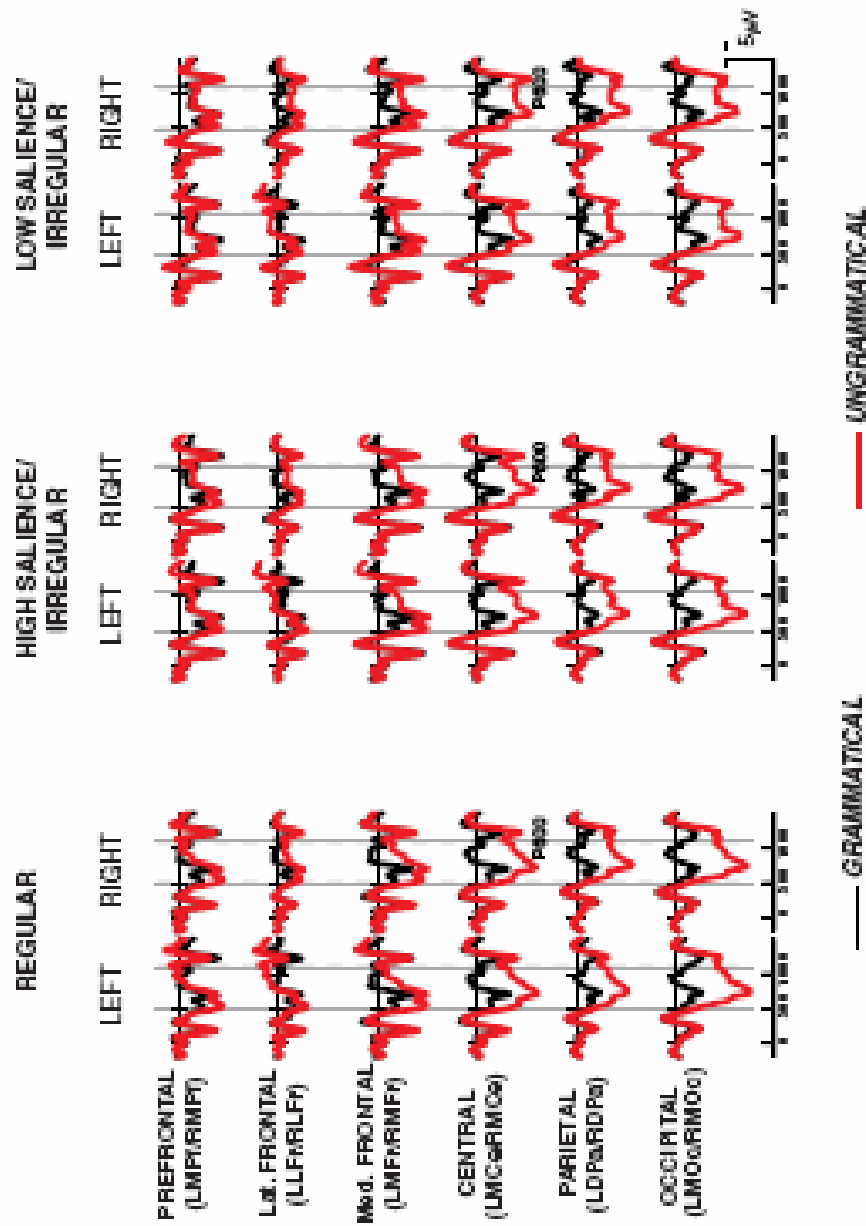
Figure 4.2. Grand average (N = 20) ERP waveforms elicited by critical words in violation (red line) and corresponding control words (black line) for each verb type. Shown are a representative subset of electrodes including left and right medial prefrontal electrodes (LMPf, RMPf), lateral frontal (LLFr, RLFr), medial frontal (LMFr, RMFr), medial central (LMCs, RMCs), mediolateral parietal (LDPs, RDPs), and medial occipital (LMOc, RMOc).

GRAMMATICALITY EFFECT
(Ungrammatical - Grammatical ERP)

——— REGULAR
——— HIGH SALIENCE/IRREGULAR
——— LOW SALIENCE/IRREGULAR
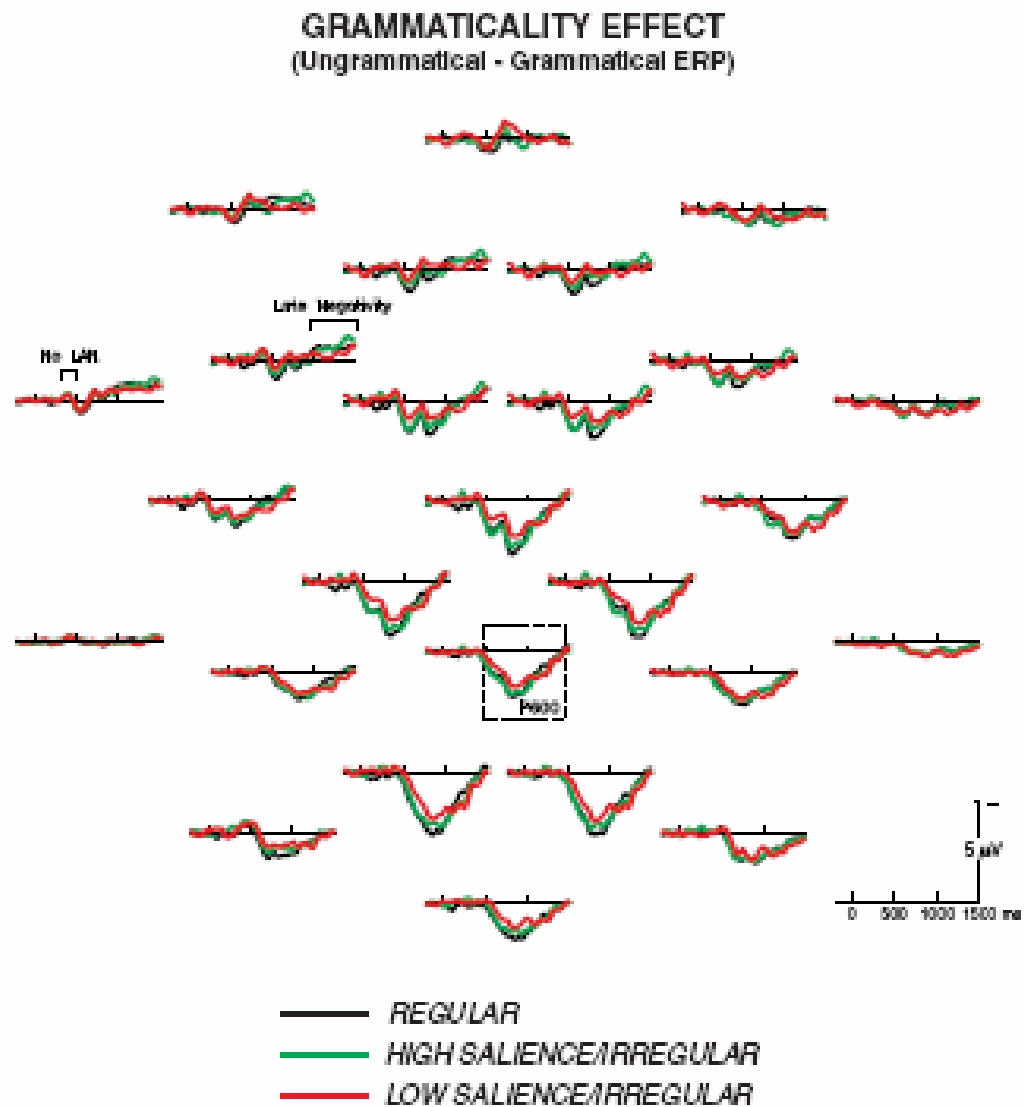
Figure 4.3. Difference ERPs, formed by subtracting grammatical from ungrammatical ERPs, showing the P600 effect for the Regular (solid line), High Salience/Irregular (dashed line), and Low Salience/Irregular (dotted line) conditions as well as the late negativity beginning at about 900 ms. Also noted is the absence of any LAN effect (300-500 ms).

Figure 4.4. Moving window analysis of the mean amplitude voltage from 300 to 1,500 ms in 50-ms non-overlapping increments for grammatical and ungrammatical critical words in each verb condition (opposite page). Figure 3A shows results for the regular verb condition; Figure 3B - high salience/irregular condition; and Figure 3C - low salience/irregular condition. Bars represent 50-ms windows for which a significant difference (p<.05) was observed between grammatical and ungrammatical conditions; bars are shaded when the ungrammatical condition is significantly more positive than the grammatical; open bars represent windows in which the ungrammatical condition is significantly more negative than the grammatical. Shading of bars in black represents posterior electrodes (central, temporal/parietal, anc occipital); shading in gray is for the remaining electrodes (prefrontal, frontal). Effects are marked only when two or more adjacent 50-ms windows are significant; electrodes shown are a representative subset. Note: No negativity at any anterior electrodes was observed in the 300 to 500 ms (LAN) period, nor between 0 to 300 ms (latter not shown).

A. Regular verbs
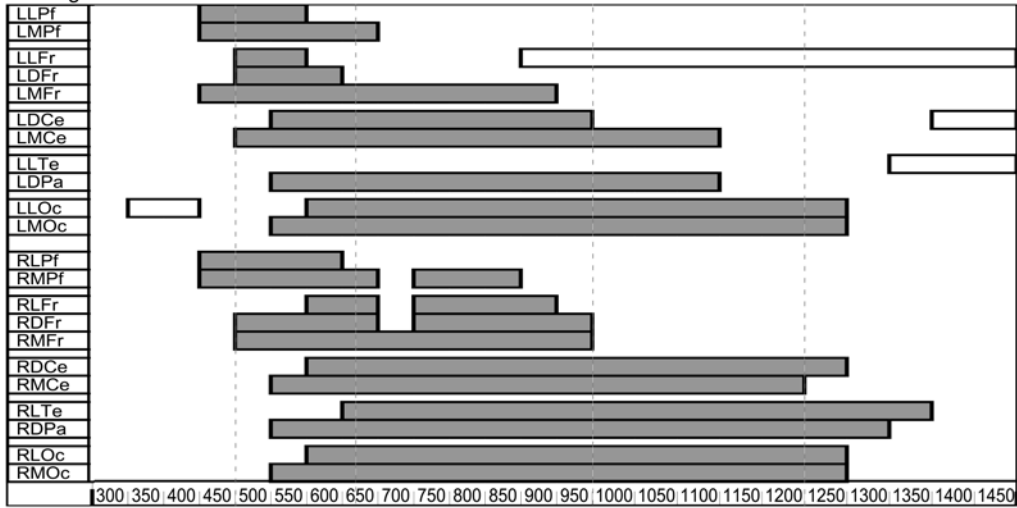
B. High Salience/Irregular verbs
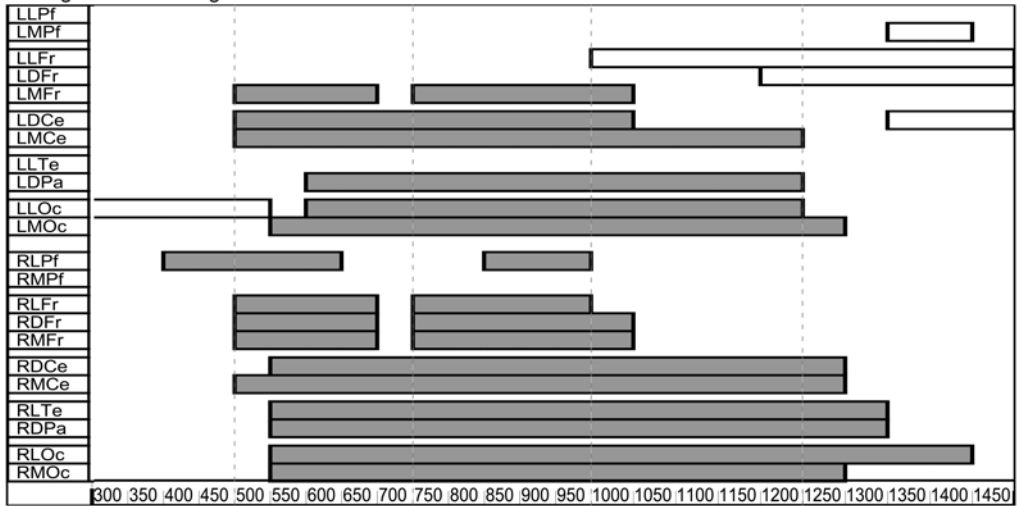
C. Low Salience/Irregular verbs
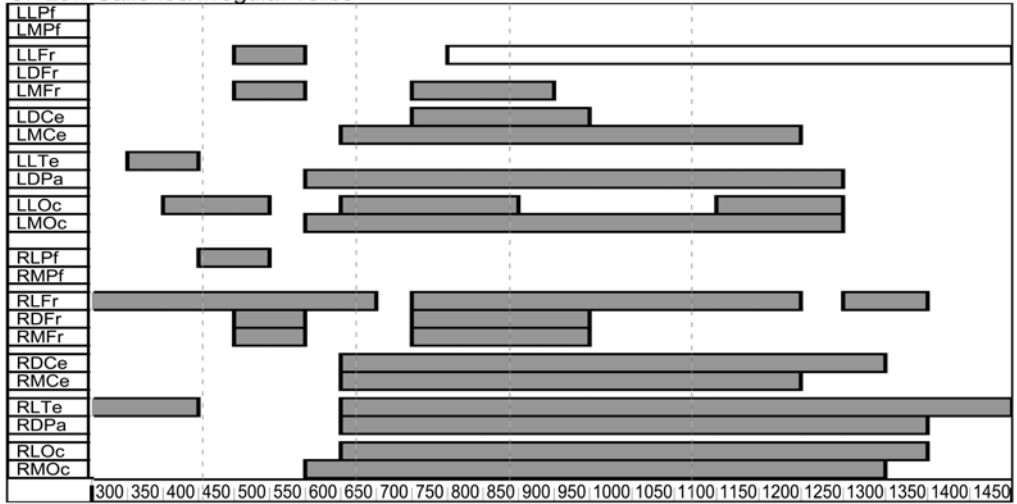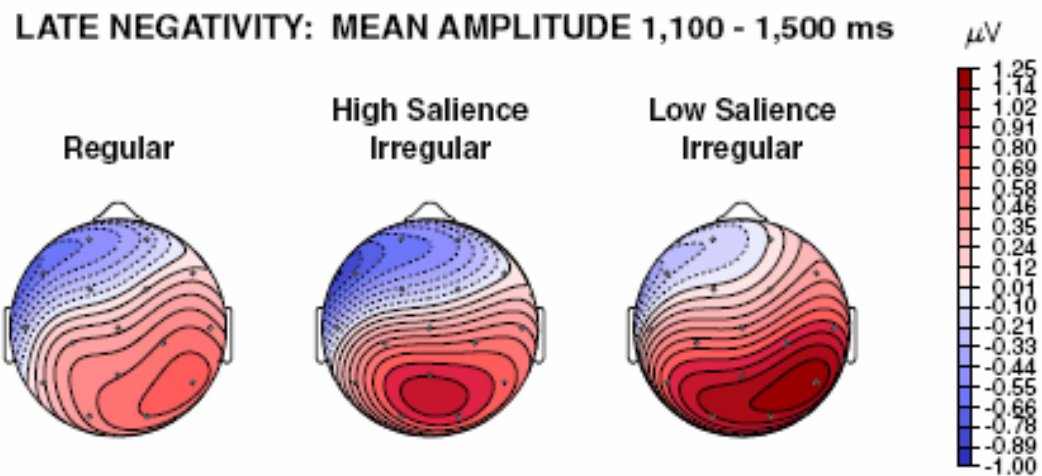
Figure 4.5. Spline-interpolated voltage maps showing the scalp distribution of the late negative effect (mean amplitude of the difference waves (Ungrammatical - Grammatical) for the 1,100 - 1,500 ms time window) for each verb type. Blue shades indicate sinks; red shades - sources. The left column shows the Regular verb condition; middle column: High Salience/Irregular; right column: Low Salience/Irregular.
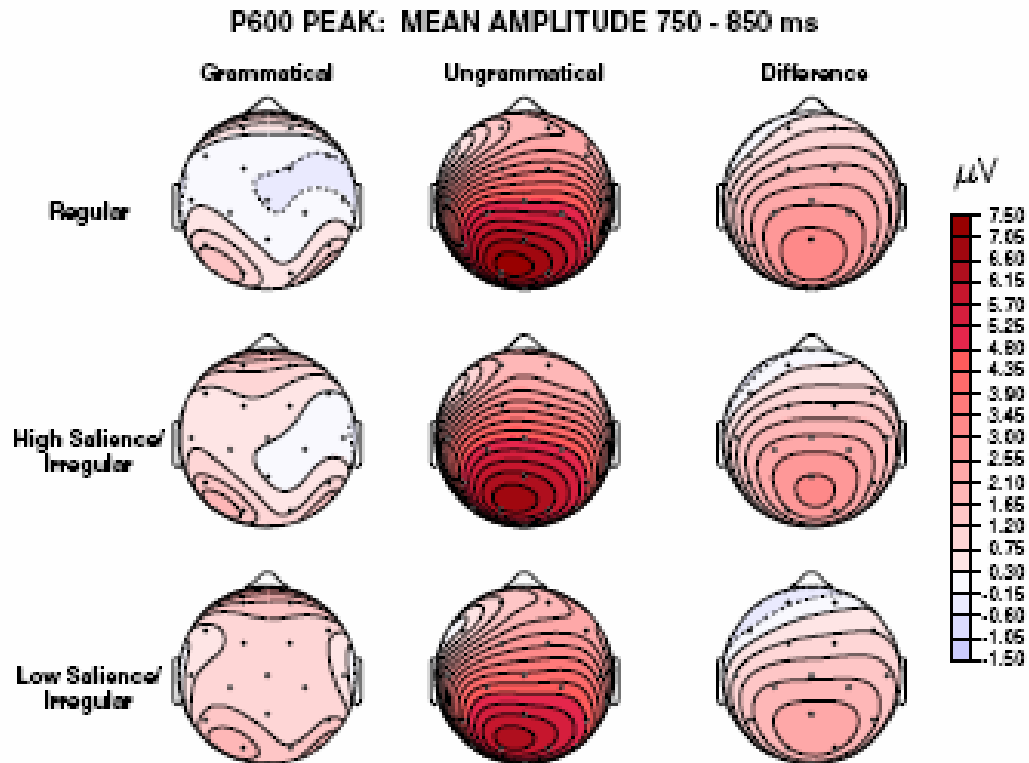
Figure 4.6. Spline-interpolated voltage maps showing the scalp distribution of the P600 effect (mean amplitude in 750 - 850 ms time window) for each verb type showing the data for grammatical (left column) and ungrammatical (middle column) conditions, as well as for the difference (Ungrammatical - Grammatical; right column) between these two conditions. The top row shows the Regular verb condition; middle row: High Salience/Irregular; bottom row: Low Salience/Irregular.
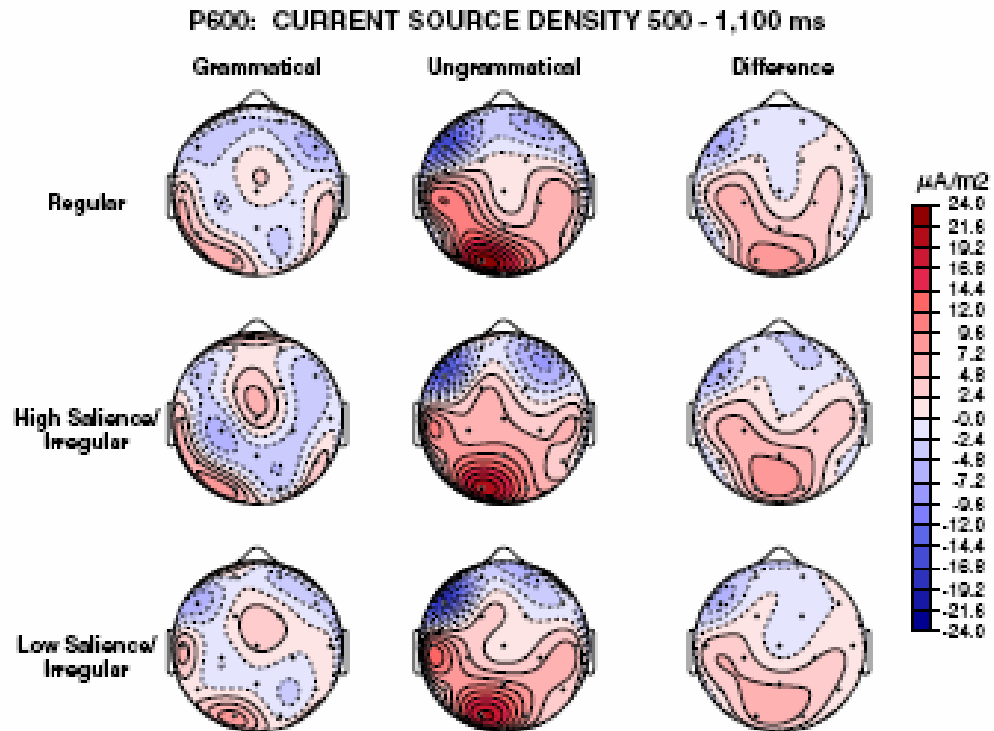
Figure 4.7. Spline-interpolated current source density maps calculated for the 500-1,100 ms time windows for each verb type showing the data for grammatical (left column) and ungrammatical (middle column) conditions, as well as for the difference (Ungrammatical - Grammatical; right column) between these two conditions. The top row shows the Regular verb condition; middle row: High Salience/Irregular; bottom row: Low Salience/Irregular.

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Chapter 5

Salience and syntactic processing across the hemispheres: an event-related brain potential study

5.1. Abstract

Syntactic processing is widely considered a left hemisphere phenomenon but whether the right hemisphere also makes a contribution remains largely unexamined, despite suggestions in the split-brain and lesion literatures that the right hemisphere may make some contribution. In previous studies (see chapter 3 of this dissertation), we combined event-related brain potentials (ERPs) and behavioral measures with the visual half-field paradigm to investigate each hemisphere's processing of correct and incorrect grammatical number agreement marked either lexically (antecedent/reflexive pronoun: "The grateful niece asked herself/*themselves...") or morphologically (subject/verb: "Industrial scientists develop/*develops..."). Results obtained suggested both hemispheres reacted similarly to violations in the lexical condition but only the left hemisphere appreciated morphological violations. Due to a confound in the stimuli, however, we were unable to adjudicate between two possible interpretations of these findings. One interpretation is that the right hemisphere appreciates lexical but not morphological markings, reflecting a high-level, language-specific hemispheric difference in syntactic processing. Alternatively, a lower-level, perceptually based difference may underlie the difference: the right hemisphere may be less able to appreciate the violation in the morphological condition because it is perceptually less salient. In this chapter, we report findings from two experiments (behavioral, ERP) which include

morphological and lexical conditions, but which manipulate salience of lexical

markings to help adjudicate between these two alternatives. The past-participle verb

form ("His new theory has caught...") has regular and irregular forms. For many

verbs, a morpheme ("-ed") is added to the base verb to form the participle

("exhibited"; morphological condition). Other verbs use an irregular form ("caught",

"flung"; lexical condition). We manipulate the grammaticality of sentences by using

either the grammatical participle form, or for the ungrammatical variant of each

sentence, the verb's base form ("His new theory has caught/*catch the attention...").

As sentences are presented visually, perceptual salience is operationalized as the

number of letters difference between grammatical and ungrammatical critical words.

Thus, "caught/*catch" represents a high salience difference, and "flung/*fling" - low

salience. The behavioral results suggest that the observed processing differences

are based at the perceptual level. However, the pattern of ERP results obtained

were not in accord with our predictions and do not lend themselves to any clear

conclusions with respect to the hypothesis investigated.

5.2. Introduction

The first known theory of hemispheric specialization states: "There are

accordingly two brains in the head. The one gives us our intellect, the other provides

the faculty of perception. That is to say: the brain on the right side is the one that

perceives, whereas the left brain is the one which understands" (Lokhorst, 1996, p.

9) According to Lokhorst (1996), this theory dates back to classical antiquity (no

earlier than the third century B.C.) and is preserved in a Latin codex dating back to

the late eleventh or early twelfth century. This text preserved in this codex is the

only known pre-1800 writing about hemispheric specialization.[1]

The first modern claim of hemispheric specialization was made by Broca

(1865) when he reported that all cases of speech deficits he had observed were

associated with damage to a certain area of the left hemisphere (the third frontal

convolution)[2]. Since Broca, many functional asymmetries between the

hemispheres have been described, although language is perhaps the most well-

known cognitive asymmetry. Although Broca (1865) was explicit in not claiming that

the general faculty of language (*faculté générale du langage)* resided in the left

hemisphere, in the decades which followed, many researchers began to view the

left hemisphere as superior to the right, in part due to studies which claimed some

or all higher intellectual functions were located in the left hemisphere (Harrington,

1987). With time, the predominant opinion evolved and came to regard the left

hemisphere as dominant for all aspects of language (Hellige, 1993). However, over

the last few decades, much evidence accumulated for right hemisphere

contributions and even right hemisphere dominance for some areas of language.

For example, the current view of language holds that both hemispheres

contribute to semantic aspects of language, although the hemispheres appear to

differ in terms of how each organizes semantic information, the time course, and

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[1] Lokhorst (1996) states he discovered the theory in 1981 but that " … classical philologists already knew about this theory, but they had largely kept this knowledge to themselves." (p. 3) and also mentions that he knows of only one non-philological reference to the theory, dating to 1917. The creator of the theory is unknown as is the context in which it was created. The theory was preserved in a short list containing four other theories concerning the soul, blood vessels, *phrenitis*, and functions of various parts of the heart. The codex was published in 1532 and again in 1901 (Lokhorst, 1996).

[2] Broca (1863) reported eight cases which supported a view that speech was localized to the third frontal convolution and noted they were all in the left hemisphere, but expressed reluctance to make a claim of localization to the left hemisphere based on eight cases.

nature of activating and integrating that information (Beeman, Friedman, Grafman, & Perez, 1994; Burgess & Lund, 1998; Burgess & Simpson, 1988; Chiarello, 1991; , 1998; Chiarello, Burgess, Richards, & Pollock, 1990; Chiarello, Senehi, & Nuding, 1987; Christman, 1989; Faust, Babkoff, & Kravetz, 1995; Federmeier & Kutas, 1999). Additionally, the right hemisphere is important for and may be dominant in processing related to prosody and intonation (Behrens, 1989; Brownell, Simpson, Bihrle, & Potter, 1990; Buchanan et al., 2000; George et al., 1996; Perkins, Baran, & Gandour, 1996; Ross, 1985; Ross & Mesulam, 1979; Ross, Thompson, & Yenkosky, 1997; Weylman, Brownell, Roman, & Gardner, 1989) and the pragmatic aspects of language (for reviews, see Brownell, Gardner, Prather, & Martino, 1995; Brownell, Michel, Powelson, & Gardner, 1983; Hough, 1990), including understanding idiomatic phrases (Stemmer, 1994) and metaphor (Bottini et al., 1994; Brownell et al., 1990), processing of jokes (Behrens, 1989; Coulson & Williams, 2005; Coulson & Wu, 2005; Shammi & Stuss, 1999; Wapner, Hamby, & Gardner, 1981) and puns (Behrens, 1989), understanding indirect requests (Delis, Wapner, Gardner, & Moses, 1983; Stemmer, 1994; Weylman et al., 1989) and at least some aspects of discourse comprehension (Brownell et al., 1995; Delis et al., 1983; St George, Kutas, Martinez, & Sereno, 1999).

An extreme example which was instrumental in demonstrating that the right hemisphere has some language ability is that of complete commissurotomy patients, in which the corpus callosum (and sometimes the anterior commissure and hippocampal commissure) is cut, thereby removing virtually all communication between the hemispheres. Studies of the abilities of the disconnected hemispheres in these patients have shown that although the right hemisphere has no speech, it is

not word-deaf as had previously been thought. For example, Zaidel (1978) showed

that commissurotomy patients had right hemisphere auditory lexicons which were

only slightly inferior to that of the left hemisphere and that the right hemisphere can

access its lexicon directly from the orthographic representation (lexical route).

Furthermore, up until recently, based on evidence from both brain damaged and

normal populations, it was widely thought that only the left hemisphere had access

to the phonological route, in which reading is accomplished by converting the

orthographic representation to a phonological one in order to access the lexicon.

Contradicting this view is a study by Weekes, Capetillo-Cunliffe, Rayman, Iacoboni,

and Zaidel (1999) of processing in normal brains that provides evidence that the

right hemisphere can read via the phonological route, but the more limited

processing resources of the right hemisphere make this route less efficient and

subject to more individual variability.

Syntactic processing is one area of language which is still widely considered

to be a strictly left hemisphere function, a view influenced by a large body of

research with patient populations that has shown that lesions to certain areas of the

left hemisphere are far more devastating to syntactic aspects of language than are

lesions in the same areas of the right hemisphere. Consequently, very few studies

have examined whether right hemisphere damage may cause subtle deficits in

syntactic processing; research instead has focused on the gross deficits resulting

from left hemisphere lesions. While it is clear that right hemisphere damage does

not generally result in the kinds of obvious deficits to syntactic processing that left

hemisphere damage can cause, this does not necessarily imply that the right

hemisphere contributes nothing. Indeed, understanding any right hemisphere

involvement in syntactic processing may help facilitate recovery to some degree from functional deficits due to left hemisphere damage.

While few studies have been conducted to examine a possible right hemisphere contribution for syntactic processing, there are suggestions in the literature that deficits in syntactic processing do result from right hemisphere damage. Schneiderman and Saddy (1988) examined performance of two patient groups, left brain damaged (LBD) and right brain damaged (RBD), as well as controls, on two different word insertion tasks involving different kinds of syntactic analysis. These two tasks differed in terms of the kind of reanalysis of sentence elements required to successfully insert a word into a sentence. For one task (nonshift insertion), the RBD group outperformed the LBD, as expected. However, on a second task (shift insertion), the LBD group (right hemisphere intact) outperformed the RBD group, a result which is not predicted by the view that syntactic processing is strictly a left hemisphere phenomenon. In another study, Caplan, Hildebrandt, and Makris (1996) examined processing in LBD and RBD patient group of syntactically simple versus syntactically complex sentences. While the LBD group showed a greater degree of impairment, the RBD group also showed impairment on the syntactically complex sentences relative to controls.

A study by Murasugi and Schneiderman (2005) used the sentence anagram task to investigate syntactic abilities of RBD and LBD patients. While the LBD patients in this study had previously been diagnosed as mildly to moderately aphasic, the RBD patients had not previously been diagnosed with any language disturbances. The sentence anagrams were divided into two types: "predicted", which require that an underlying empty category be replaced with a lexical item (an

example sentence is "John considers himself intelligent and Doug does too"; successful completion of this sentence anagram requires realizing that "does" replaces the phrase "considers himself intelligent") and "non-predicted", also involving empty categories; however, in these, the empty category remains empty in the sentence (e.g., "John seems easy to upset [ec]" in which the empty category refers to "John"). This study found that while both patient groups were impaired relative to the controls on the "predicted" items, only the LBD patients showed significantly impaired performance relative to the controls on the "non-predicted" items. These results suggest that RBD patients have some difficulty related to processing of empty categories, although the authors were unable to precisely specify what that difficulty is.

The studies listed above all suggest that the right hemisphere may make contributions to syntactic processing (or at minimum, can compensate after left hemisphere damage), although it remains unclear what exactly the nature of these contributions might be. They do, however, argue against views which reject any right hemisphere involvement in syntactic processing and make it clear that additional research on the right hemisphere's potential contribution is necessary. Additionally, these studies all examined processing in patient populations. While research conducted with patient populations can provide important information regarding the neural organization for cognitive functions, as with all research, there are limitations to the conclusions which can be made. For example, lesions are never identical from patient to patient and even if two patients have similar lesions, the degree of functional loss may differ. Thus, it may be the case that a damaged area has some residual function remaining, but quite difficult for a researcher to

determine the nature or extent of that function, or whether the other hemisphere is compensating for the damaged hemisphere.

An alternative approach to investigating the functional capacities of each hemisphere is to examine processing in neurologically intact individuals, without a history of brain injury. Although with normal brains there is no experimental way to test the functioning of one hemisphere independent of the other, the visual half-field paradigm allows researchers to approximate such a hypothetical experiment. The visual half-field paradigm takes advantage of the anatomy of the visual pathways in order to present a stimulus initially to only one hemisphere of a normal brain. Stimuli presented in one visual field or the other more than one degree laterally from a central fixation point project directly only to the visual cortex of the contralateral hemisphere. In a visual half-field paradigm, participants fixate a central point and stimuli are presented in either the right visual field (RVF) or left visual field (LVF) for 200 ms or less – about the time required to initiate and execute an saccade. The subsequent differences in processing which are frequently observed as a function of which hemisphere the stimulus goes to initially provide a window through which we can begin to understand hemispheric contributions to processing. Specifically, one can infer whether both hemispheres contribute to processing the stimulus and if so, whether there is any quantitative or qualitative difference in the contribution of each hemisphere.

Behavioral research has used the visual half-field paradigm extensively to investigate hemispheric differences for certain language phenomena but the vast majority of this research has looked at processing of individual words rather than sentence-level processing. Moreover, very little research has used the visual half-

field paradigm to examine syntactic processing. In one study, Liu, Chiarello, and Quan (1999) asked participants to read three-word noun phrases (consisting of an article, adjective, and a noun) in which the noun (the target word) was presented lateralized in two different task conditions: lexical decision and target naming. The articles required the noun to be either singular (e.g., "this") or plural (e.g., "these"), or were neutral (e.g., "the") and permitted either singular or plural nouns. The authors found that ungrammatical cues delayed recognition of the target words presented to either cerebral hemisphere and they concluded that at least for noun phrases, both hemispheres are sensitive to number agreement.

In a series of three experiments, Kemmer, Coulson, and Kutas (2009; see chapter 3 of this dissertation) combined the visual half-field paradigm with both behavioral and ERP techniques to examine hemispheric capabilities for processing grammatical number agreement. The results of these experiments suggested that the two hemispheres were able to appreciate grammatical number marked lexically with reflexive pronouns (reflexive pronouns/antecedent agreement), but that the right hemisphere had greater difficulty than the left appreciating grammatical number marked morphologically on verbs (subject/verb agreement).

These results are in agreement with a study by Zaidel (1983) of two commissurotomy patients suggesting that the right hemisphere finds it easier to process subject/verb grammatical number agreement in the third person when it is signaled lexically using an auxiliary, such as "*is*" or "*are*" (the cat *is* eating/the cats *are* eating) rather than when it is signaled morphologically by the presence or absence of the third person singular simple present tense inflection "-*s*" (the cat eat*s*/the cats eat). In contrast, left hemisphere performance showed little difference

between the two marking types. On the basis of this and other studies with commissurotomy and hemispherectomy patients, Zaidel (1990) concluded that the "disconnected right hemisphere can comprehend … a variety of grammatical and syntactic structures extending from functors to tense markers and to simple syntactic transformations such as the passive or negative" (p. 124). However, Zaidel also suggests that the right hemisphere may have more difficulty with some linguistic categories than with others. He proposes a hierarchy for the right hemisphere which, going in order from easiest to most difficult, includes lexical items (nouns, verbs, adjectives, adverbs, and prepositions), morphological constructions, grammatical categories (case, number, gender, tense), and (most difficult) syntactic structures such as predication and complementation.

One possible conclusion based on the finding of Kemmer et al. (2009) is that the hemispheres differ at a high, language-specific, processing level.   In other words, the right hemisphere is able to process lexical grammatical markings but has greater difficulty with morphological grammatical markings. This conclusion would be similar to that put forth by Zaidel (1990). However, an alternative explanation for the Kemmer et al. (2009) finding that the right hemisphere had greater difficulty in the subject/verb compared to the reflexive condition could be that the difference is due to lower level differences between the hemispheres in perceptual processing. In the subject/verb agreement condition, the presence or absence of a single letter (/-s/) on the verb differentiated grammatical from ungrammatical conditions. In contrast, in the reflexive condition, the difference between singular and plural reflexive pronouns ("themselves" versus "himself" or "herself") differentiated grammatical from ungrammatical. Noticing the presence or absence of a single

letter on the verb would require higher spatial frequency resolution than would noticing the difference between herself/himself and themselves. In other words, the difference between the grammatical and ungrammatical items in the reflexive condition is visually more salient for the right hemisphere than is the difference in the subject/verb condition.

Such a possibility is supported by the literature concerning global/local asymmetries across the hemispheres. The right hemisphere seems better able to process global aspects of stimuli while the left hemisphere seems better able to process local aspects of stimuli (Delis, Robertson, & Efron, 1986; Heinze, Hinrichs, Scholz, Burchert, & Mangun, 1998; Heinze & Munte, 1993; Lamb & Robertson, 1989; Martin, 1979; Martinez et al., 1997; Robertson & Delis, 1986; Robertson, Lamb, & Knight, 1988; Robertson, Lamb, & Zaidel, 1993). Ivry and Robertson's (1998) double filtering by frequency (DFF) theory is based on the proposal that these global/local differences emerge because of differences between the hemispheres at the perceptual level for processing spatial (or auditory) frequencies: the right hemisphere amplifies the relatively lower spatial frequencies of a visual stimulus– which tend to be more important for global aspects of stimuli, while the left hemisphere amplifies the relatively higher spatial frequencies – which tend to be more important for local aspects of stimuli. The implication of the DFF theory for the Kemmer et al. (2009) findings is that it may have been more difficult for the right hemisphere to differentiate between grammatical and ungrammatical items in the subject/verb condition (a difference of only one letter) due to poorer resolution of higher frequencies, compared to that of the left hemisphere. For the reflexive condition, differentiating grammatical from ungrammatical items did not require the

finer resolution of higher frequencies; for this condition, the lower frequency resolution of the right hemisphere was adequate for differentiating between the two.

In a review, Christman (1989) points out that the literature examining spatial frequency asymmetries between the hemispheres argues that decreasing exposure duration of visual stimuli has the effect of reducing the availability of higher frequencies relative to lower. Accordingly, if the right hemisphere is less specialized than the left for extracting higher frequency information, then for tasks requiring discrimination of high frequency information, it may require comparatively long exposure durations to attain the same performance as the left hemisphere at relatively shorter durations. In this case, there would be a range of exposure durations for which the left hemisphere showed relatively small (or no) performance decrements at shorter vs. longer durations. This is because at both durations, the left hemisphere is able to extract the high frequency information that is necessary to the task, resulting in left hemisphere performance that is at or near ceiling levels. In contrast, for the same exposure durations, the right hemisphere would show comparatively large performance decrements for the shorter vs. longer duration: as duration increases, the right hemisphere's performance would increase because it is able to extract more of the necessary information.

The results observed by Kemmer et al. (2009; chapter 3 of this dissertation) in experiments 1 and 2 show this kind of a pattern. In experiment 1, exposure duration was 100 ms, while in experiment 2, exposure duration was 200 ms. For the subject/verb ungrammatical condition with LVF presentation, there was a larger drop in accuracy (18.8% difference) in experiment 1 (57.4%) than there was in experiment 2 (76.2%). In contrast, accuracy for the reflexive ungrammatical

condition with LVF presentation was 82.9% in experiment 2 versus 88.9% in experiment 1 (6% difference). In other words, we observed a larger drop in right hemisphere performance in the subject/verb condition with decreased exposure duration, compared to the much smaller drop in performance in the reflexive condition. This pattern of results is consistent with the hypothesis that our results are due to perceptual-level processing differences – differences in processing spatial frequencies – between the hemispheres.

Kemmer et al. (2009) also examined ERP responses to same stimuli (experiment 3). Although to our knowledge, no previous ERP studies have examined syntactic processing using the visual half-field paradigm, ERP studies with central presentation have frequently reported a P600: a broad, centro-parietally distributed positivity (ungrammatical items more positive than grammatical) with an onset at about 500 ms and a duration of at least several hundred milliseconds. Some studies have also reported early left anterior negativities (LANs), typically in the 300 to 500 ms time window, although both the distribution and timing of these negativities has been quite variable. Additionally, the LAN is not consistently observed, even when stimuli are nearly identical (c.f., Osterhout & Mobley, 1995, exp. 1 versus exp. 3).

Kemmer et al. (2009) found that for the reflexive condition, ungrammatical items elicited a P600 response with an onset at about 600 ms, lasting about 400 ms at posterior sites, and similar in amplitude for both LVF and RVF presentation. In contrast, in the subject/verb condition, only RVF presentation elicited a P600 response (similar in onset, duration, and latency to that observed in the reflexive condition). In contrast, LVF presentation showed no P600 effect whatsoever; rather,

over anterior electrodes, there was a sustained negativity (grammatical items more positive than ungrammatical), larger over left hemisphere than right hemisphere sites (particularly left lateral), beginning roughly at 500 ms and lasting until the end of the epoch (1,500 ms post-stimulus).

As argued in Kemmer et al. (2009), in the reflexive condition, the similar brain response – a P600 – for both LVF and RVF presentation of lexically-marked number agreement, and its similarity to the response observed with central presentation of stimuli (as reported in Kemmer, Coulson, De Ochoa, & Kutas, 2004), suggests engagement of similar neural generators and processing mechanisms for this condition. In contrast, in the subject/verb condition, we observed qualitatively different responses as a function of visual field: RVF presentation elicited a P600 response, while LVF presentation elicited a sustained negativity. As mentioned above, this pattern is consistent with the findings of Zaidel (1983) that the left hemisphere is better at processing lexical as opposed to morphological markings. Alternatively, as argued above, due to the confound in our stimuli, the pattern could also be due to hemispheric differences at a perceptual level.

5.2.1. The present experiments

As discussed above, the confound in visual salience of stimuli used in the Kemmer et al. (2009) experiments made difficult a determination of whether our observed pattern of results was due to the hemispheres differing at a high, language-specific, processing level, or whether it was due to differences between the hemispheres at the perceptual level for processing spatial frequencies. The stimuli used in the current experiments removes this confound. In two experiments, we examine processing of grammatical and ungrammatical critical words in

sentences requiring past participle verb forms. Three verb conditions are included: regular verbs, high salience/irregular verbs, and low salience/irregular verbs (see Methods for greater detail). At a perceptual level, the high salience/irregular verb condition is similar to the reflexive condition in Kemmer et al. because the ungrammatical form (the infinitival form) differs from the grammatical form (the participle) by two or more letters (e.g., bring versus brought). In contrast, the low salience/irregular verb condition is similar to the subject/verb condition in Kemmer et al. in that the ungrammatical critical word differs from the grammatical by only one letter (e.g., fling versus flung).

At a language-specific level, the regular verb condition is similar to the subject/verb condition in that for both, the ungrammatical and grammatical words are founded on a common verb base (stem) which is concatenated with a morphological suffix (e.g., -s, -ed) via a rule processing system (Ullman et al., 2005). Thus, both the subject/verb and the regular verb conditions are morphological conditions. The irregular verb conditions in the current study are similar to that of the reflexive condition in that the word used as the violation is considered a different lexical entry from the grammatical form (e.g., herself versus themselves; bring versus brought). Thus, the reflexive and the two irregular verb conditions are lexical conditions.

We reasoned that if our previous results were due to the hemispheres differing at a language specific level, we should observe that the results for the two irregular verb conditions (both high and low salience) pattern together and also with that seen previously for the reflexive condition. In contrast, the regular verb condition should pattern with that seen previously for the subject/verb condition.

Alternatively, if our previous results were due to the hemispheres differing at a lower perceptual level based on differences between the hemispheres in processing spatial frequencies, the high and low salience conditions should show different patterns of results. The high salience condition results should be similar to that seen previously in the reflexive condition, while results for the low salience should be similar to that seen previously in the subject/verb condition.

5.3. Methods

5.3.1. Design

The design for this experiment was a 3 x 2 x 3 within-subjects design. The factors included Verb Type (regular, high salience/irregular, low salience/irregular), Grammaticality (grammatical, ungrammatical), and Visual Field (left, center, right). The dependent variables were response times and accuracy; for response time analyses, data from correct responses only were included in the analysis.

5.3.2. Materials

There were 360 experimental sentences (average number of words: 10.7; range: 7 to 17) and 186 filler sentences, including 120 sentences (half grammatical) for another experiment in which subject/verb agreement was manipulated, and 66 filler sentences (half grammatical) which included syntactic manipulations other the those being manipulated for the current experiment or the subject/verb agreement manipulation.

There were three experimental conditions (120 sentences per condition): regular verbs, high salience/irregular verbs ("high salience"), and low salience/irregular verbs ("low salience"; see Table 5.1 for sample experimental sentences). For each condition, half of the sentences were grammatical and the

critical word was the past participle form of a verb. For syntactic violations, the

(ungrammatical) critical word was the infinitival form of the verb. Regular verbs are

those verbs for which the past participle form adds -ed to the infinitive (e.g.,

exhibited). The high salience condition included those verbs for which the past

participle form and infinitival form (e.g., caught vs. catch) differed by 2 or more

letters, whereas for the low salience condition, the difference was one letter (e.g.,

flung vs. fling).

For each experimental condition, 30 verbs were used; each verb occurred in

four different sentences frames, twice grammatical and twice ungrammatical (two

had singular subjects; two had plural subjects). A participant viewed only one list;

each sentence frame occurred once in each list. Within a list, each experimental

verb was presented twice (in different sentence frames) to the same visual field,

once in a grammatical sentence and once in an ungrammatical sentence, with this

pair having the same grammatical number (both either singular or plural). A given

list included for each sentence either the violation, or its grammatical counterpart,

never both.

Lists were created in the following manner. Using a computer algorithm, the

list of verbs for each sentence type were first placed in random order. The "Base A"

list was created as followed: The four sentence frames corresponding to each verb

were randomly assigned to be presented to two of the three visual fields (LVF and

Central; Central and RVF, or LVF and RVF); this assignment was rotated across

each set of four frames such that an equal number of sentences were presented to

each visual field. For each set of four sentence frames, the two singular sentences

were then randomly assigned to one of the two possible visual fields (with one of

these two randomly assigned to be grammatical and the other - ungrammatical); the

two plural sentences were then assigned to one of the two possible remaining visual

fields (with one sentence randomly assigned to be grammatical and the other –

ungrammatical); assignment of the singular and plural sentences to each visual field

was done such that equal numbers of singular and plural sentences were assigned

to each visual field. From this "Base A" list, a second "Reverse A" list was created

which reversed the visual field assignment of the four singular and plural sentence

frames for each verb. Then, a "Mirror Base A" and a "Mirror Reverse A" list were

created in which the grammaticality assignment of each sentence was changed.

This process created four lists. Then, to completely counterbalance the pairings of

the four sentence frames across all visual fields, four "B lists" were created

corresponding to each the four "A lists" ("Base A", "Reverse A", "Mirror Base A", and

"Mirror Reverse A") by changing visual field assignment as follows: if the "A list"

assigned a sentence from to LVF, it was assigned to Central presentation in the "B

list"; if the "A list" assignment was Central, it became RVF in the "B list"; if the A list

assignment was RVF, it became LVF in the "B list". Finally, four "C lists" were

created in the same manner as the "B lists" except that if the "A list" assignment was

LVF, it became RVF in the "C list" (central became LVF, and RVF became central).

Thus, across a total of 12 lists, Grammaticality, Visual Field, and Verb Type were

completely counterbalanced.

The 546 sentences of each list were then ordered randomly using a

computer algorithm. For each presentation condition (LVF, central, RVF), each list

included 20 grammatical regular verbs, 20 violation regular verbs; 20 grammatical

high salience verbs, 20 violation high salience verbs; 20 grammatical low salience

verbs, 20 violation low salience verbs; 20 grammatical subject-verb agreement

(filler), 20 violation subject-verb agreement (filler); 11 grammatical filler, and 11

violation filler sentences. Each participant viewed only one list.

Verbs were matched for frequency using the Francis and Kučera (1982)

norms. For the regular condition, verbs had an average frequency of 174

occurrences per million (SD = 141; range = 28 to 625); in the high salience

condition, average frequency was 188 (SD = 199; range = 7 to 487); and for the low

salience condition, average frequency was 159 (SD = 166; range = 6 to 583). In the

grammatical condition, regular verbs averaged 7.9 letters in length (SD = 1.2;

range = 6 to 10 letters); for ungrammatical, 5.9 letters (SD = 1.2; range = 4 to 8

letters). High salience verbs averaged 5.5 letters (SD = 1.6; range = 3 to 10 letters)

for grammatical; for ungrammatical, 4.9 letters (SD = 1.4, range = 3 to 10 letters).

For low salience, grammatical verbs averaged 4.4 letters (SD = 1.1; range = 3 to 8

letters) and ungrammatical - 4.5 letters (SD = 1.0; range = 3 to 8 letters). Critical

words always occurred in sentence-medial position and across all sentences, were

preceded by 3.8 words on average (range: 3 to 6) and followed by 5.8 words on

average (range: 3 to 10 words). Overall sentence length and the average number of

words preceding and following the critical word were balanced across experimental

conditions.

5.3.3. Participants

Twenty-two UCSD undergraduate students participated in the experiment for

course credit or pay (14 women; ages ranged from 18 to 27; average was 19.2

years). All subjects provided health and medical information, including history of

psychiatric disorders, drug use, neurological disease, medications currently being

taken, vision, and others; subjects were excluded from experiment participation as appropriate. All subjects were monolingual, right-handed (assessed using the Edinburgh Inventory, (Oldfield, 1971)), and had normal or corrected-to-normal vision.

5.3.4. Norming studies

Prior to collecting data for this experiment, a number of studies were conducted to verify the actual usage of the participial verb forms, to establish the cloze expectancy for the verbs, and to verify the visual salience classifications for irregular verbs. These norming studies are described in the Methods section of chapter 4 of this dissertation.

5.3.5. Experimental procedures

Participants were tested in a single experimental session lasting about 3.5 hours. Participants were seated 40 inches in front of a monitor in a sound-proof, electrically shielded recording chamber. Experimental and filler sentences were presented one word at a time every half second for a duration of 200 ms; critical words were presented for 200 ms duration and followed by an inter-stimulus interval (ISI) of 700 ms. The critical verb in each sentence was presented to either left, central, or right visual field; the remaining words of the sentence were presented centrally. Critical words subtended from 1.2 - 4.9 degrees of horizontal visual angle; vertical angle subtended was approximately one-half degree). When presented laterally, the inner edge of critical words was 1.5 degrees from the central fixation point.

Before each sentence a fixation cross appeared for 900 ms, followed by a random interval between 617 and 1,017 ms in duration. Additionally, a small central

fixation dot, positioned approximately 0.25 degrees below the bottom edge of words, remained on the screen permanently, to facilitate correct fixation. Participants were instructed to read each sentence for comprehension, fixate the fixation point until after the sentence ended, and to attempt not to blink or move during this period. Participants also were asked to make an acceptability judgment at the end of every sentence: after the final word of a sentence disappeared, participants were to indicate as quickly and as accurately as possible whether or not the sentence was well-formed.

In addition, to ensure that participants read the entire sentence for comprehension and to discourage them from engaging in any strategies due to the presence of grammatical violations, a random one-third of the sentences were followed by a comprehension probe sentence that appeared in its entirety in a red font. Participants were asked to indicate whether this comprehension probe had approximately the "same content" as its associated experimental sentence. As response times were not of interest here, participants were instructed to strive for accuracy at the expense of speed.

First, participants were familiarized with the stimulus presentation parameters and the task via a practice block of 30 sentences; if necessary, the practice block was repeated to ensure that participants were not moving their eyes when stimuli were presented. Experimental sentences were then presented in 18 blocks of 30 or 31 trials each with short breaks between blocks and a longer break halfway through the experiment. As in the practice block, participants' electrooculogram (EOG) traces were monitored on-line for eye movements; feedback was given if saccades began occurring to ensure as few trials as possible

contained artifact (data were analyzed offline and all trials with movement or other artifact were excluded). The same hand, counterbalanced across participants, was used to indicate a "good sentence" and "same content" and was switched halfway through the experiment. The practice block was presented again after the mid-break until participants were accustomed to the hand mapping switch. An ERP experiment with central presentation of critical words for these stimuli, with identical experimental and recording procedures (other than not having lateralized critical word stimuli) is reported in chapter 4.

5.3.6. Recording procedures

The electrooculogram (EOG) was recorded from three electrodes placed around the eyes. Lateral eye movements were monitored via electrodes placed at the outer canthus of each eye in a bipolar montage. Blinks were monitored with an electrode placed on the infraorbital ridge of the right eye and referred to the left mastoid. Electrical impedances were kept below 3.0 KΩ. The data were sampled at 250 Hz. The EOG was amplified by Nicolet amplifiers set at a bandpass of 0.016 to 100 Hz. The EOG was monitored during the experiment to ensure that subjects were not making saccades to the critical word or blinking during presentation of the experimental sentence.

5.4. Results

5.4.1. Accuracy: omnibus ANOVA

The omnibus ANOVA showed that participants' responses overall were more accurate for grammatical (96.1%) than ungrammatical items (89.2%), $F(1,21) = 64.81$, $p = .000$ (see Table 5.2 for accuracy and response time data). There were also reliable main effects of Verb Type (Regular: 94.7%, High salience:

92.8%, Low salience: 90.4%), $F(2,42) = 13.88$, $p = .000$, $\varepsilon = .79$, and of Visual Field

(central: 97.3%, RVF: 94.3%, LVF: 86.4%), $F(2,42) = 57.62$, $p = .000$, $\varepsilon = .66$.

Significant interactions included Grammaticality x Visual Field,

$F(2,42) = 11.57$, $p = .000$, $\varepsilon = .77$, Verb Type x Visual Field,

$F(4,84) = 3.52$, $p = .011$, $\varepsilon = .82$, and Verb Type x Grammaticality x Visual Field,

$F(4,84) = 3.44$, $p = .022$, $\varepsilon = .73$.

5.4.1.1. Planned two-way comparisons

Two-way comparisons showed that for each sentence type, responses for

the grammatical condition were reliably more accurate than responses for

ungrammatical for all visual fields, with one exception: central presentation in the

high salience condition showed no reliable difference between grammatical and

ungrammatical conditions (see Table 5.2 for results of statistical tests and Figure 5.1

for plots of response time and accuracy data).

Comparisons between two sentence types, keeping constant grammaticality

and visual field, showed that responses were more accurate for the regular

compared to low salience condition with the exception of central presentation of

grammatical sentences ($p = .698$). The lack of a reliable difference in this

comparison is likely due to a ceiling effect as accuracy was very high for both

regular (99.6%) and low salience (98.0%) verbs. Comparisons between high

salience and low salience conditions showed a difference in the pattern of results as

a function of grammaticality. Comparisons between grammatical high salience and

low salience conditions showed no reliable differences in accuracy, regardless of

the visual field of presentation. However, for ungrammatical sentences, responses

were more accurate for high salience compared to low salience for central ($p = .000$)

and LVF (p = .003), but not RVF (p = .414), presentation. Finally, comparisons between regular and high salience sentences showed no reliable differences with one exception: for ungrammatical sentences presented to RVF, accuracy was higher for the regular verb condition (p = .010). However, ungrammatical sentences presented to central (p = .105) and LVF (p = .062) showed a trend for responses to regular sentences to be more accurate.

Two-way comparisons across visual field, keeping constant sentence type and grammaticality, were generally reliable, with responses in central presentation always being more accurate than LVF, and RVF more accurate than LVF. However, comparisons of accuracy between central and RVF presentation were <u>not</u> reliable, with one exception: for ungrammatical high salience, central was more accurate than RVF (p = .000; additionally, grammatical low salience sentences showed a trend for central presentation to be more accurate than RVF, p = .066).

We also calculated d-prime and beta for the accuracy data; these values are shown in Table 5.3. We ran an ANOVA on the d-prime results and it showed no reliable main effects or interactions. We also calculated beta values for each participant, converted each with a natural log transform, and then calculated averages. For natural log of beta, a positive value reflects a bias to respond "ungrammatical", while a negative value reflects a bias to respond "grammatical"[3]. Our results showed that for all verb types, LVF presentation resulted in a relatively small bias to respond "grammatical", while central and RVF presentation resulted in a generally stronger bias to respond "ungrammatical".

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[3] For raw, non-transformed values, a beta greater than 0 and less than 1 reflects a tendency to respond "grammatical", while a value greater than one reflects a tendency to respond "ungrammatical".

5.4.2. Response times: omnibus ANOVA

Participants' responses overall were faster for grammatical (1,053 ms) than ungrammatical (1,153 ms) items, $F(1,21) = 36.88$, $p = .000$ (see Table 5.2 for accuracy and response time data). There were also significant main effects of Verb Type (Regular: 1,062 ms, High Salience: 1,097 ms, Low Salience: 1,149 ms), $F(2,42) = 29.71$, $p = .000$, $\varepsilon = .85$, and Visual Field (central: 1,019 ms, RVF: 1,086 ms, LVF: 1,204 ms), $F(2,46) = 57.92$, $p = .000$, $\varepsilon = .92$. There were no significant interactions.

5.4.2.1. Planned two-way comparisons

Two-way comparisons showed that for each sentence type (keeping constant visual field), responses for grammatical items were reliably faster than responses for ungrammatical for both central and RVF presentation. For LVF presentation, responses were reliably faster for grammatical compared to ungrammatical in the low salience condition only, although there was a trend for significance ($p = .068$) in the regular condition as well (see Table 5.2 for results of statistical tests and Figure 5.1 for plots of response time and accuracy data).

Comparisons between sentence types (keeping visual field and grammaticality constant) showed that in general, response times were faster for the regular compared to the low salience condition. This difference was reliable (RVF/grammatical; central/ grammatical; central/ungrammatical; LVF/ungrammatical) or marginal (RVF/ungrammatical; LVF/grammatical) for all comparisons. Speed of response for the regular verb condition compared to the high salience verb condition was generally not reliably different, with two exceptions: response times were faster in the regular verb condition for grammatical sentences

presented centrally and to the RVF (ungrammatical sentences presented centrally showed a trend for responses in the regular verb condition to be faster, p = .090). Finally, the only reliable difference in speed of response between high and low salience conditions was for ungrammatical sentences with LVF presentation (responses were faster in the high salience condition, p = .001), although there was also a trend for responses in the high salience/ungrammatical condition to be faster for RVF (p = .086) and central (p = .064) presentation of ungrammatical sentences.

Two-way comparisons between visual field, keeping constant sentence type and grammaticality, were generally reliable, with responses in central presentation always being faster than RVF or LVF, and RVF faster than LVF. Only one comparison was marginal rather than reliable: responses were marginally faster for RVF compared to LVF presentation for the ungrammatical high salience condition (p = .070).

5.5. Discussion, Experiment 1

In this experiment, we examined processing of grammatical and ungrammatical sentences requiring the past participle verb form, using the visual half-field paradigm to present the critical word of each sentence either centrally or lateralized to LVF or RVF. The dependent measures were response time and accuracy data. We included both regular and irregular verbs, with irregular verbs divided into two categories, high and low salience, based on the difference in visual salience between the grammatical past participle form and ungrammatical infinitive.

Participants' response accuracy for grammaticality judgments was well above chance in all conditions, indicating that both hemispheres were able to appreciate the difference between grammatical and ungrammatical verb forms. For

grammatical items, accuracy was high – over 90% - for each visual field; for ungrammatical items, accuracy was somewhat lower, although the lowest average accuracy (75.5% for LVF presentation of low salience) represents well above chance performance.

We did observe a difference in the pattern of results as a function of verb type and visual field. For grammatical items, there were no reliable differences between central and RVF presentation, although the low salience condition showed a trend (p = .066) for responses to be less accurate for RVF presentation. For ungrammatical items, there were no reliable differences between central and RVF presentation with the exception of the high salience condition which showed a large drop in accuracy with RVF presentation (central: 98.4%; RVF: 88.6%).

For LVF compared to central presentation, LVF was reliably less accurate than central presentation for both grammatical and ungrammatical conditions, for each of the three verb types. For grammatical items, the drop in accuracy, although reliable, was fairly small - average accuracy with LVF presentation was still over 90% for each of the three verb types. The drop in accuracy between central and LVF presentation was larger for ungrammatical items, but was about the same size across all three verb types: 14.0% for regular verbs; 15.6% for high salience verbs, and 16.9% for low salience verbs. For LVF compared to RVF presentation, RVF was reliably more accurate for both grammatical and ungrammatical conditions for all three verb types.

The results for response times showed a similar pattern to that observed for accuracy, although response times were reliably faster for central compared to RVF presentation for each verb type, in both grammatical and ungrammatical conditions.

(As mentioned in the Results, the lack of a reliable difference in accuracy in any two-way comparison between central and RVF presentation may have been due to a ceiling effect.) Additionally, in the high salience/ungrammatical condition, the difference between response times for LVF and RVF presentation was marginal (p = .070).

5.5.1. Implications for regular/irregular debate

The overall pattern we observed does not suggest there is a difference in processing speed or accuracy between regular and irregular verbs, and argues against the view that processing of the two types of verbs differs in any qualitative manner. Instead, the data from the two-way comparisons showed a fairly consistent pattern of responses, with the regular verb condition being faster (reliable differences included: grammatical: RVF, central; ungrammatical central, LVF; trend for RVF) and more accurate (reliable differences included: grammatical: RVF, LVF; ungrammatical: RVF, central, LVF) than responses in the low salience condition. In contrast, differences between the regular and high salience conditions were generally not reliable (exceptions: accuracy, RVF/ungrammatical; response times: RVF/grammatical, central/grammatical).

5.5.2. Relative hemispheric specialization for spatial frequencies

Recall that in the introduction, we argued that our previous results (Kemmer et al., 2009) may have been due to differences across the hemispheres in relative specialization for various spatial frequencies. Accordingly, if the right hemisphere is more specialized for lower frequencies, it should have more difficulty with detecting the violation in the low salience, compared to high salience, condition. We observed such a pattern. High salience was more accurate (91.5%) and responses were

faster (1,201 ms) than low salience (accuracy: 90.6%; p = .013; response time: 1,325 ms; p = .001) for ungrammatical items. The failure to find reliable differences between high and low salience for RVF presentation, coupled with the observation of reliable differences for LVF presentation, suggests that the right hemisphere is less sensitive to higher frequencies than is the left hemisphere.

In addition, the regular condition is generally reliably faster and more accurate (or shows a trend toward this) than the low salience condition in LVF. This is consistent with the hypothesis that the right hemisphere is less sensitive to higher frequencies. Recall that we argued that detecting the violation in the low salience condition is more difficult because violations vs. controls differ by one letter, whereas in the high salience condition, the difference is two or more letters. The same argument can be made for the regular vs. low salience comparisons. In the regular condition, there are always two letters different between violations and controls (violations are missing the –ed at the end of the verb which forms the participle, e.g., exhibit vs. exhibited).

Lending additional support to this argument is the fact that for LVF presentation, comparisons between the high salience and regular verb conditions were not reliable. The high salience condition averages out to somewhat more than two letters different between violations and controls, compared to the regular condition having just two letters different . Why, then, are no reliable differences observed in LVF? One possibility is that in this experiment, the right hemisphere was able to detect violations since the difference from controls was two contiguous letters. Additionally, for the regular condition, the violation is consistent across all verbs: -ed is absent from the end of the word. In contrast, the violation in the high

salience condition may occur in various positions in the word: word-internal (wind vs. wound; stand vs. stood) or involve more complicated differences (tear vs. torn). The consistency in the violation in the regular condition may facilitate detecting it because strategizing (for example, directing attention to the end of the word) has a greater expected pay-off than it does in the high salience condition.

These findings provide converging evidence with our previous finding (Kemmer et al., 2009) that increased critical word duration produced greater performance gains for LVF than RVF presentation for our subject/verb condition (lower salience) compared to the reflexive condition (higher salience). Additionally, the results from that study suggested that a shorter critical word duration created greater processing difficulties overall for the subject/verb condition. The manipulation of critical word duration was a sort of manipulation of salience of the critical word, thus our results from the present experiment and the two behavioral experiments presented in Kemmer et al. converge.

5.6. Experiment 2

Experiment 2 used the same stimuli that were used in experiment 1, but ERPs were recorded, allowing us to view the brain's ongoing electrical response online as participants read sentences. The experimental procedure was very similar to experiment 1; differences are noted below.

5.7. Methods

5.7.1. Design

The design for experiment 2 was a 3 x 2 x 2 within-subject design. The factors included verb type (regular, high salience/irregular, low salience/irregular),

grammaticality (grammatical, ungrammatical), and visual field (left, right). The dependent variables were ERPs and accuracy data.

5.7.2. Materials

Stimuli used in the lateralized ERP experiment were identical to the stimuli used in the previously-described behavioral experiment. Lists were created somewhat differently critical words in the ERP experiment were created only to LVF or RVF.

A total of eight experimental lists were created with Grammaticality, Visual Field, and Sentence Type completely counterbalanced across the lists. For each experimental condition, 30 verbs were used; each verb occurred in four different sentences frames, twice grammatical and twice ungrammatical (two had singular subjects; two had plural subjects). A participant viewed only one list; each sentence frame occurred once in each list. Within a list, each experimental verb was presented twice (in different sentence frames) to the same visual field, once in a grammatical sentence and once in an ungrammatical sentence, with this pair having the same grammatical number (both either singular or plural). A given list included for each sentence either the violation, or its grammatical counterpart, never both.

Lists were created in the following manner. Using a computer algorithm, the list of verbs for each sentence type were first placed in random order. A "base" list was created as follows: For each set of four sentence frames for a verb, the two singular sentences were randomly assigned to one of visual field (with one of these two randomly assigned to be grammatical and the other - ungrammatical); the two plural sentences were then assigned to the other visual field (with one sentence randomly assigned to be grammatical and the other – ungrammatical); assignment

of the singular and plural sentences to each visual field was done such that equal numbers of singular and plural sentences were assigned to each visual field. From this "base" list, a second ("mirror") list was created which reversed grammaticality: sentences that were grammatical in the first list were ungrammatical in the second list and vice versa. Two additional ("reverse") lists were then created in which visual field was counterbalanced. This process created four lists. To completely counterbalance the pairings of the four sentence frames with respect to grammatical number and grammaticality, another "opposite" list was created from the "base" list in which the grammaticality assignment for the two plural sentence frames was reversed. From this list, a "mirror" list, and two "reverse" lists were created, in the manner described above. This process created an additional four lists. Across all eight lists, grammaticality, visual field, and grammatical number were completely counterbalanced.

The 546 sentences of each list were then ordered randomly using a computer algorithm. For each presentation condition (LVF, RVF), each list included 30 grammatical regular verbs, 30 violation regular verbs; 30 grammatical high salience verbs, 30 violation high salience verbs; 30 grammatical low salience verbs, 30 violation low salience verbs; 30 grammatical subject-verb agreement (filler), 30 violation subject-verb agreement (filler); 15 or 16 grammatical filler, and 15 or 16 violation filler sentences (for a total of 33 filler sentences in each list). Each participant viewed only one list.

5.7.3. Participants

Twenty-six UCSD undergraduate students participated in the experiment for course credit or pay (14 were women; ages ranged from 18 to 22; average age was

19.5 years). All subjects provided health and medical information, including history

of psychiatric disorders, drug use, neurological disease, medications currently being

taken, vision, and others; subjects were excluded from experiment participation as

appropriate. All subjects were monolingual, right-handed (assessed using the

Edinburgh Inventory, Oldfield, 1971), and had normal or corrected-to-normal vision.

5.7.4. Experimental procedures

With the exception of the details noted here, the experimental procedure was

identical to that for experiment 1, including procedures for familiarizing participants

with stimulus presentation, the inclusion of comprehension sentences, and

presentation of experimental sentences.

Participants were tested in a single experimental sessions lasting about 4.0

hours. Participants were seated 40 in. in front of a monitor in a sound-proof,

electrically shielded recording chamber. Experimental and filler sentences were

presented one word at a time every half second for a duration of 200 ms; all words

of these sentences were presented in a black font. The critical verb in each

sentence was presented to either left or right visual field; the remaining words of the

sentence were presented centrally.

Before each sentence a fixation cross appeared for 900 ms, followed by a

random interval between 617 and 1,017 ms in duration. Additionally, a small central

fixation dot, positioned approximately 0.25 degrees below the bottom edge of words,

remained on the screen permanently, to facilitate correct fixation. Participants were

instructed to read each sentence for comprehension, fixate the fixation point until

after the sentence ended, and to attempt not to blink or move during this period.

Participants also were asked to make an acceptability judgment at the end of every

sentence: After the final word of a sentence disappeared, participants were to indicate as quickly and as accurately as possible whether or not the sentence was well-formed.

5.7.5. Recording procedures

The electroencephalogram (EEG) was recorded from 26 tin electrodes, embedded in an electrode cap, each referenced to the left mastoid. Right mastoid was recorded as well; ERP averages were re-referenced offline to the average of activity recorded at the right and left mastoids. Scalp recording sites included: Prefrontal: left lateral (LLPf), left medial (LMPf), midline (MiPf), right medial (RMPf), right lateral (RLPf); Frontal: left lateral (LLFr), left mediolateral (LDFr), left medial (LMFr), right medial (RMFr), right mediolateral (RDFr), right lateral (RLFr); Central: left mediolateral (LDCe), left medial (LMCe), midline (MiCe), right medial (RMCe), right mediolateral (RDCe); Parietal: left mediolateral (LDPa), midline (MiPa), right mediolateral (RDPa); Temporal: left lateral (LLTe), right lateral (RLTe); Occipital: left lateral (LLOc), left medial (LMOc), midline (MiOc), right medial (RMOc), right lateral (RLOc). Lateral eye movements were monitored via electrodes placed at the outer canthus of each eye in a bipolar montage. An electrode was placed on the infraorbital ridge of the right eye and referenced to the left mastoid to monitor blinks. Electrical impedances were kept below 2.5 KΩ. The data were sampled at 250 Hz. The EEG and electrooculogram (EOG) were amplified by Nicolet amplifiers set at a bandpass of 0.016 to 100 Hz.

5.7.6. ERP data analysis

Prior to analysis, data were examined for artifacts such as eye movements, blinks, amplifier blocking, and excessive muscle activity; 7.8% of the grammatical

trials (6.9% for regular verbs/LVF; 8.2% for regular verbs/RVF; 8.0% for high salience/LVF; 9.1% for high salience/RVF; 5.8% for low salience/LVF; 8.8% for low salience/RVF) and 7.9% of the ungrammatical trials (9.0% for regular verbs/LVF; 7.3% for regular verbs/RVF; 6.7% for high salience/LVF; 9.5% for high salience/RVF; 7.0% for low salience/LVF; 7.9% for low salience/RVF) were rejected. ERP averages were re-referenced offline to the average of activity recorded at the right and left mastoids. ERPs were timelocked to the onset of the target words and a 200 ms prestimulus baseline was used for all analyses; artifact rejection tests were conducted out to 1,500 ms post-stimulus onset. Only sentences for which the participant made the correct grammaticality response were included in averages.

We quantified the P600 effect by measuring the mean amplitude for the 600 to 1,100 ms latency window, synchronized to the onset of the critical word. We also analyzed the mean amplitudes for an earlier time window, 300 to 500 ms, as other investigators have reported a left anterior negativity (LAN) for this time window for some syntactic violations. After visual inspection of the ERP waveforms, we also examined, on a post-hoc basis, the 350 to 550 ms time window with high salience verbs with LVF and RVF presentation, the 300 to 700 ms time window for low salience verbs with RVF presentation, and the 400 to 600 ms time window for low salience verbs with LVF presentation. For post hoc analyses, *p* values given are uncorrected.

For the 600 to 1,100 ms time window, mean amplitudes were initially subjected to a repeated measures ANOVA with four within-subject factors including Verb Type (regular, high salience, low salience), Grammaticality (grammatical vs. ungrammatical), Visual Field (left, right), and Electrode (26 levels); this analysis is

referred to as the "full analysis". When the full analysis revealed an interaction of Electrode with Verb Type, Grammaticality, or Visual Field, a distributional analysis consisting of an ANOVA with six within-subject factors including Verb Type, Grammaticality, Visual Field, Hemisphere (left vs. right), Laterality (lateral vs. medial electrodes), and Anteriority (five levels: four prefrontal electrodes [LLPf, LMPf, RLPf, RMPf], four frontal electrodes [LLFr, LMFr, RLFr, RMFr], four central electrodes [LDTe, LMCe, RDTe, RMCe], four temporal or parietal electrodes [LLTe, LDPa, RLTe, RDPa], four occipital electrodes [LLOc, LMOc, RLOc, RMOc]) was conducted (see Figure 5.2). To better characterize the P600 effect (distributed mainly over posterior sites) in the 600 to 1,100 ms window, we conducted a modified distributional analysis which included mean amplitude measures for only posterior electrodes using the difference ERPs (computed via a point-by-point subtractions of ERPs elicited in the grammatical condition from those for the ungrammatical condition). Using the difference ERPs allowed us to cancel out the effects coming from the underlying voltage differences in the raw ERPs which varied as a function of verb type. This "posterior" distributional analysis included within-subject factors of Verb Type, Visual Field, Hemisphere, Laterality, and Anteriority (three levels: four central electrodes [LDTe, LMCe, RDTe, RMCe], four temporal or parietal electrodes [LLTe, LDPa, RLTe, RDPa], four occipital electrodes [LLOc, LMOc, RLOc, RMOc]).

For the remaining time windows analyzed, ANOVAs were performed in a similar manner although the experimental factors included in the ANOVA varied as specified below for each. Throughout this report, the phrase "posterior sites" will refer to central, temporal/parietal, and occipital electrode sites, while "anterior sites"

will refer to prefrontal and frontal sites. Grammaticality effects are measured by making a point-by-point subtraction of the ERP to the grammatical condition from the ERP to the ungrammatical condition. A "positivity" results from the ungrammatical condition being more positive than the grammatical, whereas a "negativity" results from the grammatical condition being more positive than the ungrammatical.

Our significance level was set at $p \leq .05$ and for all analyses involving more than one degree of freedom, the Geisser-Greenhouse (1959) correction for violations of sphericity was applied; uncorrected degrees of freedom but corrected p values are reported.

Early sensory components were measured as follows (collapsing across the conditions): the P1 as the average positive peak between 50 and 125 ms, the N1 as the average negative peak between 75 and 175 ms, the P2 as the average positive peak between 150 and 250 ms, and the N2 as the average negative peak between 250 and 350 ms.

5.8. Results

5.8.1. Overt behavior

As expected, participants were reliably more accurate in classifying grammatical (mean = 96.4%) than ungrammatical sentences (mean = 89.1%); main effect of Grammaticality, $F_{(1,23)}=60.49$; $p = .000$. There was also a reliable right visual field advantage as responses for responses for RVF (95.8%) were more accurate than those for LVF (89.7%), $F_{(1,23)}=68.30$; $p = .000$. These main effects were modulated by two reliable interactions. The Grammaticality x Visual Field interaction, $F_{(1,23)}=19.34$, $p = .000$, reflected the fact that while responses for RVF

were overall more accurate (grammatical: 98.1%; ungrammatical: 93.4%) than for

LVF (grammatical: 94.6%; ungrammatical: 84.9%), the drop in accuracy for

ungrammatical (compared to grammatical) was much greater for LVF than RVF

presentation. Additionally, there was a Type x Grammaticality interaction,

$F(2,46)=4.40$, $p = .018$, $\varepsilon = .98$. This interaction was due to accuracy for

grammatical items being approximately equal across the three verb types (regular:

97.0%; high salience: 95.8%; low salience: 96.3%), for ungrammatical items

(regular: 88.9%; high salience: 90.8%; low salience: 87.6%) the drop in accuracy

was greater for regular and low salience conditions compared to high salience.

5.8.2. Comprehension probes

The overall high accuracy rate (95%) on comprehension probes indicated

that participants were attending to and comprehending the experimental sentences

they were reading.

5.8.3. ERPs

5.8.3.1. Early visual potentials

As is typical for ERPs to visually presented words, in all conditions we

observed a P1 component peaking at around 91 ms, an N1 component peaking at

around 113 ms (both for measurements including only anterior sites and only

posterior sites), a P2 component peaking at around 169 ms, and an N2 peaking at

around 308 ms. For each component, we also conducted a full analysis on the peak

latency in the relevant time window. For the N1 over anterior sites, there was a

main effect of Grammaticality, $F(1,23) = 4.72$, $p = .040$ (grammatical: 114.9 ms;

ungrammatical: 113.5 ms). To investigate the source of this main effect, we ran

ANOVAs for each verb type individually; none of these analyses showed any

reliable main effect or interaction with Grammaticality (the high salience condition did show a trend towards significance, p = .101). Additionally, for the P2, there was a main effect of verb type, $F(2,46)$ = 4.95, p = .011 (regular: 167.1 ms; high salience, 168.8 ms; low salience:170.6 ms). Post-hoc two-way comparisons across verb type showed that the difference in peak latencies between regular and low salience verbs was reliable, main effect of Verb Type, $F(1,23)$ = 9.29, p = .006; there was also a trend towards significance for the difference between regular and high salience verbs (p = .131) and for the difference between high and low salience verbs (p = .118).

With visual half-field presentation, lateralized stimuli should produce a larger amplitude N1 over the hemisphere contralateral to visual field of presentation, particularly at temporal/parietal and occipital sites. To assess whether this was the case, we conducted a modified distributional analysis (including two levels in the anterior to posterior direction: temporal/parietal and occipital) for the mean amplitude in the 75 to 175 ms (N1) time window. This analysis revealed a significant Visual Field x Hemisphere interaction, $F(1,23)$ = 53.79, p = .000, with LVF presentation eliciting a larger amplitude N1 over right hemisphere (RH) sites and RVF presentation eliciting a larger N1 amplitude over left hemisphere (LH) sites. This result confirms that presentation of stimuli was successfully lateralized and initially went to only the contralateral hemisphere (see Figure 5.3).

5.8.3.2. ERP effects following sensory components

Grand average ERPs elicited by grammatical and ungrammatical critical words in the regular verb condition, for both RVF and LVF presentation (N=24) are shown in Figure 5.4 for a representative subset of electrodes. Figure 5.5 shows the

corresponding grand average ERPs for the high salience/irregular verb condition, while Figure 5.6 shows the same for the low salience/irregular verb condition. Figure 5.7 shows the difference ERPs (point-by-point subtraction of the ERP to the grammatical condition from the ERP to the ungrammatical condition) for LVF and RVF presentation for the regular verbs; Figure 5.8 and Figure 5.9 show the same for high and low salience verbs, respectively. Figure 5.10 shows the difference ERPs elicited by lateralized presentation overlaid with those elicited by central presentation (results for central presentation are reported in chapter 4) for each verb type for a representative subset of electrodes.

Following the early sensory components, violations elicited a P600 component over both hemispheres, regardless of visual field of presentation and regardless of whether the participles were regular or irregular: verbs rendering the sentence ungrammatical were more positive-going over centro-parietal sites than were equivalent words in the grammatical sentences, beginning at about 600 ms and lasting until at least 1,100 ms at posterior sites. For LVF presentation, there were no reliable differences in mean amplitude (600 to 1,1100 ms time window) of the P600 (visual inspection suggests the P600 is slightly larger for regular verbs with no difference between high and low salience verbs). In contrast, for RVF presentation, the P600 for low salience and regular verbs were more similar and for both, the P600 was reliably larger than for high salience verbs. We analyzed the P600 using mean amplitude measures for a longer time window (600 to 1,100 ms) than is typical in the literature (we also conducted analyses for the 600 to 900 ms time window; results for this shorter time window were very similar to those for the 600 to 1,100 ms time window). We did not observe an earlier onset positivity at

prefrontal sites (as we had observed with central presentation of these stimuli; see chapter 4 of this dissertation).

We did not observe a negativity in the LAN time window (300 to 500 ms) for either LVF or RVF presentation of regular verbs. LVF presentation of regular verbs did, however, elicit a small, broadly-distributed positivity, in this time window, slightly larger at medial than lateral sites for temporal/parietal and occipital electrodes (slightly larger over LH), and slightly larger at lateral than medial sites for prefrontal and frontal sites (slightly larger over right hemisphere).

We also observed negativities preceding the P600 for both RVF and LVF presentation of both low and high salience verbs. These negativities had different scalp distributions and time courses, however. The negativity for RVF presentation of high salience verbs is similar to an N400 in terms of its distribution, timing, and duration. This negativity is of fairly short duration, beginning at about 350 ms and lasting only about 200 ms, larger over medial than lateral sites, and is largest over central sites but extends to occipital and frontal sites. LVF presentation of high salience verbs yielded a much smaller amplitude negativity, but its distribution differed from that seen for RVF presentation – over anterior sites, it was most prominent medially; the negativity was smaller over posterior sites and most prominent over lateral sites.

The negativity for RVF presentation of low salience verbs represents the earliest effect of grammaticality across the three verb types: violations are characterized by a negativity at anterior sites, most pronounced at left prefrontal sites, beginning at about 300 ms, but extending to left frontal sites. This negativity extends to at least 1,000 ms post-stimulus over prefrontal sites; duration is much

shorter for frontal sites. LVF presentation of low salience verbs yielded a much

smaller anterior negativity of much shorter duration (between approximately 400 and

600 ms post-stimulus). This negativity was larger for medial than lateral sites for

prefrontal, frontal, and central sites (being most prominent at frontal), while for

temporal/parietal and occipital sites, it was more prominent at lateral sites.

5.8.3.3. Analyses of mean amplitude: 600 to 1,100 ms (P600)

The distributional analysis for the 600 to 1,100 ms time window showed that

ungrammatical items (3.57 μV) were reliably more positive than grammatical items

(2.72 μV), main effect of Grammaticality, $F(1,23) = 8.54$, $p = .008$. The main effect

of Verb Type was also reliable, $F(2,46) = 15.63$, $p = .000$, $\varepsilon = .96$ (regular: 3.69 μV;

high salience: 2.77 μV; low salience: 2.96 μV), as was the main effect of Visual

Field, $F(1,23) = 4.56$, $p = .044$ (LVF: 2.97 μV; RVF: 3.31 μV). The six-way

interaction of Verb Type x Grammaticality x Visual Field x Hemisphere x Laterality x

Anteriority was reliable, $F(8,184) = 3.35$, $p = .007$, $\varepsilon = .63$, as were multiple lower-

order interactions.

This six-way interaction was due in part to the underlying voltage differences

across the verb types in the raw ERPs, as well as the various negativities observed

over anterior electrodes. Thus, in order to focus on just the P600 effect which is

most prominent over posterior electrodes, we conducted an analysis of the

difference ERPs which included just posterior electrodes.[4]

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[4] We did observe a reliable Visual Field x Hemisphere x Laterality x Anteriority interaction, $F(4,92) = 24.21$, $p = .000$, $\varepsilon = .43$, for the 600 to 1,100 ms time window which in part, was due to the fact that with LVF presentation, LH sites(both lateral and medial) were overall more positive than RH sites. For RVF presentation, for lateral, RH sites were more positive than LH, whereas for medial, LH and RH sites showed about the same mean amplitude

5.8.3.4. Analyses of mean amplitude: 600 to 1,100 ms, posterior electrodes only (P600)

For the posterior-only distributional analysis on the difference ERPs, there were no reliable main effects; however, two interactions were reliable. The Verb Type x Visual Field x Hemisphere interaction, $F(2,46) = 3.76$, $p = .031$, $\varepsilon = .98$, reflected differences in the distribution of the P600 effect across the hemispheres as a function of visual field. For high salience verbs, for both LVF and RVF presentation, the P600 effect was bisymmetrically distributed across the two hemispheres (LVF: LH, 0.50 μV; RH, 0.58 μV; RVF: LH, 0.22 μV; RH, 0.18 μV). For the low salience verbs, LVF presentation resulted in a similarly bisymmetrical distribution (LVF: LH, 0.56 μV; RH, 0.48 μV), whereas RVF presentation elicited a P600 larger over RH than LH sites (RVF: LH, 0.41 μV; RH, 0.75 μV). For the regular verbs, both LVF and RVF presentation elicited a P600 effect which was larger over RH, but the asymmetry was more pronounced for LVF presentation (LVF: LH, 0.55 μV; RH, 0.78 μV; RVF: LH, 0.71 μV; RH, 0.83 μV).

The Visual Field x Laterality x Anteriority interaction, $F(2,46) = 5.63$, $p = .007$, $\varepsilon = .78$, reflected the fact that the P600 effect was more pronounced at medial than lateral sites, and largest at occipital sites. However, the difference in the size of the P600 across medial and lateral sites was slightly larger for LVF than RVF presentation.

(except at occipital sites, where RH sites were more positive than LH). This appears to be the negativity which Coulson and Severens (2007) have argued "signals attentional selection of the stimulus for further processing" (p. 177) and reflects that one hemisphere is more involved in processing than the other.

5.8.3.5. Analyses of mean amplitude: 600 to 1,100 ms (P600), baseline: -200 to 450 ms, posterior electrodes only

Visual inspection of the ERP waveforms suggested that measurement of mean amplitude for the P600 effect elicited by RVF presentation of high salience verbs was affected by the N400-like negativity which precedes the P600 in this condition. Thus, we also ran analyses for the 600 to 1,100 ms time window on mean amplitude measures using a baseline extending from 200 ms prestimulus to 450 ms post-stimulus. As we were primarily interested in the P600 grammaticality effect, we used mean amplitude values based on difference ERPs. This analysis showed no reliable main effects, but three interactions were reliable[5].

The Verb Type x Visual Field x Hemisphere interaction, $F(2,46) = 6.37$, $p = .004$, $\varepsilon = .93$, reflects slightly different distributions of the P600 across the hemispheres as a function of visual field and verb type. For regular verbs, both RVF and LVF presentation resulted in the P600 being larger over RH than LH sites, but LVF presentation resulted in a slightly greater asymmetry. For high salience verbs, LVF and RVF presentation both resulted in a bisymmetrical P600 distribution across the hemispheres. Finally, for low salience verbs, LVF presentation resulted in the P600 effect being slightly larger over LH than RH sites, while RVF presentation resulted in a P600 effect that was slightly larger over RH than LH sites, with the asymmetry slightly larger for RVF presentation. This interaction was modulated by a reliable Verb Type x Visual Field x Hemisphere x

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[5] We also measured peak-to-peak amplitude for high salience verbs in the 600 to 1200 ms time window for the difference ERPs, using our standard baseline (200 ms prestimulus to 0 ms (stimulus onset)). Only one electrode, LDCe ($p = .029$), showed a difference in peak-to-peak amplitude as a function of visual field of presentation; this difference would not be reliable after correction for the post hoc analysis.

Anteriority interaction, $F(4,92) = 2.97$, $p = .037$, $\varepsilon = .78$, reflecting the fact that the

P600 effect was largest over occipital sites for all verb types and for both LVF and

RVF presentation.

Finally, the Verb Type x Hemisphere x Laterality x Anteriority interaction,

$F(4,92) = 2.70$, $p = .036$, $\varepsilon = .89$, was reliable. For regular verbs, the P600 is larger

over RH than LH and larger over medial than lateral sites, but the difference across

the hemispheres is larger at lateral sites and small at medial sites, with essentially

no difference at central medial sites. For high salience verbs, the P600 effect is

larger at medial than lateral sites, but is bisymmetric over LH and RH sites. For low

salience verbs, the effect is also larger over medial than lateral sites. However,

comparing across the hemispheres shows that for medial sites, there is no

difference between RH and LH sites, whereas for lateral sites, the P600 effect is

slightly larger at RH than LH sites.

5.8.3.6. Analyses (post-hoc) of mean amplitude: 600 to 1,100 ms (P600),

baseline: -200 to 450 ms, posterior electrodes only, high salience only

A distributional analysis including only high salience verbs was also

conducted on the mean amplitude for the 600 to 1,100 ms time window, posterior

electrodes only, with the modified baseline (extending from 200 ms prestimulus to

450 ms post-stimulus; see Figure 5.11). There were no reliable main effects or

interactions; however, there was a marginal interaction of Visual Field x Laterality x

Anteriority, $F(2,46) = 2.85$, $p = .069$, $\varepsilon = .949$. The overall size of the P600 is slightly

larger for LVF than RVF presentation. Additionally, for both LVF and RVF

presentation, the P600 is larger at medial than lateral sites and largest at occipital

sites (exception: for LVF lateral sites, the P600 is the same size at central and

occipital). With LVF presentation, however, the difference between lateral and medial sites is slightly larger than is the case for RVF.

5.8.3.7. Analyses of mean amplitude, 2-way comparisons between verb types, 600 to 1,100 ms (P600), baseline: -200 to 450 ms, posterior electrodes only, difference ERPs

To determine whether the P600 differed for the mean amplitude between 600 and 1,100 ms as a function of verb type for each visual field, we conducted two-way comparisons between the verb types using the difference ERPs. Comparisons between regular and low salience verbs were not reliable for either LVF or RVF presentation using our normal baseline (200 ms prestimulus to stimulus onset). There were, however, reliable interactions for comparisons of regular versus high salience verbs (as well as a trend for Verb Type to be reliable for RVF presentation). However, in order to rule out any effect of the negativity preceding the P600 for RVF presentation of high salience verbs (discussed above), we also ran these statistical analyses using a modified baseline of 200 ms prestimulus to 450 ms post-stimulus.

For comparison of regular vs. high salience verbs with RVF presentation, the main effect of Verb Type just reached significance, $F(1,23) = 4.21$, $p = .052$: mean amplitude was larger for regular than high salience verbs (regular: 0.750 μV; high salience: 0.346 μV). Additionally, the Verb Type x Laterality interaction was reliable, $F(1,23) = 4.35$, $p = .009$. The P600 was larger for the regular than high salience verbs. Additionally, for both types, the P600 was larger for medial than lateral sites; however, for regular verbs, the difference between medial (1.04 μV) than lateral (0.46 μV) was larger than was the case for the high salience verbs (lateral, 0.23 μV; medial, 0.46 μV).

For comparison of regular vs. high salience verbs with LVF presentation, Verb Type x Hemisphere x Laterality x Anteriority interaction was reliable, $F(2,46) = 4.32$ $p = .045$, $\varepsilon = .733$ (which modulated the Verb Type x Laterality x Anteriority interaction, $F(2,46) = 6.52$ $p = .003$, $\varepsilon = .994$. This interaction did not reflect an overall difference in the size of the P600 between regular (0.52 μV) and high salience (0.49 μV) verbs. Instead, it reflected very small differences in the distribution of the P600: at lateral occipital sites, it was more pronounced for regular verbs, while for lateral central and temporal/parietal sites, it was slightly more pronounced for high salience verbs. For medial sites, the P600 was slightly larger at temporal/parietal sites for regular verbs; no difference existed as a function of verb type for central and occipital sites.

Furthermore, the comparison between high and low salience verbs with RVF presentation showed a reliable Verb Type x Hemisphere interaction, $F(1,23) = 4.44$, $p = .046$. The P600 was larger overall for the low salience verbs. Moreover, for the high salience verbs, the P600 was bisymmetrical (LH: 0.38 μV; RH: 0.31 μV). In contrast, for the low salience verbs, the P600 was more pronounced over RH (0.70 μV) than LH (0.41 μV) sites.

5.8.3.8. Analyses of onset latency for P600, regular and low salience conditions

For the regular verb condition and the low salience verb condition, visual inspection of the ERP waveforms suggested there may be a difference in onset latency of the P600 for LVF and RVF presentation. To determine if there was a difference in onset latency, we analyzed the difference ERP elicited by LVF versus RVF presentation with two measures: fractional peak latency of the positivity

(measured by finding the maximum positive value in a specified time window and then determining the latency at which some percentage of this value is reached) and fractional area latency of the positivity (measured by first finding the total area of the specified polarity in the measurement window; then, beginning at the low latency and moving towards longer latencies, accumulates area of the appropriate polarity until its absolute value exceeds the fraction times the absolute value of the total area).

For the regular verb condition, we analyzed both fractional peak latency and fractional area latency at 3%, 10%, and 15% in the 600 to 1200 ms time window For none of these measures did more than one electrode reach our significance level ($p < .05$; one electrode is about what would be expected to be reliable by chance, given our significance value).[6]. For the low salience condition, there were also no reliable differences in onset between LVF and RVF presentation.

For the high salience condition, the N400-like negativity preceding the P600 with RVF presentation appears to affect the onset of the P600. However, visual inspection of a plot of the ERP difference waveforms for LVF and RVF presentation (see Figure 5.11), using a modified baseline extending from 200 ms prestimulus to 450 ms post-stimulus which minimizes the effect of the preceding negativity, do not suggest any difference in P600 onset.

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[6] We could not use an earlier latency for lower latency of the time window because of the small positivity elicited by LVF, but not RVF presentation between 300 and 500 ms.

5.8.3.9. Analysis of mean amplitude: 300 to 500 ms, LVF presentation of regular verbs

We examined the 300 to 500 ms time window to investigate a positivity (ungrammatical more positive than grammatical) seen for LVF presentation of regular verbs. Previous reports of left anterior negativities for this time window would have led us to expect (if anything) that grammatical would be more positive than ungrammatical (i.e., a negativity) for the regular verbs but this was not observed for either RVF or LVF presentation. For LVF presentation of regular verbs, between 300 and 500 ms, the main effect of Grammaticality was marginal, with ungrammatical items (2.74 μV) more positive than grammatical (2.08 μV), $F(1,23) = 4.11$, $p = .055$. Two interactions were reliable, Grammaticality x Hemisphere x Anteriority, $F(4,92) = 4.81$, $p = .004$, $\varepsilon = .79$, and Grammaticality x Laterality x Anteriority, $F(4,92) = 3.80$, $p = .007$, $\varepsilon = .55$. The Grammaticality x Hemisphere x Anteriority interaction reflects a greater positivity over RH anterior sites (prefrontal, frontal), over LH temporal/parietal sites, and little difference in the grammaticality effect (positivity) across the hemispheres for central and occipital sites. The Grammaticality x Laterality x Anteriority interaction reflects a greater grammaticality effect for medial than lateral at temporal/parietal and occipital sites, while for prefrontal, frontal, and central sites, the size of the positivity was about the same size for medial and lateral sites.

5.8.3.10. Post-hoc analysis of mean amplitude: 350 to 550 ms, RVF presentation of high salience verbs

Visual inspection of the ERP waveforms showed an N400-like negativity for the grammaticality effect between approximately 350 and 550 ms for RVF

presentation of high salience verbs. The distributional analysis showed that grammatical items (2.59 μV) were more positive than ungrammatical (1.90 μV), main effect of Grammaticality, $F(1,23) = 5.20$, $p = .032$. The grammatical effect – the negativity – was larger over medial than lateral sites and larger over posterior sites (largest at medial central sites but still large at medial frontal and occipital sites). Additionally, at lateral anterior (prefrontal, frontal) sites, the grammaticality effect was a positivity (ungrammatical more positive than grammatical), Grammaticality x Laterality x Anteriority, $F(4,92) = 2.88$, $p = .042$, $\varepsilon = .81$; Grammaticality x Laterality, $F(1,23) = 11.47$, $p = .003$; Grammaticality x Anteriority, $F(4,92) = 4.00$, $p = .027$, $\varepsilon = .41$.

5.8.3.11. Post-hoc analysis of mean amplitude: 350 to 550 ms, LVF presentation of high salience verbs

LVF presentation of high salience verbs produced a much smaller amplitude negativity with a different distribution (compared to that for RVF presentation) for the 350 to 550 ms time window. Over anterior sites, the negativity was most prominent medially, while over posterior sites, there was a smaller negativity that was most prominent over lateral sites (for medial occipital, ungrammatical was more positive than grammatical), Grammaticality x Laterality x Anteriority, $F(4,92) = 3.44$, $p = .022$, $\varepsilon = .64$.

5.8.3.12. Post-hoc analyses of mean amplitude: 400 to 600 ms, LVF presentation of low salience verbs

We observed a negativity for LVF presentation of low salience verbs: between 400 and 600 ms, grammatical items were generally more positive than ungrammatical. Statistical analysis of this time window showed a reliable interaction

of Grammaticality x Laterality x Anteriority, $F(4,92) = 4.38$, $p = .007$, $\varepsilon = .67$. This negativity was larger for medial than lateral sites for prefrontal, frontal, and central sites (being most prominent at frontal), while for temporal/parietal and occipital sites, it was more prominent at lateral sites.

5.8.3.13. Post-hoc analysis of mean amplitude: 300 to 700 ms, anterior sites only, RVF presentation of low salience verbs

We also observed a sustained negativity over anterior sites (analyzed with the mean amplitude between 300 and 700 ms) for RVF presentation of low salience verbs (over left prefrontal and left lateral frontal sites, this negativity extended beyond 700 ms). We ran a post-hoc modified "anterior-only" distributional analysis which included only two levels of anteriority, prefrontal and frontal. Grammatical items (2.78 μV) were more positive than ungrammatical (1.84 μV), main effect of Grammaticality, $F(1,23) = 4.44$, $p = .046$. The grammaticality effect – the negativity – was larger at prefrontal than frontal sites, Grammaticality x Anteriority, $F(1,23) = 7.13$, $p = .014$. Additionally, the grammaticality effect was largest over lateral LH sites and decreased in size in the rightward direction (thus, LH lateral > LH medial > RH medial > RH lateral), Grammaticality x Hemisphere x Laterality, $F(1,23) = 11.77$, $p = .002$. Additionally, at posterior sites, visual inspection of the ERP waveforms suggested that there may also be a negativity of shorter duration between 350 and 550 ms. However, a modified "posterior-only" distributional analysis (including levels of central, temporal/parietal, and occipital) for the 350 to 550 ms window showed no reliable main effects or interactions.

5.9. Discussion

In this experiment, we used ERPs to examine processing of grammatical and ungrammatical sentences requiring past participle verb forms (the critical word) presented lateralized to either LVF or RVF. We included the three categories of verbs (regular, high salience/irregular, and low salience/irregular) with the aim of differentiating between two possible explanations for our previous finding (Kemmer et al., 2009) that the two hemispheres appeared equally able to appreciate grammatical number marked lexically with reflexive pronouns (reflexive pronouns/antecedent agreement), but that for grammatical number marked morphologically on verbs (subject/verb agreement), the right hemisphere appeared to have greater difficulty than the left. Of interest was whether this difference reflected a high level, language-specific difference due to the right hemisphere having greater difficulty with morphological markings compared to lexical markings. Alternatively, the difference could reflect low-level differences in perceptual processing between the hemispheres, perhaps due to a left hemisphere superiority for resolving relatively high spatial frequencies and a right hemisphere superiority for resolving relatively lower spatial frequencies. Under this hypothesis, the right hemisphere would have greater difficulty noticing small, less salient, differences between grammatical and ungrammatical critical word stimuli (defined for the purposes of this experiment as a difference of one letter), while the right hemisphere would perform comparably better on more salient differences between critical word stimuli (defined for the purposes of this experiment as a difference of two or more letters).

5.9.1. P600

Our results showed that with both LVF and RVF presentation, for all verb types a P600 was elicited for ungrammatical compared to grammatical critical words. For RVF presentation, the P600 elicited in the high salience condition had a significantly smaller mean amplitude compared to that elicited by either the regular or low salience verb condition. The P600 did not differ reliably between regular and low salience conditions for RVF and there were no reliable difference between any of the verb types for LVF presentation. We did not observe any reliable differences in P600 onset for any verb type as a function of visual field of presentation.

This pattern of results was not expected a priori. One possible pattern we predicted for LVF presentation was that the two irregular conditions would pattern together and differ from the regular verb condition, supporting a view that the hemispheres differ at a high, language-specific level for processing these stimuli. Alternatively, we predicted that for LVF presentation, the high salience condition would differ reliably from the low salience condition and likely pattern together with the regular verb condition (for which grammatical and ungrammatical conditions differed by two letters). Instead, we observed a pattern of no reliable differences for LVF presentation between the verb types, combined with reliable differences for RVF presentation between high salience and both of the other two verb types.

Additionally, this pattern is not the identical pattern we observed in experiment 1 for behavioral responses. Recall that for RVF the regular verb condition was generally reliably faster and more accurate than the low salience condition, but the high and low salience conditions did not reliably differ. For LVF presentation, for the behavioral study, responses were again faster and more

accurate in the regular than the low salience condition, but also, for ungrammatical, high salience was faster and more accurate than low salience. There is no obvious explanation for the differences observed between experiment 1 and 2, although there is some consistency with our predictions in that high salience is reliably faster and more accurate than low salience for LVF, but not RVF. For LVF, the P600 showed no reliably differences across verb types, whereas the behavioral results did show differences, suggesting that the P600 elicited by initial presentation to the right hemisphere is less sensitive than are the behavioral measures to this kind of a salience difference.

In our previous study, we did not observe a P600 for LVF presentation in the subject/verb condition, which represented a morphological marking. If the language-specific difference (morphological vs. lexical marking) was the relevant factor, we predicted that the regular verb condition (morphological marking) would not elicit a P600 with LVF presentation. In the current study, however, a P600 was obtained. Thus, a possible conclusion could be that the differences observed were not due to language-specific differences between the hemispheres.

However, a strong conclusion here cannot be made given our data for the following reason. In the present study, we observed a P600 for the low salience/irregular RVF condition (a lexical marking). This condition was similar to the subject/verb condition in terms of salience of the violation: for both, the ungrammatical critical word differed from the grammatical by just one letter. If salience of the error was the reason for our previous results, we would have not have expected a P600 in the low salience condition with LVF presentation. Thus,

the data do not support a strong conclusion that salience was the relevant factor for our previous results, either.

One possible caveat could be that we changed the position at which critical words were lateralized. In our previous experiments, the inner edge of critical words was at 2 degrees of visual angle. We were concerned that that degree of lateralization may have made reading some critical word stimuli too difficult, as evidenced by a fairly large decrease in accuracy for the subject/verb condition in our two previous behavioral studies. We decided to move the inner edge of the critical words in the present experiment to 1.5 degrees; we felt this could be done safely, without compromising presentation to only one visual field, due to the fact that the literature suggests that at most, the middle one degree of visual field may be bilaterally represented. Additionally, as we both monitored and recorded EOG for both the behavioral and ERP experiments, this gave us another opportunity to ensure participants were fixating properly. We feel confident that stimuli were properly lateralized in our experiments. However, changing the retinal eccentricity may have changed our spatial frequency manipulation to some degree. Christman (1989) points out that increasing retinal eccentricity (along with exposure duration, as we discussed in the Introduction) has the effect of reducing the availability of higher frequencies relative to lower. In other words, the difference between the available high relative to lower frequencies likely was greater in our previous experiments, compared to our present experiment, due to our decreasing retinal eccentricity in the present experiment. However, the change we made in retinal eccentricity (0.5 degrees) was fairly small and thus, although it may have had a small effect, especially given that the retinal eccentricity in both cases was relatively

small, we do not feel that this change can fully explain the observed pattern of results for the present experiments.

5.9.2. Other ERP effects

Our stimuli elicited a number of other ERP effects which we had not predicted. We will briefly discuss each of these.

5.9.2.1. N400-like component elicited by RVF presentation in the high salience condition

We observed an N400-like component (grammatical more positive than ungrammatical) for RVF presentation in the high salience verb condition; the effect was of fairly short duration, beginning at about 350 ms and lasting about 200 ms. Its distribution was very similar to that of a classical N400: it was broadly distributed over the scalp but larger over medial sites and largest over medial central sites (but still relatively large at medial frontal and occipital sites). We also observed a similar N400-like component in Kemmer et al. (2009) for RVF presentation in the reflexive condition. As mentioned in chapter 3, the fact that we did not observe a similar N400-like component for the low salience/RVF condition weakens any explanation based in these being violations of lexical markings and reflect some kind of process related to lexical access, which could explain why we observed an N400. As mentioned in the Methods section, we carefully controlled cloze expectancy for the verb (matched across all verb conditions), thus the difference is not here. We also carefully matched verb frequencies using the Francis and Kučera (1982) norms, as well as critical word position in the sentences across verb conditions (both number of words preceding and number of words following the critical word). All critical words were followed by at least three words, thus the N400-like components we

observed do not likely reflect sentence wrap-up effects. The high salience and reflexive conditions do have in common the fact that their violations were both highly salient, although the literature does not suggest that an N400 should be elicited on this basis.

5.9.2.2. Anterior negativity (300 to 700 ms) elicited by RVF presentation of low salience verbs

The anterior negativity in the 300 to 700 ms time window (lasting beyond 700 ms over LH sites) elicited by RVF presentation of low salience verbs was observed primarily over anterior sites, larger over prefrontal than frontal, and largest over lateral LH sites (most prominent over LLPf). The distribution and onset latency of this component is consistent (to a degree) with some reports of LANs, although the LAN's distribution, onset latency, and duration are not well-defined in the literature. In Kemmer et al. (2009), we observed an anterior negativity between 400 and 800 ms for LVF presentation of the reflexive condition which is similar to the component here: it was larger over LH sites, primarily over left anterior sites, and most prominent at LLPf.

5.9.2.3. Negativity (400 to 600 ms) elicited by LVF presentation of low salience verbs

A small negativity was elicited by LVF presentation of low salience verbs in the 400 to 600 ms time window. In terms of its scalp distribution, this negativity was not similar to an N400: over posterior sites, it was more prominent laterally, while at anterior and central sites, it was more prominent medially (and largest at medial frontal sites).

5.9.2.4. Early positivity elicited by LVF presentation of regular verbs

We observed a small positivity between 300 and 500 ms for LVF presentation of regular verbs, most prominent over medial and midline sites and extending from prefrontal to occipital areas. Given the time window and proposals that the P600 may be a member of the P3b family (e.g., (Coulson, King, & Kutas, 1998). The P3b has been elicited by unexpected events as in the oddball paradigm; if one assumes that an ungrammatical items function as an "unexpected" event, one might consider the possibility that the positivity observed for LVF presentation of regular verbs might be a P3b. However, the component we observed here does not have the morphology of a P3b (the P3b generally has a clear peak while the component being discussed here does not), nor does it have the proper distribution: the P3b is generally largest parietally and in younger adults, relatively small frontally (Donchin & Heffley, 1979; Hillyard & Kutas, 1983; Polich, 2007). Exactly what cognitive function(s) are reflected by this early positive component observed for LVF presentation of regular verbs remains unclear.

5.9.3. Regular/irregular debate

A widely debated issue in the psycholinguistic literature is the representation of regular and irregular verbs in the lexicon. Are morphologically complex word forms represented as stems and affixes which are combined as needed via rules, for example, as in the dual system view (Ullman et al., 2005), or are they represented as whole word forms and a single mechanism is presumed to account for both (Rumelhart & McClelland, 1986)? For our present ERP experiment, our results showed the regular and low salience verbs patterning together with RVF presentation with respect to the mean amplitude of the P600 component, with the

mean amplitude of the P600 elicited by RVF presentation of high salience verbs being reliably smaller than both. For LVF presentation, we observed no reliable differences in mean amplitude of the P600 between verb types.

Additionally, our results from experiment 1 do not provide support for the view that there are qualitative differences in the neural representation of regular and irregular forms: In experiment 1, accuracy and response times from the regular and high salience conditions generally did not differ reliably, whereas they generally were reliably different (for RVF, central, and LVF presentation) between regular and low salience verbs.

5.9.4. Conclusion

Our results from these two experiments do not provide a clear answer to our question as to whether the results from our previous experiments were due to hemispheric differences at a high, language-specific level or due to lower level perceptual differences. The behavioral results from experiment 1 supported differences based at the perceptual level. However, the pattern of ERP results we obtained were not in accord with our predictions. Instead, for LVF presentation we observed no difference in the P600 across the verb conditions as a function of verb type. In contrast, for RVF presentation, the P600 elicited by the high salience condition had a smaller mean amplitude than was observed for the low salience and regular verb conditions, with no difference observed between these two conditions. As discussed earlier, the ERP data from the current study do not lend themselves to any clear cut conclusions with respect to the hypothesis investigated. With respect to how regular and irregular verbs are represented in the lexicon, the data from these experiments using lateralized presentation are consistent with the conclusion

made in chapter 4 (centralized presentation): we found no evidence of there being

qualitative differences between the regular and irregular verbs.

Table 5.1. Sample sentences from each condition.

Regular

Grammatical:	The modern art museum has <u>exhibited</u> these paintings before.
Ungrammatical:	*The modern art museum has <u>exhibit</u> these paintings before..

High Salience/Irregular

Grammatical:	His new theory has <u>caught</u> the attention of many scholars.
Ungrammatical:	*His new theory has <u>catch</u> the attention of many scholars.

Low Salience/Irregular

Grammatical:	That small monkey has <u>flung</u> many things at the zookeepers.
Ungrammatical:	*That small monkey has <u>fling</u> many things at the zookeepers.

Critical words are underlined in the sample sentences. An asterisk preceding a sentence conventionally indicates it is ungrammatical; asterisks were not included in experimental stimuli.

Table 5.2. Statistical results for analyses of accuracy and response time data from experiment 1.
(statistically significant results are shown in a bolded font).

Accuracy data.

Grammaticality	F(1,21) = 64.81, p=.000	Grammatical 96.2%	Ungrammatical 89.6%	
Sentence Type	F(2,42) = 13.88, p=.000	Regular 94.7%	High Salience 92.8%	Low Salience 90.4%
Visual Field	F(2,42) = 57.62, p=.000	Central 97.3%	RVF 94.3%	LVF 86.4%
	LVF vs. RVF F(1,21) = 41.64, p=.000	LVF vs. Central F(1,21) = 80.52 =, p=.000	RVF vs. Central F(1,21) = 27.33, p=.000	

Two-way comparisons for accuracy data: p values.

RVF	Reg Gr vs. Ungr p=.023	HiSal Gr vs. Ungr p=.002	LoSal Gr vs. Ungr p=.006
Central	Reg Gr vs. Ungr p=.026	HiSal Gr vs. Ungr p=.698	LoSal Gr vs. Ungr p=.002
LVF	Reg Gr vs. Ungr p=.000	HiSal Gr vs. Ungr p=.002	LoSal Gr vs. Ungr p=.000
Regular Grammatical:	Central vs. RVF p=.167	Central vs. LVF p=.004	LVF vs. RVF p=.006
Regular Ungrammatical:	Central vs. RVF p=.568	Central vs. LVF p=.000	LVF vs. RVF p=.000
High Salience Grammatical:	Central vs. RVF p=.202	Central vs. LVF p=.001	LVF vs. RVF p=.009
High Salience Ungrammatical:	Central vs. RVF p=.000	Central vs. LVF p=.000	LVF vs. RVF p=.030
Low Salience Grammatical:	Central vs. RVF p=.066	Central vs. LVF p=.005	LVF vs. RVF p=.006
Low Salience Ungrammatical:	Central vs. RVF p=.321	Central vs. LVF p=.000	LVF vs. RVF p=.000
RVF	Gr: Reg vs. HiSal p=.177	Gr: Reg vs. LoSal p=.032	Gr: HiSal vs. LoSal p=.162
Central	Gr: Reg vs. HiSal p=.105	Gr: Reg vs. LoSal p=.167	Gr: HiSal vs. LoSal p=.525
LVF	Gr: Reg vs. HiSal p=.062	Gr: Reg vs. LoSal p=.048	Gr: HiSal vs. LoSal p=.620
RVF	Ungr: Reg vs. HiSal p=.010	Ungr: Reg vs. LoSal p=.007	Ungr: HiSal vs. LoSal p=.414
Central	Ungr: Reg vs. HiSal p=.092	Ungr: Reg vs. LoSal p=.019	Ungr: HiSal vs. LoSal p=.000
LVF	Ungr: Reg vs. HiSal p=.902	Ungr: Reg vs. LoSal p=.003	Ungr: HiSal vs. LoSal p=.013

Table 6.2. (continued). Statistical results for analyses of accuracy and response time data from experiment 1.
(statistically significant results are shown in a bolded font).

Response time data

Grammaticality	F(1,21) = 36.88, **p=.000**	Grammatical 1,053 ms	Ungrammatical 1,153 ms	
Sentence Type	F(2,42) = 29.71, **p=.000**	Regular 1,062 ms	High Salience 1,097 ms	Low Salience 1,149 ms
Visual Field	F(2,46) = 57.92, **p=.000**	Central 1,019 ms	RVF 1,086 ms	LVF 1,204 ms
	LVF vs. RVF F(1,21) = 46.81, **p=.000**	LVF vs. Central F(1,21) = 89.01, **p=.000**	RVF vs. Central F(1,21) = 19.84, **p=.000**	

Two-way comparisons for response time data: _p_ values.

RVF	Reg Gr vs. Ungr **p=.000**	HiSal Gr vs. Ungr **p=.044**	LoSal Gr vs. Ungr **p=.004**
Central	Reg Gr vs. Ungr **p=.000**	HiSal Gr vs. Ungr **p=.009**	LoSal Gr vs. Ungr **p=.000**
LVF	Reg Gr vs. Ungr p=.068	HiSal Gr vs. Ungr p=.422	LoSal Gr vs. Ungr **p=.001**
Regular Grammatical:	Central vs. RVF **p=.020**	Central vs. LVF **p=.000**	LVF vs. RVF **p=.000**
Regular Ungrammatical:	Central vs. RVF **p=.002**	Central vs. LVF **p=.000**	LVF vs. RVF **p=.014**
High Salience Grammatical:	Central vs. RVF **p=.020**	Central vs. LVF **p=.000**	LVF vs. RVF **p=.000**
High Salience Ungrammatical:	Central vs. RVF **p=.045**	Central vs. LVF **p=.007**	LVF vs. RVF p=.070
Low Salience Grammatical:	Central vs. RVF **p=.018**	Central vs. LVF **p=.000**	LVF vs. RVF **p=.011**
Low Salience Ungrammatical:	Central vs. RVF **p=.005**	Central vs. LVF **p=.000**	LVF vs. RVF **p=.000**
RVF	Gr. Reg vs. HiSal **p=.007**	Gr. Reg vs. LoSal **p=.000**	Gr. HiSal vs. LoSal p=.184
Central	Gr. Reg vs. HiSal **p=.000**	Gr. Reg vs. LoSal **p=.000**	Gr. HiSal vs. LoSal p=.357
LVF	Gr. Reg vs. HiSal p=.350	Gr. Reg vs. LoSal p=.102	Gr. HiSal vs. LoSal p=.573
RVF	Ungr. Reg vs. HiSal p=1.00	Ungr. Reg vs. LoSal p=.070	Ungr. HiSal vs. LoSal p=.086
Central	Ungr. Reg vs. HiSal p=.090	Ungr. Reg vs. LoSal **p=.001**	Ungr. HiSal vs. LoSal p=.064
LVF	Ungr. Reg vs. HiSal p=.817	Ungr. Reg vs. LoSal **p=.002**	Ungr. HiSal vs. LoSal **p=.001**

Table 5.3. D-prime and natural log of beta values for accuracy data.

	d-prime	Natural log of beta
Regular		
LVF	1.7659	-0.0157
Central	1.7136	0.3137
RVF	1.7586	0.1909
High Salience		
LVF	1.9314	-0.0817
Central	2.0386	0.0602
RVF	1.6386	0.3921
Low Salience		
LVF	1.6018	-0.1327
Central	1.8027	0.5713
RVF	1.8014	0.2715

Figure 5.1.A. Accuracy data

	RVF(LH)	Central	LVF(RH)
Reg Gram	98.8%	99.6%	95.3%
Reg Ungram	95.6%	96.5%	82.6%

	RVF(LH)	Central	LVF(RH)
HiSal Gram	97.1%	98.6%	91.5%
HiSal Ungram	88.6%	98.4%	82.8%

	RVF(LH)	Central	LVF(RH)
LoSal Gram	95.4%	98.0%	90.6%
LoSal Ungram	90.5%	92.5%	75.5%
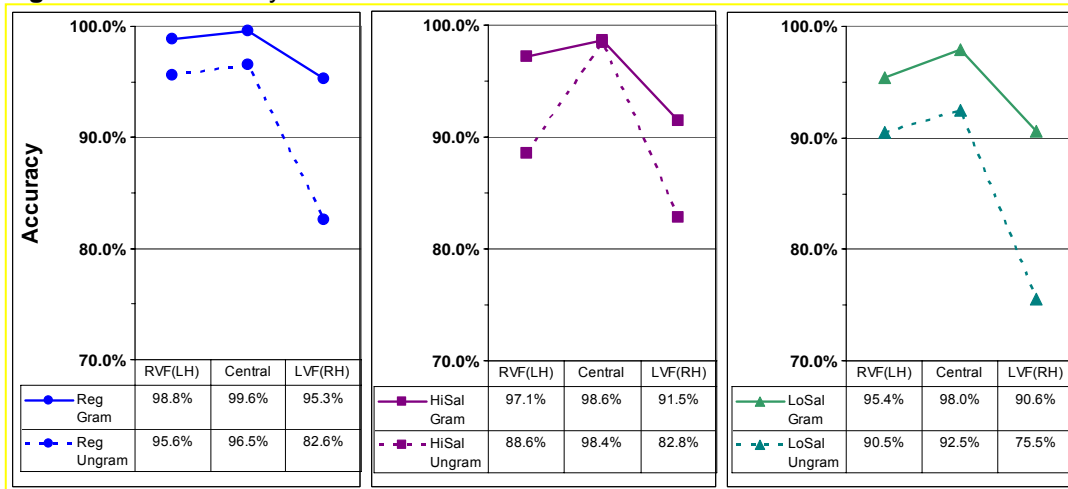
Figure 5.1.B. Response time data

	RVF(LH)	Central	LVF(RH)
Reg Gram	965	917	1137
Reg Ungram	1120	1025	1208

	RVF(LH)	Central	LVF(RH)
HiSal Gram	1044	979	1166
HiSal Ungram	1121	1072	1201

	RVF(LH)	Central	LVF(RH)
LoSal Gram	1083	999	1185
LoSal Ungram	1184	1121	1325
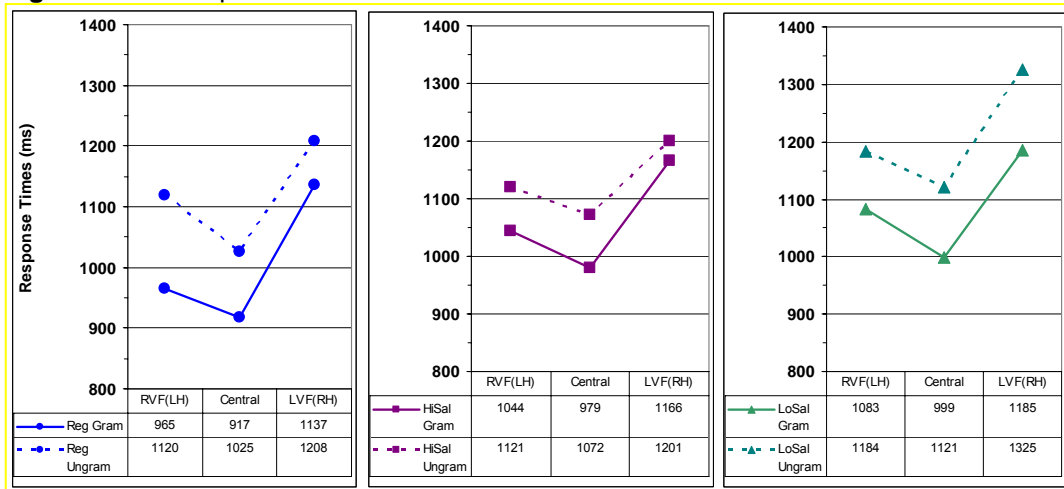
Figure 5.1. Accuracy and response time data for experiment 1. Data for the regular verb condition (column 1) are shown with a blue line, data for the high salience condition (column 2) are shown with a purple line, and data for the low salience condition (column 3) are shown with a green line. Grammatical conditions are shown with a solid line; ungrammatical with a dashed line. Figure 5.1.A shows the accuracy data; Figure 5.1.B shows response time data.
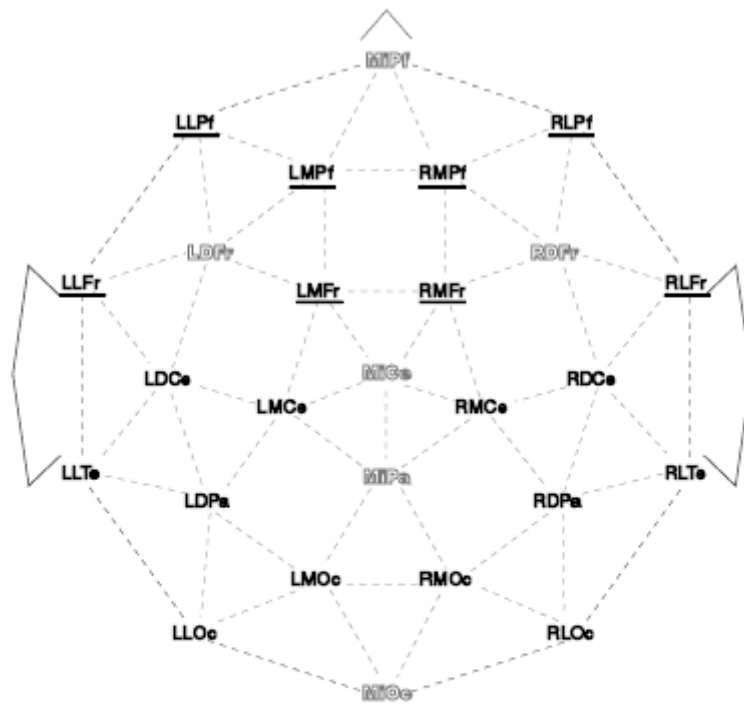
Figure 5.2. Schematic diagram of the locations of the 26 scalp electrodes, all of which were used for the full statistical analysis. The distributional analysis was restricted to the 20 electrodes with labels shown in bold print. The 8 electrodes with underlined labels were included in the "anterior only" distributional analyses; the remaining 12 electrodes with labels shown in bold print were included in the "posterior only" distributional analysis.
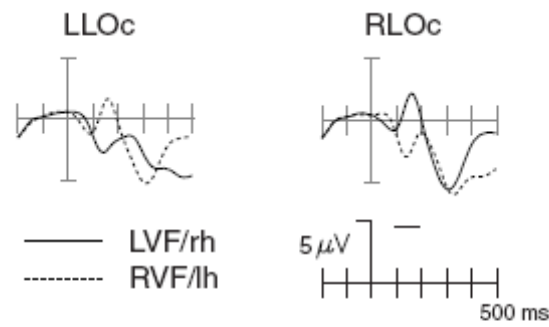
Figure 5.3 Early visual potentials elicited by presentation to the left visual field (LVF/rh; solid line) and the right visual field (RVF/lh; dashed line), collapsed across all three verb conditions at electrodes LLOc and RLOc. The first negative deflection is the N1. Stimuli presented to RVF/lh elicit an N1 which is larger over left hemisphere sites; stimuli presented to LVF/rh elicit an N1 which is larger over right hemisphere sites.

Figure 5.4. Grand average ERP waveforms elicited by violations (red line) and corresponding controls (black line) for the Regular verb condition. The earliest effect of grammaticality is seen for LVF presentation, where ungrammatical is significantly more positive than grammatical between approximately 300 and 500 ms. Subsequent to this, regardless of visual field, the response to ungrammatical items is characterized by a large positivity (600-1,100 ms) - P600 - with a posterior distribution; neither the mean amplitude nor latency of the P600 reliably differ as a function of visual field of presentation.

Figure 5.5. Grand average ERP waveforms elicited by violations (red line) and corresponding controls (black line) for the High Salience condition. The earliest effect of grammaticality is seen with RVF presentation, with the response for ungrammatical items being significantly more negative than for the grammatical items between 350-550 ms post-stimulus onset. Subsequent to this, the response to ungrammatical items elicited an enhanced positivity (relative to grammatical events) regardless of visual field of presentation. Although this P600 effect appears to be more pronounced for LVF than RVF presentations, a peak-to-peak analysis for the 600 to 1,200 ms time window (from the peak of the negativity preceding the P600 to the peak of the P600) revealed no reliable difference in the amplitude of this potential across the two visual fields.

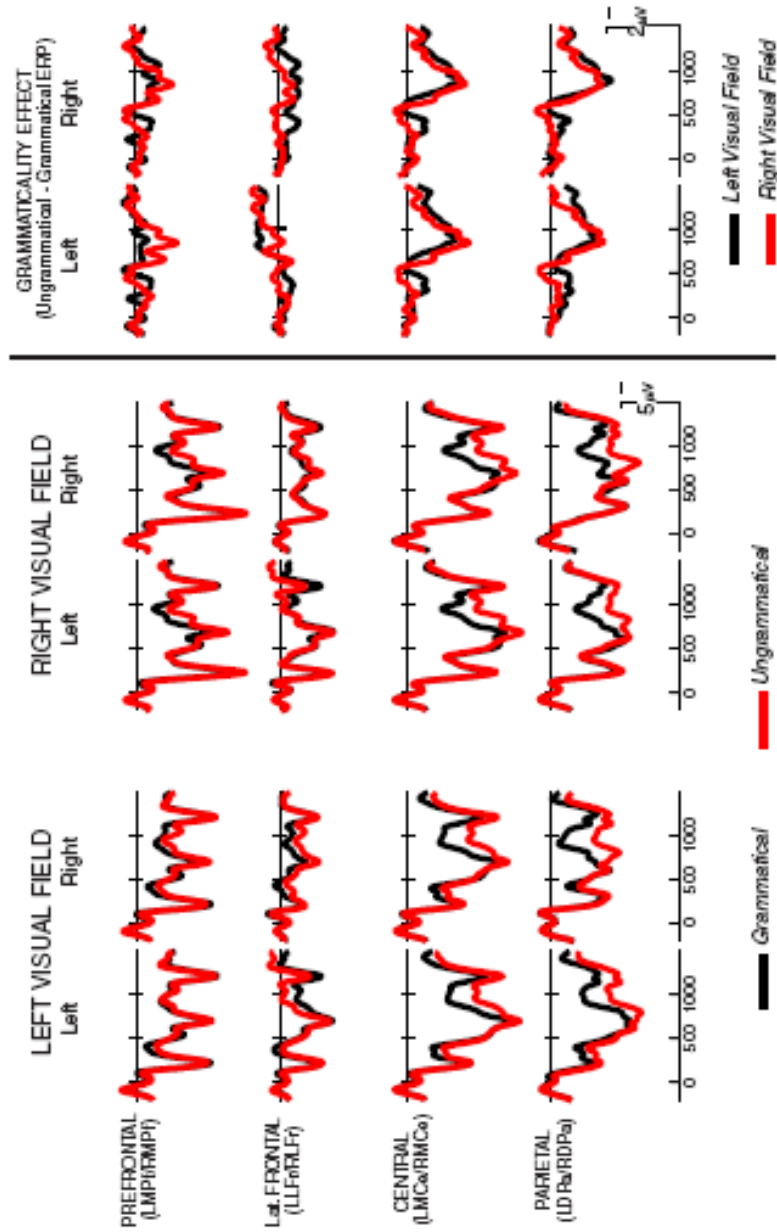Figure 5.6. Grand average ERP waveforms elicited by violations (red line) and corresponding controls (black line) for the Low Salience condition. The earliest effect of grammaticality is seen with RVF presentation, with the response for ungrammatical items being significantly more negative starting at about 300 ms over prefrontal and frontal recording sites, particularly over the left hemisphere. Thereafter, the response to ungrammatical events are characterized by a posteriorly distributed P600 with no reliable differences in mean amplitude (600 to 1,100 ms time window) or latency as a function of visual field of presentation.

REGULAR VERBS
GRAMMATICALITY EFFECT
(Ungrammatical–Grammatical ERP)

——— *Left Visual Field*   ——— *Right Visual Field*

Figure 5.7. Difference ERPs, formed by subtracting grammatical from ungrammatical ERPs, showing the P600 effect for LVF (solid line) and RVF (dotted line) presentation of Regular verbs. Noted is the absence of any LAN effect (300 to 500 ms) for presentation to either visual field. Instead, LVF presentation elicited a small, broadly distributed positivity between 300 and 500 ms

HIGH SALIENCE/IRREGULAR VERBS
GRAMMATICALITY EFFECT
(Ungrammatical—Grammatical ERP)

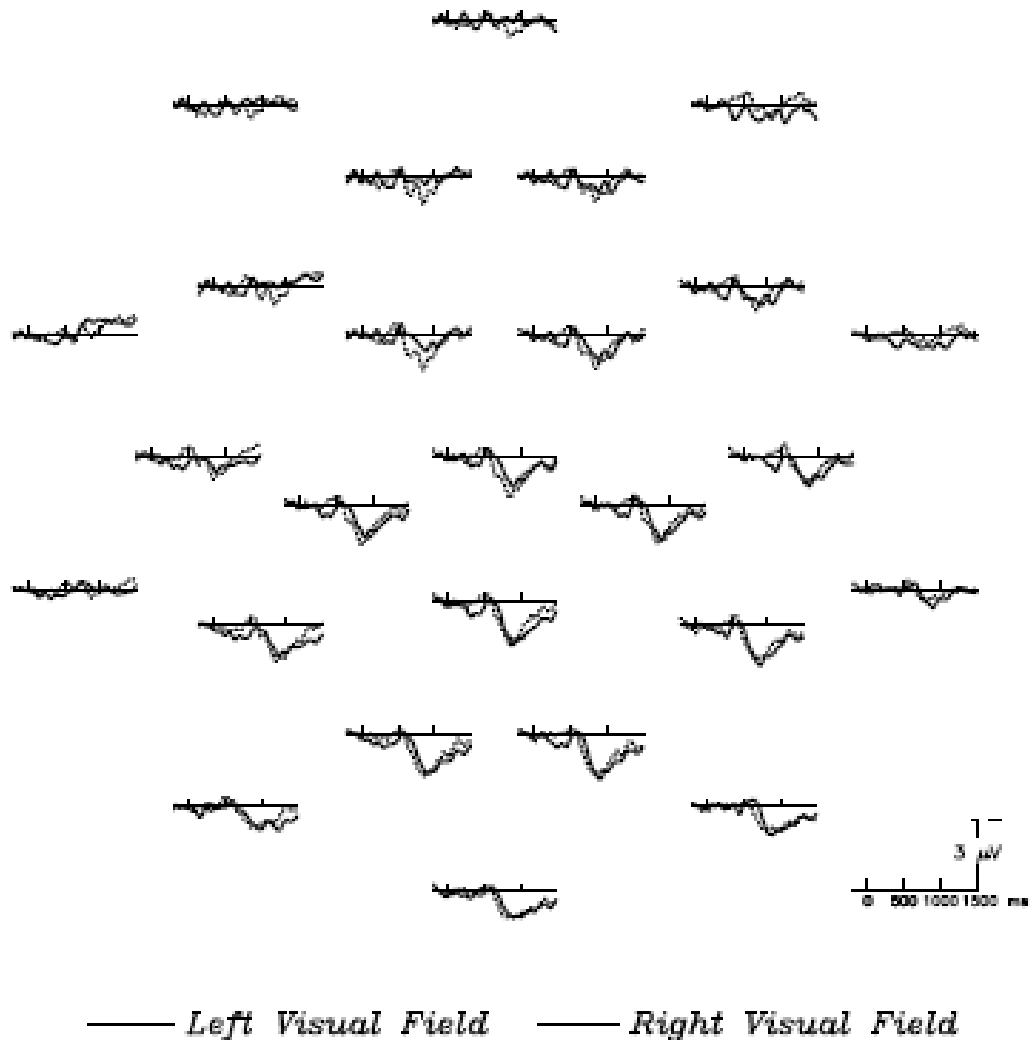——— *Left Visual Field* ——— *Right Visual Field*

Figure 5.8. Difference ERPs, formed by subtracting grammatical from ungrammatical ERPs, showing the P600 effect for LVF (solid line) and RVF (dotted line) presentation of High salience verbs. Although this P600 effect appears to be more pronounced for LVF than RVF presentations, a peak-to-peak analysis for the 600 to 1,200 ms time window (from the peak of the negativity preceding the P600 to the peak of the P600) revealed no reliable difference in the amplitude of this potential across the two visual fields. In addition, RVF presentation elicited an N400-like negativity between 350 and 550 ms. LVF presentation also yielded a smaller negativity in the 350 to 550 ms time window but its distribution over the scalp was not typical of an N400.

LOW SALIENCE/IRREGULAR VERBS GRAMMATICALITY EFFECT
(Ungrammatical—Grammatical ERP)
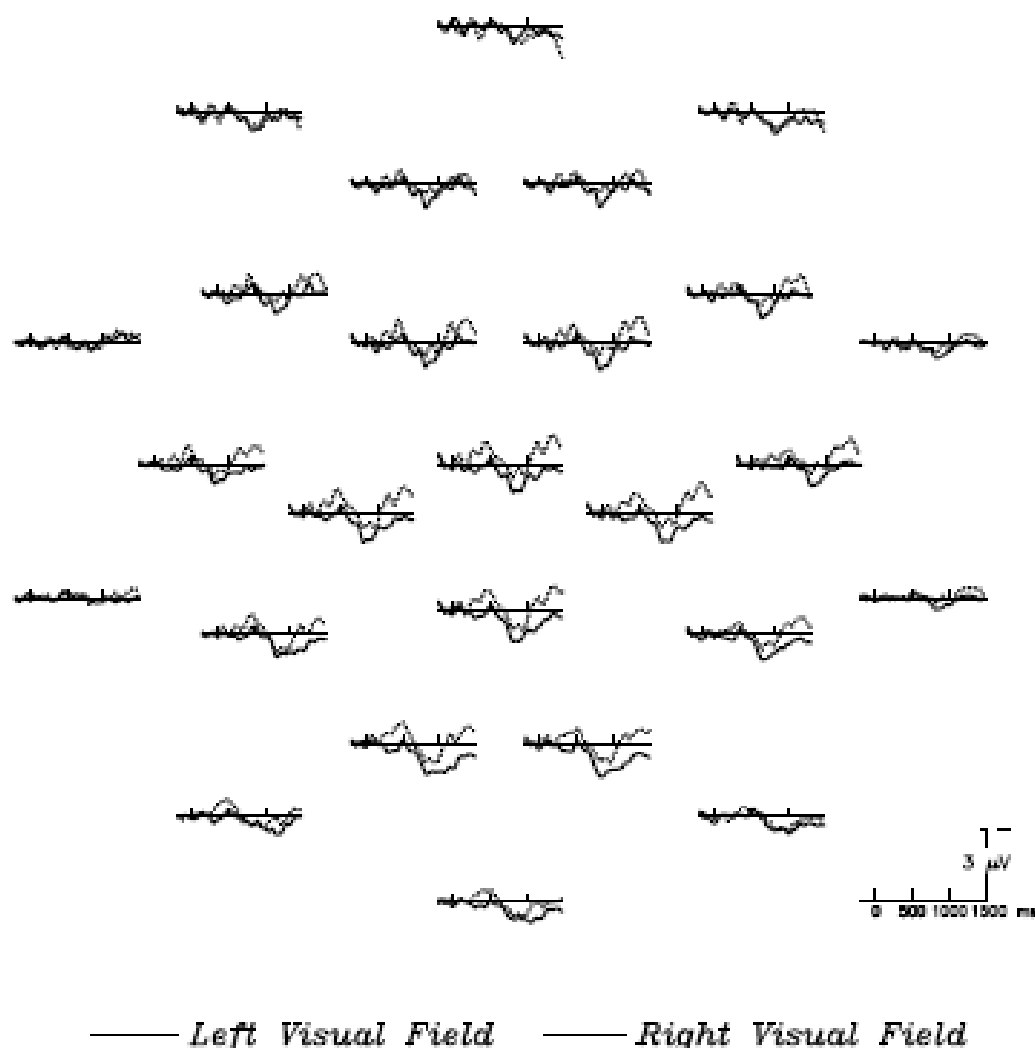
—— *Left Visual Field*   —— *Right Visual Field*

Figure 5.9. Difference ERPs, formed by subtracting grammatical from ungrammatical ERPs, showing the P600 effect for LVF (solid line) and RVF (dotted line) presentation of Low salience verbs. In addition, RVF presentation elicited an large negativity most prominent over left anterior sites between approximately 300 and 700 ms. LVF presentation yielded a much smaller, broadly distributed negativity in the 400 to 600 ms time window: at anterior sites, it was more prominent at medial sites, while at more posterior sites, it was more prominent laterally.

GRAMMATICALITY EFFECT
(Ungrammatical - Grammatical ERP)

a. *REGULAR*

b. *HIGH SALIENCE/IRREGULAR*

c. *LOW SALIENCE/IRREGULAR*

PREFRONTAL
(LMPf/RMPf)

Lat FRONTAL
(LLFr/RLFr)

CENTRAL
(LMCe/RMCe)

PARIETAL
(LDPa/RDPa)

— Central Visual Field — Left Visual Field — Right Visual Field
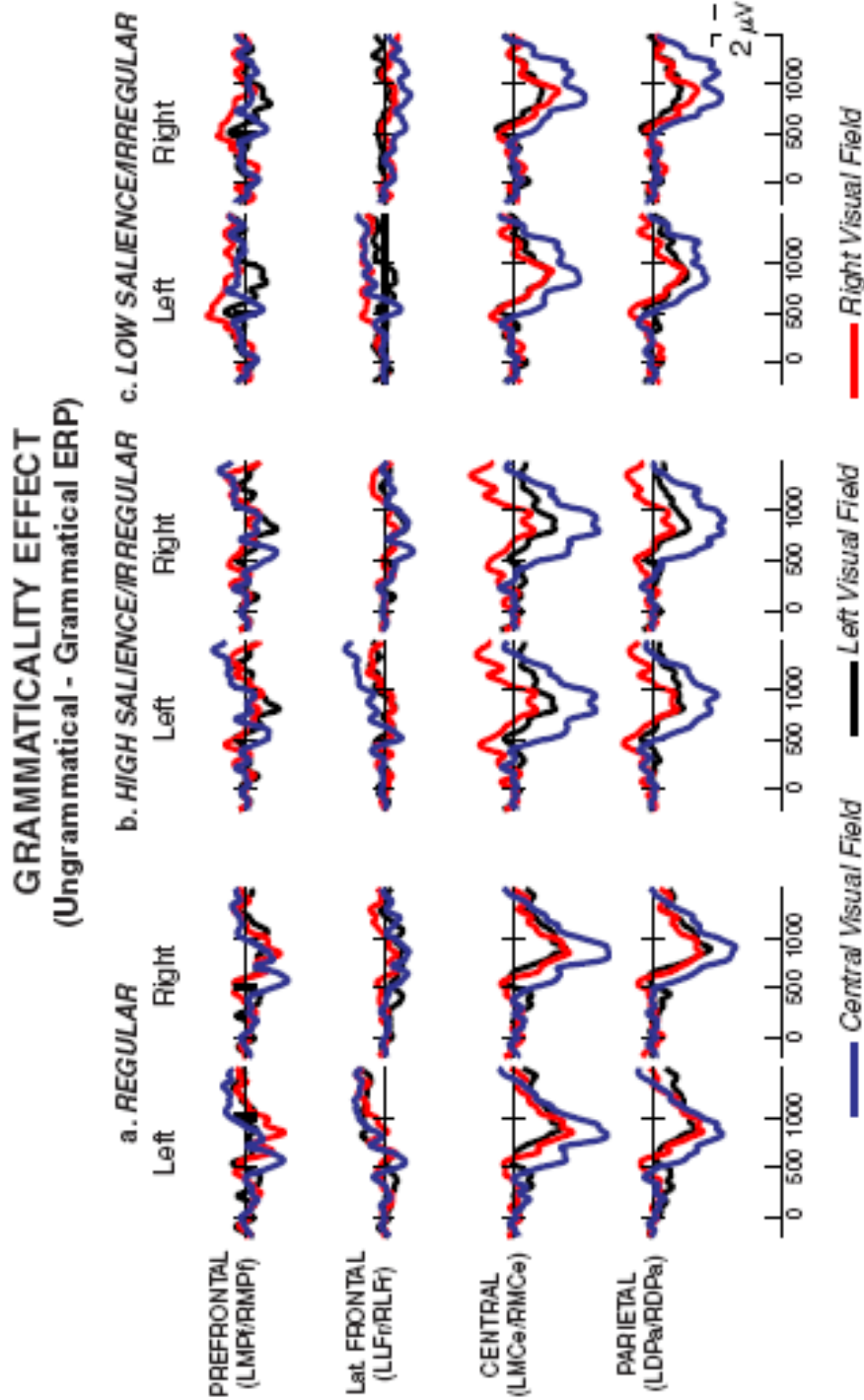
Figure 5.10. Difference ERPs for each condition formed by subtracting grammatical from ungrammatical ERPs. Difference ERPs for central presentation (blue line; reported in Chapter 4) are overlaid with difference ERPs for Experiment 2: LVF (black line) and RVF (red line) presentation (different subjects were used in experiment with central presentation). ERP wave forms in Figure 5.9a. are for the regular verb condition; Figure 5.9b., for the high salience condition, and Figure 5.9c., for the low salience condition.
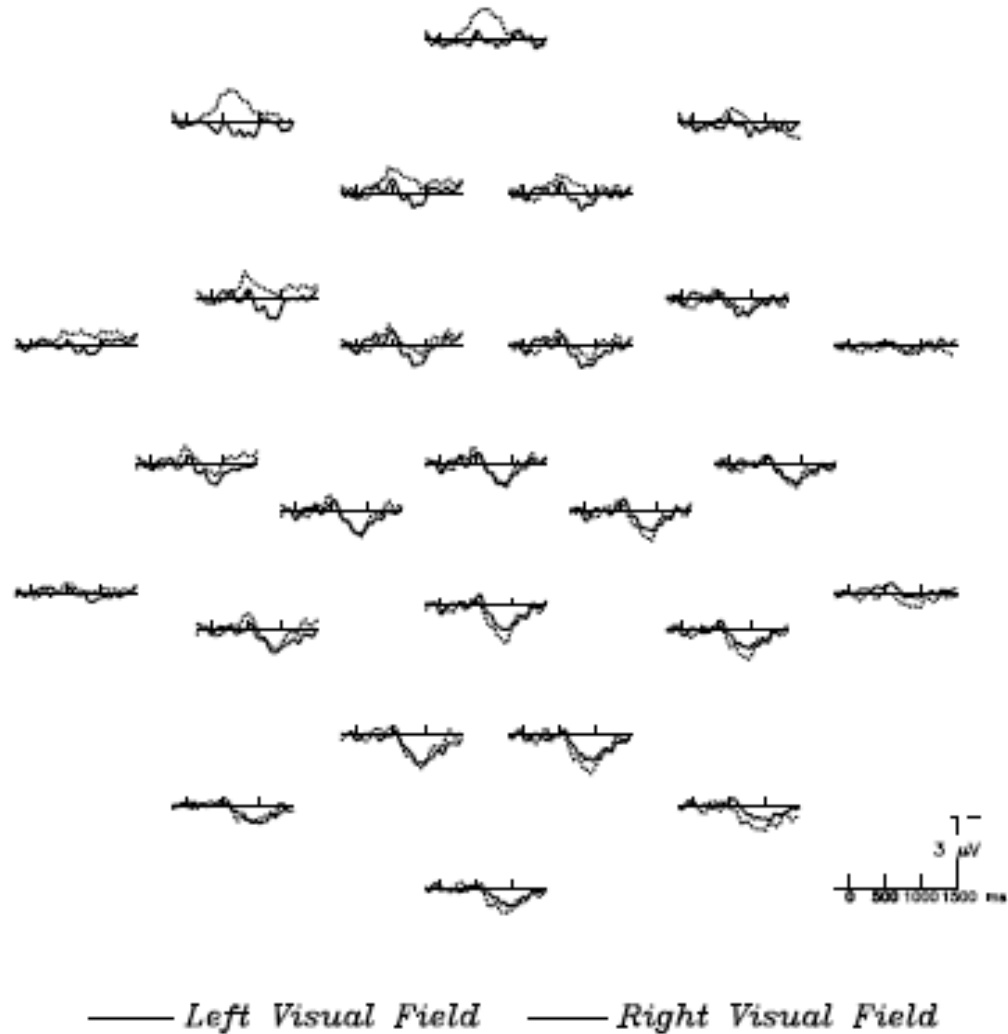
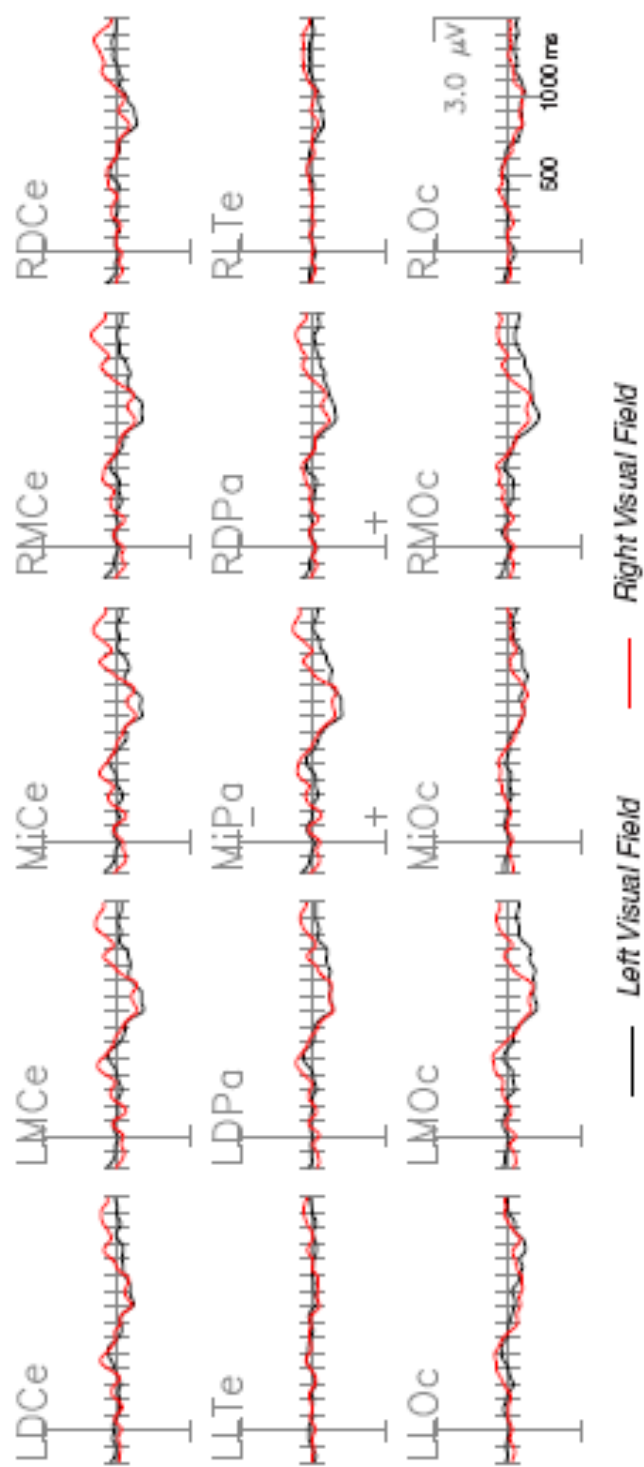Figure 5.11 Difference ERPs, formed by subtracting grammatical from ungrammatical ERPs, showing the P600 effect for LVF (black line) and RVF (red line) presentation of High salience verbs. These plots were produced using a modified baseline of 200 ms prestimulus to 450 ms post-stimulus to minimize the effect on the P600 of the negativity which precedes the P600 in the RVF presentation condition.

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Chapter 6

Summary of the dissertation

The research in this dissertation aimed to examine issues related to syntactic processing, including investigating hemispheric involvement in syntactic processing. In the area of language, one view that has been predominant is that the right hemisphere contributes little, if anything, to syntactic processing. This view is based in large part on the observation that lesions to certain areas of the left hemisphere are far more devastating to syntactic processing than are lesions to the corresponding areas of the right hemisphere. As was argued, however, such evidence does not exclude the possibility that the right hemisphere contributes to syntactic processing, albeit to a less important degree than does the left hemisphere. Additionally, while relatively few studies have carefully examined the possible contribution of the right hemisphere, there is evidence that it may make some contribution to at least certain aspects of syntactic processing. Thus, one of the goals of the dissertation was to investigate this issue further.

The materials that were designed to examine the right hemisphere contribution to syntactic processing leant themselves to examining other related research questions as well. The studies using central presentation (presented in chapters 2 and 4) serve both as a baseline for the lateralized studies (presented in chapters 3 and 5) as well as on their own, shed light on some other issues related to syntactic processing. In chapter 2 we reported a study examining the effects of normal aging on processing of grammatical number agreement. This research (Kemmer, Coulson, De Ochoa, & Kutas, 2004) represented to the best of our knowledge the first peer-reviewed investigation of syntactic processing using event-

related brain potentials (ERPs) in elderly participants. This study found no evidence that the P600 was delayed with normal aging, a surprising finding given that both the N400 and the P300 components have been found to be delayed in similar participant groups. However, the distribution of the P600 over the scalp was found to change with age, becoming more broadly distributed over the two hemispheres and more frontal, suggesting a qualitative, rather than simple quantitative change, in processing with age. The results of this study also contributes to the debate related to the functional significance of the P600, as well as to the debate in the literature on the left anterior negativity (LAN) component in that none was elicited by the morphosyntactic violation (see below for further discussion).

The data presented in chapter 4 (in addition to serving as a central baseline condition for the lateralized studies) speak to two other issues which are the subject of debate in the literature: the status of regular vs. irregular word forms and what mental processes underlie the left anterior negativity (LAN) component – i.e., its functional significance. As discussed in chapter 4, the nature and loci of the neural representation(s) of regular and irregular words also have been subject to a great deal of debate and experimental investigation. The connectionist approach proposes that there is no qualitative difference in how regular and irregular word forms are mentally represented or accessed (Rumelhart & McClelland, 1986). In contrast, other accounts such as the dual system view of Ullman et al. (2005) invoke qualitatively different mechanisms to deal with regular and irregular word forms. These approaches generally argue that irregular word forms are stored in the lexicon, but regular (morphologically complex) word forms are not; instead, these are represented as more basic forms such as stems and affixes which are combined

as needed via rules. As reported in chapter 4, we found no evidence of qualitative processing differences between regular and irregular word forms.

Likewise, a good deal of debate has occurred in the literature with respect to the LAN component. One theory, proposed by Friederici (2002), holds that the LAN reflects brain activity related (indeed, specific) to morphosyntactic processing. However, the findings in the literature are mixed in this regard (see details in chapter 4). The study presented in chapter 4 shows no LAN in any of the three verb violation conditions, including the regular verb condition. This finding adds to a growing number of studies which have failed to find a LAN to morphosyntactic violations. The failure by our and other studies to report a LAN suggests that its elicitation requires more than simple violations of morphosyntax, as Friederici's proposal suggests. Exactly what constitutes a LAN is poorly specified in the literature. In the literature one can find components referred to as LANs which are neither left nor anterior; as discussed in chapter 4. Moreover, the LAN is generally defined as being a negativity occurring in roughly the 300 – 500 ms time window, yet left anterior components, occurring in this time window, have been observed to violations which do not involve morphosyntactic processes.[1]

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[1] It remains to be determined whether the rough time window of 300 – 500 ms is correct for the LAN. Initially, the early left anterior negativity (ELAN) was thought to be elicited by the same processes as the LAN. However, additional research suggested the ELAN was a separate component and the LAN became associated with the 300 – 500 ms time window. One might ask whether anterior negativities (such as those reported in chapter 5) occurring much later than 500 ms can be considered LANs, even if elicited by non-morphosyntactic processes, or if not left-lateralized? Given Friederici's (2002) proposal, it would seem not. However, it is clear there are problems with the theory as proposed which need to be resolved. Even so, labeling as a LAN any negative component elicited by a syntactic violation (albeit not necessarily morphosyntactic) occurring in a much later time window does not seem to be merited by the evidence at this point. Before labeling such late negative components LANs, one would need to expand the theory to explain why some LANs occur fairly early, in the 300 – 500 ms time window, while others occur much later. Presumably, if (continued on next page)

6.1. Functional significance of the P600

In the experiments reported in this dissertation, the P600 has been used as an index of syntactic processing. A body of research exists showing that grammatical violations generally elicit the P600 in experiments such as those reported here. P600s have been elicited by words which are clearly ungrammatical given the preceding sentence context (Friederici & Frisch, 2000; Hagoort, Brown, & Groothusen, 1993; Kemmer et al., 2004; Osterhout & Mobley, 1995) and in temporarily ambiguous (garden-path) sentences by dispreferred continuations (Mecklinger, Schriefers, Steinhauer, & Friederici, 1995; Osterhout & Holcomb, 1992; Osterhout, Holcomb, & Swinney, 1994).

A controversy, exists, however, as to what neurocognitive processes elicitation of the P600 reflects – i.e., what is its functional significance. One view is that the P600 reflects processing costs related to reanalysis after anomaly detection (real or apparent; (Friederici, Hahne, & Mecklinger, 1996; Munte, Matzke, & Johannes, 1997; Neville, Nicol, Barss, Forster, & Garrett, 1991; Osterhout et al., 1994). Yet another has proposed that the P600 reflects difficulty with syntactic integration (Kaan, Harris, Gibson, & Holcomb, 2000).

A distinctly different type of proposal views the P600 as a member of the P300 family of components (Coulson, King, & Kutas, 1998). On such a view, the P600 is argued to reflect more general cognitive processes such as context updating in working memory which has been associated with the P300 component (Donchin, 1981; Donchin & Coles, 1988). Coulson et al. take as support for this

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both are labeled LANs, then they reflect the same mental processes, and one needs to account for the fairly significant difference in the time course of those mental processes between the two.

proposal their finding that that in parallel with the P3b, P600 amplitude increases with increasing saliency and probability of syntactic violations. Arguing against this view is the finding of Frisch, Kotz, von Cramon, and Friederici (2003) that the P600 can be dissociated from the P300: a P600 was not found in patients with lesions involving the basal ganglia, whereas a P300 was seen in such patients. Thus, the basal ganglia appear to be necessary for generation of the P600 although not for the P300, indicating that the neural generators for these two components are not identical (although it is possible that other generators of the P600 and P300 may overlap).

The studies presented in this dissertation offer mixed evidence on the issue of the relationship between the P600 and the P3 family of components. Kemmer et al. (2004; included as Chapter 2 of this dissertation) found that P600 latency was not delayed in older adults compared to younger adults. This finding argues against views which consider the P600 to be a member of the P3 family as P3 latencies have generally been shown to be delayed in older participants (for a review, see Kugler, Taghavy, & Platt, 1993). However, Kemmer et al. report that with age, the P600 has a flatter distribution across the scalp (compared to that seen for younger participants). This change in distribution with age is similar to what has been reported for the P3 and thus, supports the view that the P600 and P3 are related. Additionally, Kemmer (2009; included as chapter 4 of this dissertation) reports that P600 amplitude varies as a function of salience of the violation, consistent with the results of Coulson et al. (1998) and from the P3 literature (for a review, see Johnson, 1986).

The position taken in this dissertation with respect to underlying neurocognitive processes is an agnostic one: the P600 can serve as a useful index of syntactic processes without directly reflecting them. Indeed, the literature has not reached a consensus on this issue (Coulson et al., 1998; Osterhout & Hagoort, 1999; Osterhout, McKinnon, Bersick, & Corey, 1996). With respect to the P3, it has been strongly argued that the P3 involves multiple neural generators (Johnson, 1993) and this indeed may turn out to be true for the P600 as well (see Frisch et al. (2003) for arguments regarding P6 generators). It is possible that some of the neural generators may even overlap between the P3 family of components and the P600, although much research needs to be done in this regard to identify such neural generators. Kuperberg (2007) argues that even if some neural generators are found to be shared by both the P3 and the P600, this would not negate the importance of the P600. Such a finding would likely simply change the argument to how much overlap across neural generators is necessary to consider two components to be members of the same family.

6.2. Studies with lateralized presentation

6.2.1. Visual half-field paradigm: What can it tell us?

Chapters 3 and 5 present ERP and behavioral studies using the visual half-field paradigm in which stimuli are presented initially to just one visual field. Research suggests that stimuli presented parafoveally are processed initially by the hemisphere directly receiving the information (Hellige, 1983; Zaidel, 1983a; see chapters 3 and 5 for more detailed discussion). The resulting differences in processing can be used to infer the contributions of each hemisphere (Chiarello, 1991), at least under laboratory conditions.

Any argument that left hemisphere is solely responsible for all aspects of

syntactic (or other language-related) processing requires that in the case of LVF

presentation (initially going to right hemisphere only), information be transmitted

from the right hemisphere to the left hemisphere. Any such transmission involves

time which should cause a consistent latency delay for LVF compared to RVF

presentation in the onset (and possibly peak) of relevant ERP components.

However, such delays have not been reported for semantic processing (Coulson,

Federmeier, Van Petten, & Kutas, 2005) and likewise, were not observed in the

P600 component with lateralized presentation in the experiments presented in

chapters 3 and 5 of this dissertation (of course, such delays would be small and

there may be measurement issues). Thus, the lack of such a delay provides

evidence against views that the left hemisphere is solely responsible for syntactic

processing.

As discussed in chapter 3, ERP researchers use a number of approaches to

confirm stimuli are initially presented to just one hemisphere, including using the

electrooculogram online to ensure proper fixation and offline to remove trials

contaminated by eye movement, as well as offline analysis of early visual field

components. Additionally, the performance gain data from the two behavioral

experiments presented in chapter 3 of this dissertation provide evidence that stimuli

are processed in the hemisphere to which they are initially presented. In these two

experiments, the critical word duration was 100 ms in the first and 200 ms in the

second. As expected, responses were faster and accuracy higher with the longer

critical word duration for both subject/verb and reflexive conditions; we referred to

this improvement as a performance gain. We then compared for each sentence

type whether performance gains were larger in RVF or LVF. For the reflexive

condition, we observed that performance gains were greater for RVF compared to

LVF presentation, suggesting that for reflexives, the left hemisphere gains more

than the right hemisphere from longer critical word duration. For the subject/verb

condition, however, we observed the reverse: performance gains were greater for

LVF than RVF presentation. This pattern suggests that increasing critical word

duration benefits the right hemisphere more than the left hemisphere. This

difference between the two sentence types argues against claims that stimuli

presented initially to the right hemisphere are simply somehow transferred to the left

hemisphere for processing, as some have argue, and which must follow from a view

which claims syntactic processing is exclusively a left hemisphere function (Zaidel,

2001). If transfer of that sort were occurring, one would not expect performance

gains (due to increased critical word duration) to differ as a function of sentence

type and visual field of presentation.

6.2.2. Results from the lateralized experiments: Chapter 3

In chapter 3 we presented the results from the behavioral and ERP

experiments which used lateralized presentation; violations were either of

subject/verb (morphological) grammatical number agreement or reflexive

pronoun/antecedent (lexical) grammatical number agreement. The results from

these experiments showed that for the lexical condition, lateralized presentation to

just one hemisphere elicited behavioral performance that was equal, regardless of

the hemisphere initially receiving the stimulus. In the ERP experiment, a P600 of

similar amplitude and latency was elicited by violations for both LVF and RVF

presentation. Negativities were observed as well. With RVF presentation, violations

elicited a N400-like response between about 350 and 550 ms, most prominent

medially and frontally, but extending to occipital sites. In contrast, LVF presentation

elicited a frontally distributed, left lateralized negativity, beginning at about 400 ms

and lasting at least several hundred milliseconds. The similar P600 response to

violations relative to controls for both LVF and RVF presentation suggests

similarities between the hemispheres in appreciating lexically marked grammatical

number agreement in terms of the processes reflected in the P600 brain response

(at the level of the neocortex). However, the differences in the negativity as a

function of visual field suggest that processing is not identical between the two

hemispheres.

In contrast, in the morphological condition, LVF presentation resulted in

response times that were slower and less accurate (behavioral experiment). For the

ERP experiment, whereas a P600 was elicited by violations with RVF presentation,

no P600 was observed for LVF presentation. For LVF presentation, we instead

observed late anterior negativities (more pronounced at left than right anterior sites),

with the onset for LVF at about 500 ms, whereas for RVF, onset was about 1,000

ms; both extended until the end of the epoch (1,500 ms). The presence of the P600

for RVF presentation compared to the absence of it for LVF presentation suggests a

qualitative difference in neural processes underlying the P600 as a function of visual

field.

Our findings were consistent with a proposal by Zaidel (1983b) that the right

hemisphere finds processing of morphological markings more difficult than

processing of lexical markings. This proposal suggests there may be a language-

specific hemispheric difference in syntactic processing. However, our stimuli also

had a possible confound: the violation in the morphological condition was perceptually less salient than was the violation in the lexical condition. Thus, the difference we observed may have been due to hemispheric differences in low-level perception, rather than differences at a language-specific level.

6.2.3. Results from the lateralized experiments: Chapter 5

The experiments presented in chapter 5 were designed to help investigate whether the differences we observed in chapter 3 were due to high level or low level processing differences between the two hemispheres. In two experiments, we examined processing of grammatical and ungrammatical critical words in sentences requiring past participle verb forms. Three verb conditions were included: regular verbs, high salience/irregular verbs, and low salience/irregular verbs. At a perceptual level, the high salience/irregular verb condition was similar to the reflexive condition because the ungrammatical form (the infinitival form) differs from the grammatical form (the participle) by two or more letters (e.g., bring versus brought). In contrast, the low salience/irregular verb condition is similar to the subject/verb condition in that the ungrammatical critical word differs from the grammatical by only one letter (e.g., fling versus flung). We reasoned that if our previous results were due to the hemispheres differing at a language specific level, we should observe that the results for the two irregular verb conditions (both high and low salience) pattern together and also with that seen previously for the reflexive condition. In contrast, the regular verb condition should pattern with that seen previously for the subject/verb condition. Alternatively, if our previous results were due to the hemispheres differing at a lower perceptual level based on differences between the hemispheres in processing spatial frequencies, the high

and low salience conditions should show different patterns of results. The high

salience condition results should be similar to that seen previously in the reflexive

condition, while results for the low salience should be similar to that seen previously

in the subject/verb condition.

The results we obtained were mixed. The behavioral results provided some

support for the hypothesis that our previous results may have been due to

hemispheric differences in relative specialization for spatial frequencies. Most

importantly, we observed that for LVF presentation, responses in the high salience

ungrammatical condition were reliably faster and more accurate than for low

salience ungrammatical items. In contrast, with RVF presentation, this comparison

was not reliable.

However, the ERP results reported in chapter 5 were not in accord with our

predictions. For all verb types, for both LVF and RVF presentation, we did observe

a P600 effect. This finding is different from the experiment in chapter 3 where no

P600 effect was found for LVF presentation in the morphological condition.

However, the mean amplitude of the P600 effect for the high salience condition with

RVF condition was reliably smaller than that for the regular and low salience

conditions. This pattern was not expected. One possible ERP pattern we predicted

for LVF presentation was that the two irregular conditions would pattern together

and differ from the regular verb condition, supporting a view that the hemispheres

differ at a high, language-specific level for processing these stimuli. Alternatively,

we predicted that for LVF presentation, the high salience condition would differ

reliably from the low salience condition and likely pattern together with the regular

verb condition (for which grammatical and ungrammatical conditions differed by two

letters). The pattern was also not what we would have predicted based on the results from central presentation of the same stimuli (reported in chapter 4), where the P600 in the low salience condition was slightly smaller and later, relative to the two other conditions.

Thus, overall, the results from chapter 5 do not provide the clarification we were seeking to the question of whether the differences we observed in chapter 3 in syntactic processing ability of the two hemispheres were due to higher, language specific differences, or lower, perceptual level differences. While the behavioral results somewhat support the perceptual hypothesis, the ERP results do not clearly support either, and additional research will be necessary to resolve this issue.

6.3. Future directions

Although few, there are a number of studies in the literature which suggest that the right hemisphere does contribute to syntactic processing. These are an obvious point from which to base future investigations using ERPs combined with the visual half-field paradigm. For example, Schneiderman and Saddy (1988) asked participants to insert words into sentences; these sentences differed in the kind of reanalysis of sentence elements required for successful insertion. For one task (nonshift insertion task), as expected, the right brain damaged (RBD) group outperformed the left brain damaged (LBD) group. However, in the second task (shift insertion), correct insertion of the new word required a syntactic role shift of an existing word in the sentence (shift insertion). On this task, the LBD group (right hemisphere intact) outperformed the RBD (left hemisphere intact) group, a result that is not predicted by the view that syntactic processing is a strictly left hemisphere (LH) phenomenon. Similar results were found by De Vreese, Neri, Rubichi, and

Salvioli (1996) in a study involving the same tasks using Italian patients and controls. Thus, investigations aimed at understanding the difference between the right hemisphere's (RH) contribution in the shift and nonshift insertion tasks would help to better understand the right hemisphere's competence for syntax.

In an fMRI study, Caplan, Hildebrandt, & Makris (1996) found that RBD patients showed impairment on syntactically complex sentences, relative to controls. While LBD patients showed a greater degree of impairment than the RBD group, the RBD group's impairment on a syntactic task suggests some right hemisphere contribution to syntactic processing. Caplan et al. suggested that the reason why LBD patients showed more impairment than RBD patients was that "their lesions affected neural structures that are more crucially involved in syntactic processing" (p. 944). In other words, while left hemisphere structures likely are more important for syntactic processing, the findings of Caplan et al. suggest the right hemisphere makes some contribution. More careful investigations aimed at examining exactly what both right hemisphere and left hemisphere contributions are will lead to better understanding of syntactic processing in general.

6.4. Conclusions

Overall, the research presented in this dissertation provides support for the hypothesis that the right hemisphere is capable of certain kinds of syntactic processing, at least under laboratory conditions using lateralized presentation. Although our data alone do not speak to whether the right hemisphere participates in syntactic processing under normal (central presentation) conditions, research such as that cited in the previous section showing deficits in syntactic processing after right hemisphere damage provides support that it does. The research findings

presented here (together with the relatively few other studies examining the right hemisphere contribution) suggest that there is a need for greater investigation into hemispheric contributions to syntactic processing. Moreover, the finding that the right hemisphere likely has some ability to process syntax has potential applications, even without showing that it does so under normal conditions. For example, for therapies after left hemisphere brain damage which results in syntactic deficits, this finding suggests that the right hemisphere possibly could be trained to assume some of the processing previously done by the left hemisphere.

While examining hemispheric contributions to syntactic processing was the primary goal of this research, the stimuli used in the various experiments lent themselves to investigating other issues relevant to syntactic processing as well. The results from the central presentation studies presented in chapter 2, comparing syntactic processing in college-age and elderly participants, represent an important contribution to the literature on aging. We observed no delay with age in the onset latency or reduction in the amplitude of the P600 component, a surprising finding given that other ERP components (e.g., P3 and N400) have shown robust delays in onset latency. The observation that the distribution of the P600 over the scalp did change with age suggests that at least with respect to the mental functions which contribute to the P600, changes caused by age are more qualitative (engaging different brain regions) than a simple quantitative change in speed of processing. Finally, the studies presented in chapters four and five provide data relevant to the regular/irregular debate in the literature. Our results were more supportive of the connectionist view: Our findings did not show any evidence of there being a

qualitative difference in the mental representations of regular and irregular word forms.

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