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

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Abstract

Despite indications in the split-brain and lesion literatures that the right hemisphere is capable of some syntactic analysis, few studies have investigated right hemisphere contributions to syntactic processing in people with intact brains. Here we used the visual half-field paradigm in healthy adults 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 suggested similar processing regardless of visual field of presentation. In the subject/verb condition, we observed similar response times and accuracies for central and right visual field (RVF) presentations. For left visual field (LVF) presentation, response times were longer and accuracy rates were reduced relative to RVF presentation. An event-related brain potential (ERP) study using the same materials revealed similar ERP responses to the reflexive pronouns in the two visual fields, but very different ERP effects to the subject/verb violations. 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 RVF stimuli. These data suggest that both hemispheres can process lexically marked pronoun agreement violations, and do so in a similar fashion. Morphologically marked subject/verb agreement errors, however, showed a distinct LH advantage.

Keywords

ERP; Hemispheric asymmetry; Language; P600; Syntactic processing; Visual half-field

1. Introduction

Since Broca's 19th century report on the importance of the left hemisphere for speech production (Broca, 1965), language processing has been considered the paradigmatic case of a lateralized cognitive function in which the left hemisphere (LH) dominates, and the right (RH) plays a subordinate, and relatively minor role (Harrington, 1987, p. 75). However, more recent evidence from neuropsychological, metabolic, and electrophysiological studies of both normal and brain-damaged individuals has led to the current consensus that many aspects of language processing involve both hemispheres (Beeman and Chiarello, 1998),

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especially processing at the phonological (Hickok and Poeppel, 2007) and semantic (Federmeier and Kutas, 1999) levels of representation. In fact, there are some linguistic abilities for which the RH is considered to be dominant. This includes certain aspects of prosody, such as processing intonation contours (Behrens, 1989; Ross and Mesulam, 1979) and at least some aspects of discourse analysis (Brownell et al., 1983, 1995) such as the interpretation of one-line jokes (Coulson and Williams, 2005; Coulson and Wu, 2005). Nonetheless, the view that syntactic processing is strictly a LH function remains largely unchanged.

Skepticism regarding the RH capacity for grammatical processing is somewhat unwarranted, however, as very few studies have addressed this issue. Moreover, those that have done so suggest the RH has at least some syntactic processing ability (see Murasugi and Schneiderman, 2005, for a review). For example, in a classic study on this topic, Schneiderman and Saddy (1988) 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 both tasks, patients were asked to insert a given word into a sentence to form a new, grammatical sentence. For example, patients were tasked with inserting “wool” into “She brought the sweater that was mended.” In this so-called non-shift item, it is possible to insert the word while maintaining the original analysis of the sentence (viz. “She brought the wool sweater that was mended.”) Schneiderman and Saddy also tested so-called shift items, in which insertion of the word (e.g., “daughter”) in the sentence (“Cindy saw her take his drink”) required participants to partially reanalyze the structure of the initial sentence. That is, whereas the “her” in the initial sentence functions as the agent of the drink-taking event, the “her” in the revised sentence (“Cindy saw her daughter take his drink”) serves to modify a different agent of the drink-taking event (Cindy’s daughter). RBD patients did quite well on the non-shift insertion task, outscoring their LBD counterparts, consistent with the claim that the intact left hemisphere subserves grammatical processing. In contrast, on the shift insertion task (requiring role reassignment of a word), the LBD group actually outscored the RBD group. These data argue for the syntactic competence of the RH, and suggest that the two hemispheres might make somewhat different contributions to syntactic processing.

Further support for the claim that the RH performs some syntactic analysis comes from the commissurotomy literature. In particular, Zaidel (1983b) reports results from two adult split brain patients suggesting that the isolated RH may process subject/verb grammatical number agreement when it is signaled lexically (using an auxiliary, such as “is” or “are”: the cat is eating/the cats are eating) but not when signaled morphologically (by the presence or absence of the third person singular simple present tense inflection “s”: the cat eats/the cats eat). In contrast, isolated LH performance showed little difference between the two. Zaidel (1990) suggests that the RH finds certain linguistic categories easier to process than others, and proposes a hierarchy of ease of processing from lexical items (easiest) to morphological constructions to grammatical categories (case, number, gender, tense), with the most difficult being syntactic structures such as predication and complementation. However, Zaidel’s (1990) model of RH syntactic competence is based on a small number of split-brain patients and may not generalize to the intact brain. Here we use the divided visual field paradigm in healthy adults to address Zaidel’s (1990) prediction that the RH is more sensitive to grammatical information marked lexically (that is, it is signaled by an entire word) than morphologically (that is, it is signaled by meaningful unit within a word, such as the ‘pre-’in ‘prefix’ or the ‘s’ in ‘dogs’).

Apart from its celebrated use in commissurotomy patients (Gazzaniga and Hillyard, 1971; Gazzaniga and Sperry, 1967), the visual half-field paradigm also allows investigation of the RH’s ability to process syntax using neurologically intact individuals. In this paradigm, stimuli are presented in either the right visual field (RVF) or the left (LVF), resulting in the initial stimulation of only the contralateral hemisphere. Research suggests that, even in neurologically intact individuals, half-field presentation results in the increased participation of the contralateral hemisphere in the processing of the stimulus (Hellige, 1983; Zaidel, 1983a). Differences in performance as a function of visual field thus allow inferences as to whether both hemispheres typically contribute to the processing of a given sort of stimulus, and, if so, whether there are differences in each hemisphere's contribution (Chiarello, 1991).

Although most research using the visual half-field paradigm has targeted hemispheric differences in semantic processing, there is at least one prior study investigating syntactic processing in neurotypical individuals. Liu et al. (1999) used the visual half-field paradigm to elucidate the role of each hemisphere in grammatical priming. Using three-word noun phrase stimuli, they found that ungrammatical cues delayed recognition of the target words presented to either hemisphere. These data were interpreted as supporting the idea that both hemispheres are sensitive to number agreement. Findings reported by Liu et al. (1999) are not in keeping with Zaidel (1990) claim that the RH is not sensitive to morphologically marked number agreement. 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. Liu et al.'s findings might reflect task induced strategies rather than normal sentence processing mechanisms.

1.1. The present study

The present study used the visual half-field paradigm with healthy adults to investigate the capabilities of each hemisphere for a relatively simple syntactic process: grammatical number agreement. To do so we asked participants to read sentences and make judgments as to their grammaticality. For each sentence, the grammaticality or ungrammaticality of the sentence depended on a critical word which was presented in either the left visual field (LVF), the right visual field (RVF), or centrally. In order to assess the claim that the RH is more sensitive to syntactic information marked lexically than morphologically, we employed two different kinds of sentences. In our "reflexive" condition, number agreement between a reflexive pronoun and its antecedent was signaled lexically ("The grateful niece asked herself/*themselves how she could repay her aunt"). In our subject/verb condition, number agreement between a subject and a verb was signaled morphologically ("Industrial scientists develop/*develops many new products"). In experiments 1 and 2, the dependent variables were accuracy and reaction times for speeded grammaticality judgments. On this task, sensitivity to number agreement would be signaled by faster and more accurate responses to grammatical than ungrammatical sentences. Hemispheric differences in grammatical processing capability would be expected to show up as interactions between grammaticality and visual field (VF) of presentation, with larger grammaticality effects in one VF than the other. If the RH is indeed more sensitive to lexically than morphologically conveyed information, we might expect to observe greater evidence for hemispheric differences in the processing of the subject/verb than the reflexive sentences.

In experiment 3 we combined the visual half-field paradigm with the recording of event-related brain potentials (ERPs) in order to examine how lateralizing the critical words in either the left VF or the right affected the brain's real time processing of these stimuli. Concurrent recording of ERPs allows the investigator both to gauge how well VF presentation results in the participation of the contralateral hemisphere in stimulus processing (see, for example, Coulson et al., 2005), and to examine how VF presentation changes the brain response to the experimental manipulation (e.g., Federmeier and Kutas, 1999). If VF presentation impacts the size of an experimental effect on an ERP component, for example, we might infer that one hemisphere is more sensitive to the experimental variable than the other (see, for example, Coulson and Williams, 2005). Alternatively, VF presentation might result in experimental effects on different ERP components, suggestive of qualitative processing differences between the hemispheres (see, for example, Huang et al., 2010). If, however, VF presentation only impacted the onset latency of experimental ERP effects, it would suggest that stimuli are processed by the dominant hemisphere, and that VF presentation serves only to – alternately – speed up or delay their delivery.

The linguistic materials used in the present study were the same as those used in an ERP study reported by Kemmer et al. (2004) in which all materials were presented centrally. Kemmer et al. (2004) found that relative to syntactically well-formed control sentences, both sorts of grammatical number violations elicited a sustained centro-parietal positivity evident between 500 and 800 ms after word onset (P600). These data were in keeping 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 and Mobley, 1995; Dutch: Hagoort and Brown, 2000; Hagoort et al., 1993; Vos et al., 2001; German: Münte et al., 1997). Sensitivity to the grammaticality of these materials might be expected to be manifest in a P600 effect. Quantitative hemispheric differences in sensitivity to grammaticality would be suggested by larger grammaticality effects with presentation to one VF over the other (e.g. larger P600 effects with presentation in the RVF/LH). Alternatively, if VF presentation resulted in grammaticality effects on different components of the ERP, it would signal qualitative differences in grammatical processing across the hemispheres.

2. Experiment 1

2.1. Methods

All procedures were approved by the Institutional Review Board at the University of California, San Diego, and were therefore performed in accordance with the ethical standards set forth in the 1964 Declaration of Helsinki.

2.1.1. Participants—Twenty-four UCSD undergraduate students participated in experiment 1 for course credit or pay (15 females; age range: 18 to 28; M_{age}: 19.8 years). All the participants were monolingual, right-handed (assessed using the Edinburgh Inventory, Oldfield, 1971), and had normal or corrected-to-normal vision. None reported any history of psychiatric disorders, learning disorders, drug use, or neurological disease. All participants gave informed consent prior to their inclusion in the study.

2.1.2. Materials—Materials included 240 experimental sentences and 60 filler sentences. Experimental sentences were divided into two categories: 120 sentences with potential subject/verb agreement errors, and 120 with potential number agreement errors between reflexive pronouns and their antecedent (see Table 1 for sample experimental sentences). Within each experimental category, half of the sentences (60) were presented in their ungrammatical form, while the other 60 were presented in their grammatical form. Multiple lists were employed so that the same participant viewed only one version of each sentence, but across participants all experimental sentences appeared in both their grammatical and ungrammatical forms. Filler sentences were included to discourage participants from predicting particular sorts of grammatical violations, and therefore included a variety of grammatical and ungrammatical sentence structures. Violations in the filler sentences involved syntactic structures different from those in the experimental sentences. Filler sentences were the same on all lists.

Experimental sentences ranged in length from 5 to 12 words. Critical words ranged from 5 to 10 letters. 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; and 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 and Kučera, 1982). Each main verb appeared only once across all sentence types (including practice, filler, or experimental). 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 six 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 20 items in each cell of the 3 × 2 × 2 design, viz. 3 levels of Visual Field (LVF, Central, RVF), 2 Sentence Types (Reflexive Pronoun, Subject/verb Agreement), and 2 levels of Grammaticality.

2.1.3. Experimental procedure—The participants were tested in a single experimental session lasting about 3 h. Participants were seated 40 in. in front of a monitor in a sound-proof, electrically shielded recording chamber. Before each sentence, a fixation cross appeared for a duration of 1000 ms. Additionally, a small central fixation dot, positioned approximately 0.25° below the bottom edge of words, remained on the screen permanently to facilitate correct fixation. The participants were instructed to read each sentence for comprehension, fixate the dot until after the sentence ended, and not to blink or move during this period. The participants were also asked to make an acceptability judgment for each sentence. Experimental and filler sentences were presented one word at a time. For all except for the critical words, presentation duration was 200 ms, followed by a 300 ms inter-stimulus interval. Critical words were presented for 100 ms and followed by an 800 ms inter-stimulus interval. Critical words subtended from 1.2 to 5.0° of horizontal visual angle; vertical angle subtended was approximately one-half degree. When presented laterally, the inner edge of critical words was 2.0° from the central fixation point. All but one word of each sentence was presented in a blue font; the remaining word (always the critical word) was presented in black. The 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 to and including that word.

To ensure that the participants read the entire sentence for comprehension, a random one-half of the sentences were also followed by a comprehension probe sentence that appeared in its entirety in a red font. The 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, the participants were instructed to try to respond as accurately as possible. The comprehension probe appeared on the screen until the participant made a response.

First, the participants were familiarized with the stimulus presentation parameters and the task via a practice block of 30 sentences. The participants were monitored to ensure that they remained fixated on the fixation point throughout the entire sentence, especially when the words were lateralized. Feedback was provided to train them in this; as necessary, the practice block was repeated until the participants demonstrated high accuracy while fixating properly. Experimental and filler sentences were then presented in 10 blocks of 30 sentences 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 the participants were accustomed to the hand mapping switch.

2.1.4. EOG recording—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 blinking or making eye movements during the presentation of the experimental sentences. If the experimenter started seeing saccades, participants were given feedback, and slightly longer breaks were provided between blocks. Given that lateralized words were presented here for 100 ms, and planning and executing saccades requires at least 180 ms (Rayner, 1978), we deemed it unlikely that the odd eye movement would improve participants’ performance. Consequently, EOG was not used to reject trials in experiment 1. This was in contrast to Experiments 2 and 3 – where stimulus duration was twice as long as in experiment 1 – and it was at least conceivable that saccades could impact performance.

2.1.5. Analysis—The dependent variables were response times and accuracy; for response time analyses, data from only correct responses were included in the analysis. Analysis involved repeated measures ANOVA with within-participants factors Sentence Type (subject/verb grammatical number agreement, reflexive pronoun/antecedent grammatical number agreement), Visual Field (left, center, right), and Grammaticality (grammatical, ungrammatical). Omnibus ANOVAS were followed up with planned comparisons intended to discern whether accuracy rates and response times for each sentence type differed as a function of visual field of presentation. Comparisons included LVF vs. RVF in each of the four conditions (subject/verb, grammatical and ungrammatical; reflexive, grammatical and ungrammatical).

2.2. Results

2.2.1. Accuracy: omnibus ANOVA—Accuracy rates can be seen in Fig. 1A. Rates ranged from 52% to 100% in the LVF (median = 79%), 56% to 100% in the RVF (median = 93%), and from 57% to 100% with central presentation (median = 93%).

As expected, the participants were more accurate for grammatical (91.7%) than ungrammatical items (77.7%), Grammaticality, $F(1,23) = 33.93$, $p = .000$; more accurate for central presentation (90.3%), followed by RVF (85.8%), and was lowest for LVF (78.1%) presentation, Visual Field $F(2,46) = 37.86$, $p = .000$, $\varepsilon = .82$; and more accurate for the reflexive (86.7%) compared to the subject/verb condition (82.7%), Sentence Type, $F(1,23) = 15.03$, $p = .001$. However, these main effects were all qualified by higher order interactions (Grammaticality × Sentence Type, $F(2,46) = 9.80$, $p = .005$; Sentence Type × VF, $F(2,46) = 30.00$, $p = .000$, $\varepsilon = .87$; Grammaticality × Sentence Type × VF, $F(2,46) = 9.61$, $p = .000$, $\varepsilon = .93$). Fig. 1A indicates that these interactions reflect a difference between grammaticality effects for subject/verb sentences presented in the LVF/RH compared to all other conditions. Whereas grammaticality effects were similar for both sorts of sentences presented in the central and right visual fields, accuracy rates were lower overall for subject/verb sentences presented in the LVF, especially when they were ungrammatical.

2.2.2. Planned comparisons—For reflexive sentences, no reliable differences in accuracy were observed between LVF and RVF presentation for either grammatical (p = .322) or ungrammatical (p = .496) items. For subject/verb sentences, RVF presentation yielded reliably more accurate responses than LVF for both grammatical (p = .001) and for ungrammatical (p = .000) items.

2.2.3. Response times: omnibus ANOVA—Responses time can be seen in Fig. 1B. As expected, participants' responses overall were faster for grammatical (1055 ms) compared to ungrammatical (1190 ms) conditions, $F(1,23) = 6.47$, $p = .018$. There was also a significant main effect of Visual Field (central: 1035 ms; RVF: 1121 ms; LVF: 1211 ms), $F(2,46) = 23.68$, $p = .000$, $\varepsilon = .84$. Responses were faster for the reflexive (1046 ms) than subject/verb (1199 ms) condition, Sentence Type $F(1,23) = 26.80$, $p = .000$. While responses were overall slower for subject/verb compared to reflexive, slowing was more pronounced for subject/verb ungrammatical than grammatical, Sentence Type × Grammaticality, $F(2,46) = 12.08$, $p = .002$, especially for words presented in the LVF, Sentence Type × VF, $F(2,46) = 16.24$, $p = .000$, $\varepsilon = .75$, Sentence Type × Grammaticality × VF, $F(2,46) = 3.06$, $p = .057$, $\varepsilon = .98$.

2.2.4. Planned comparisons—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). Both grammatical (p = .002) and ungrammatical (p = .003) subject/verb sentences elicited shorter response times with RVF than LVF presentation.

2.3. Discussion

In experiment 1, we examined the capabilities of each hemisphere to process grammatical number marked in two different ways: lexically (reflexive condition) and morphologically (subject/verb condition). For the lexically marked number violations (reflexive condition), LVF and RVF presentation yielded similar response times and accuracy rates, suggesting that both hemispheres were similarly sensitive to number agreement violations. In contrast, for the morphologically marked number agreement violations (subject/verb condition), LVF presentation resulted in worse performance as indexed by lower accuracy rates and longer response times.

In sum, experiment 1 indicated that the RH was less proficient than the LH in processing our morphologically marked number agreement condition (subject/verb), but not in the lexically marked (reflexive) one. These data are thus in keeping with the proposal that the RH has a greater capacity to process lexically than morphologically marked number agreement (compared to morphologically, Zaidel, 1983b, 1990). However, one concern regarding experiment 1 is that apparent functional asymmetry in grammatical processing might be an artifact of hemispheric differences in visual processes that affect each hemisphere's ability to decode the orthographic word form. On this alternative explanation, observed effects of VF were an artifact of the short duration of the lateralized words (100 ms), which penalizes the RH more than the LH. To investigate the plausibility of this alternative explanation, we ran a second behavioral experiment, identical to the first, except that critical words were presented for 200 ms instead of 100 ms. Increasing stimulus duration is expected to help equalize visual processing demands and thus provide a more sensitive index of hemispheric differences in sensitivity to grammatical violations.

3. Experiment 2

Experiment 2 was conducted to investigate the possibility that effects reported above were due wholly or in part, to hemispheric differences in visual perception that were accentuated by the relatively short presentation duration employed in experiment 1. The 100 ms duration was initially chosen to match that used in previous visual hemi-field experiments, and intended to ensure that participants could not successfully saccade to the laterally presented words (Liu et al., 1999). However, in contrast to many studies reported in the literature, we recorded and monitored EOG during stimulus presentation, allowing us to detect when the participants moved their eyes during stimulus presentation, and to eliminate the trials in which they did. Thus, we ran a version of experiment 1 in which critical word duration was increased from 100 to 200 ms. If observed differences in grammaticality effects as a function of visual field primarily reflect hemispheric differences in visual rather than language processing, we might expect those differences to be attenuated by the longer presentation durations used in experiment 2.

3.1. Methods

3.1.1. Participants—Twelve UCSD undergraduate students participated in experiment 2 for course credit or pay (7 females; age range: 18 to 28; M_{age}: 20.0 years). All gave informed consent to participate. All participants were monolingual, right-handed (assessed using the Edinburgh Inventory, Oldfield, 1971), and had normal or corrected-to-normal vision. None reported any history of psychiatric disorders, learning disorders, drug use, or neurological disease.

3.1.2. Materials—The materials were identical to those used in experiment 1.

3.1.3. Procedure—All aspects of the procedure were conducted as in experiment 1 except for the presentation duration of the critical word in each sentence. In experiment 1, critical words were presented for 100 ms and followed by an 800 ms inter-stimulus interval. In experiment 2, critical words were presented for 200 ms and followed by a 700 ms inter-stimulus interval. The stimulus onset asynchrony between the critical word and the word that followed it were thus identical in the two experiments.

3.1.4. EOG recording—As in experiment 1, the 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 infra-orbital ridge of the right eye and referred to the left mastoid. All other aspects of this recording were identical to those employed in experiment 1.

3.1.5. Analysis—Prior to analysis, EOG data were examined for saccades; trials with saccades were not included in the analyses. 2.5% of the LVF trials (5.4% for reflexive/grammatical; 0% for reflexive/ungrammatical; 5% for subject/verb/grammatical; 2.5% for subject/verb/ungrammatical) and 6.6% of the RVF trials (6.7% for reflexive/grammatical; 0% for reflexive/ungrammatical; 9.6% for subject/verb/grammatical; 10% for subject/verb/ungrammatical).[1] The difference between LVF and RVF trials rejected approached significance ($F(1,11) = 4.68$, $p = .053$). For central visual field trials, no trials were rejected in the reflexive condition; one participant had trials rejected due to saccades in the subject/

[1]A number of factors contributed to the fairly low percentage of saccades in the study. In all three experiments, participants were trained in a practice session to maintain eye fixation and were observed closely during the experiment to ensure that saccades were kept to a minimum. If the researcher started seeing saccades, feedback was given to the participant, and slightly longer breaks were provided between blocks.

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verb condition (1 trial (overall 0.42%) rejected for subject/verb/grammatical; 3 trials (overall 1.25%) rejected for subject/verb/ungrammatical). Across subjects and conditions, the median number of trials rejected (20 trials per condition) ranged from 0 to 2. The number of trials rejected due to saccades for an individual subject varied by condition, ranging from a low of zero to a high of 0 to 6, depending on the condition.

3.2. Results

3.2.1. Accuracy: omnibus ANOVA—Accuracy rates can be seen in Fig. 1C. Rates ranged from 67% to 99% in LVF (median = 91%), from 82% to 100% in RVF (median = 96%), and 82% to 100% with central presentation (median = 95%).

The 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, $F(2,22)$, $p = .000$, $\varepsilon = .87$ (central: 94.3%; RVF: 93.6%; LVF: 87.3%). A number of interaction effects were also observed, Sentence Type × VF, $F(2,22) = 9.64$, $p = .007$, $\varepsilon = .74$; Sentence Type × Grammaticality × VF, $F(2,22) = 3.60$, $p = .049$, $\varepsilon = .77$. As in experiment 1, the interactions reflect a larger grammaticality effect on the subject/verb sentences presented to the LVF (see Fig. 1C).

3.2.2. Planned comparisons—For reflexive sentences, RVF was reliably more accurate than LVF for grammatical items ($p = .015$) but there was no difference for ungrammatical items ($p = .469$). 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.

3.2.3. Response times: omnibus ANOVA—Response times can be seen in Fig. 1D. Responses were faster for grammatical (981 ms) than ungrammatical (1161 ms) sentences, $F(1,11) = 41.61$, $p = .000$. There was also a significant main effect of Visual Field (central: 1010 ms < RVF: 1,046 ms < LVF: 1,057 ms), $F(2,22) = 45.42$, $p = .000$, $\varepsilon = .83$. The participants' responses overall were slightly faster for subject/verb (1019 ms) than reflexives (1123 ms), main effect of Sentence Type, $F(1,11) = 19.13$, $p = .001$. The interaction between Sentence Type and Grammaticality approached significance, $F(2,22) = 4.03$, $p = .070$, but otherwise there was no evidence of any higher-order interactions.

3.2.4. Planned comparisons—Responses to RVF were generally faster than for LVF presentation, although the effect in the grammatical reflexive condition was marginal (subject verb, grammatical, $p = .022$, ungrammatical, $p = .013$; reflexive, grammatical $p = .055$, ungrammatical, $p = .023$).

3.3. Discussion

Experiment 2 was conducted to investigate whether 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 Fig. 1C, D). Although response times in experiment 2 failed to reveal evidence for hemispheric differences in sensitivity to number agreement errors, accuracy rates did. As in experiment 1, accuracy rates for grammaticality judgments on morphologically marked subject/verb agreement errors were more pronounced for stimuli presented to the LVF than for any other comparison. Thus, even as overall accuracy rates increased with the longer duration of the critical words in experiment 2, LVF presentation still yielded particularly poor performance on morphologically marked agreement errors.

3.3.1. 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. 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 were greater for RVF than LVF presentation—in other words, in the reflexive condition, the LH gained more than the right from the longer critical word duration. In contrast, for the subject/verb condition, it was the RH which benefited more from the increased critical word duration: performance gains are greater for LVF than RVF presentation. However, differences across the two experiments must be interpreted with caution in view of the different number of participants in each ($N = 24$ in experiment 1 vs. $N = 12$ in experiment 2).

2. Experiment 3

In experiment 3, we report an experiment using ERPs; this real time measure of the brain response to critical words will complement the information from the behavioral (end-product) measures used in experiments 1 and 2.

3.4. Methods

3.4.1. Participants—Thirty-six UCSD undergraduate students participated in the experiment for course credit or pay (18 females; age range: 18 to 33; $M_{age} = 19.5$ years). Informed consent was obtained for all the participants. All the participants provided health and medical information, including history of psychiatric disorders, learning disorders, drug use, neurological disease, medications currently being taken, vision, and others; the subjects were excluded from experiment participation as appropriate. All the subjects were monolingual, right-handed (assessed using the Edinburgh Inventory, Oldfield, 1971), and had normal or corrected-to-normal vision.

3.4.2. Materials—The materials 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 (LVF), 30 grammatical subject/verb (RVF), 30 violation subject/verb (LVF), 30 violation subject/verb (RVF), 30 grammatical reflexive pronoun (LVF), 30 grammatical reflexive pronoun (RVF), 30 violation reflexive pronoun (LVF), 30 violation reflexive pronoun (RVF), 15 grammatical fillers (LVF), 15 grammatical fillers (RVF), 15 violation fillers (LVF), and 15 violation fillers (RVF). Each list included for each sentence either the number violation or its grammatical counterpart, never both.

3.4.3. Experimental procedure—With the exception of the details noted here, the experimental procedure was identical to that for experiment 2, including procedures for familiarizing participants with stimulus presentation, the inclusion of comprehension sentences, and presentation of experimental sentences.

The participants were tested in a single experimental sessions lasting about 3.5 h. The 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 the 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° below the bottom edge of words, remained on the screen permanently, to facilitate correct fixation. The 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. The participants were also asked to make an acceptability judgment at the end of the sentence: After the final word of a sentence disappeared, the participants were to indicate as quickly and as accurately as possible whether or not the sentence was well formed.

3.4.4. Recording procedures—The electroencephalogram (EEG) was recorded from 26 tin electrodes, embedded in an electrode cap, each referenced to the left mastoid. The 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), and right lateral (RLPf); Frontal: left lateral (LLFr), left mediolateral (LDFr), left medial (LMFr), right medial (RMFr), right mediolateral (RDFr), and right lateral (RLFr); Central: left mediolateral (LDCe), left medial (LMCe), midline (MiCe), right medial (RMCe), and right mediolateral (RDCe); Parietal: left mediolateral (LDPa), midline (MiPa), and right mediolateral (RDPa); Temporal: left lateral (LLTe), and right lateral (RLTe); and Occipital: left lateral (LLOc), left medial (LMOc), midline (MiOc), right medial (RMOc), and 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.

3.4.5. Behavioral data analysis—Accuracy scores in terms of percent correct were analyzed with repeated measures ANOVA using factors Sentence Type (subject/verb grammatical number agreement, reflexive/antecedent grammatical number agreement), Grammaticality (grammatical, ungrammatical), and Visual Field (left, right). Response times are not reported for this experiment because participants made grammaticality judgments at the end of the sentence rather than immediately after the critical word.

3.4.6. ERP data analysis—Prior to analysis, EEG 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. Of the rejected trials, 5.8% of LVF trials and 7.5% of RVF trials were rejected due to saccades; this difference was significant, $F(1,35) = 6.85$, $p = .013$. Across subjects, the median number of trials rejected (30 trials per condition) was 2 in all conditions except for subject/verb/ungram/LVF and reflexive/ungram/LVF, for which the median was 1. The number of trials rejected due to saccades for an individual subject varied by condition, ranging from a low of zero to a high of 5–9, depending on the condition.

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 1500 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 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 Fig. 2).

In addition, we conducted planned omnibus ANOVAs for each sentence type separately with five within-subject factors including Grammaticality, Visual Field, Hemisphere, Laterality, and Anteriority as described previously.

Our significance level was set at $p \leq .05$ and for all analyses involving more than one degree of freedom, the Greenhouse and Geisser (1959) correction for violations of sphericity was applied; uncorrected degrees of freedom but corrected *p* values are reported.

3.5. Results

3.5.1. Accuracy rates—Accuracy rates ranged from 48% to 97% in LVF (median = 78.8%), and from 64% to 100% in RVF (median = 88.2%). As expected, participants were reliably more accurate in classifying grammatical (M = 94%) than ungrammatical sentences (M = 71%), Grammaticality, $F(1,35) = 144.94$, $p = .000$. Grammaticality judgments were more accurate for RVF (87%) than LVF (77%) presentation, Visual Field, $F(1,35) = 174.32$, $p = .000$. Additionally, responses were more accurate for reflexives (86%) than subject/verb (78%); Sentence Type, $F(1,35) = 35.56$, $p = .000$. All interactions were significant: Sentence Type × VF, $F(1,35) = 140.73$, $p = .000$; Sentence Type × Grammaticality, $F(1,35) = 28.85$, $p = .000$; Grammaticality × VF, $F(1,35) = 49.63$, $p = .000$; Sentence Type × Grammaticality × VF, $F(1,35) = 51.33$, $p = .000$.

Planned two-way comparisons showed that for the grammatical reflexive condition, there was no reliable difference in accuracy between RVF (93.3%) and LVF (94.5%) presentation, $F(1,35) = 1.06$, $p = .311$. For the ungrammatical reflexive condition, however, 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.

3.5.2. EOG—EOG time locked to critical words were examined off-line for saccades; trials with saccades were eliminated from analysis. Saccades were more likely in grammatical (2.25 trials rejected on average) compared to ungrammatical (1.73 trials rejected), $F(1,35) = 9.52$, $p = .004$. Additionally, saccades were slightly more likely for RVF (2.24 trials rejected) compared to LVF (1.74 trials rejected) presentation, $F(1,35) = 6.85$, $p = .013$.

3.5.3. ERPs—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 VF × Hemisphere interaction, $F(1,23) = 45.02$, $p = .000$, with LVF presentation eliciting a larger amplitude N1 over RH sites and RVF presentation eliciting a larger N1 amplitude over LH sites. This result confirms that presentation of stimuli was successfully lateralized, leading to greater stimulation of the contralateral hemisphere (see Fig. 3.)

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 Fig. 4 for a representative subset of electrodes. Fig. 5 shows the corresponding grand average ERPs for the subject/verb condition. Fig. 6 shows the difference waves (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; Fig. 7 shows the same for the subject/verb condition.

Results of the omnibus analysis of ERPs measured 300–500 ms after the onset of the critical words are given in Table 2. Experimental manipulation of grammaticality, sentence type, and visual field all gave rise to differences in the pattern of voltage recorded at the scalp, as indexed by significant interactions between these factors and topographic factors. Notably, interactions of the Visual Field factor with Hemisphere, Laterality, and Anteriority suggest the initial visual field of presentation led to the recruitment of different brain regions, in spite of the fact that by 300 ms post-onset more than enough time had passed for inter-hemispheric transfer to occur. Moreover, a higher order interaction was also present between sentence type, grammaticality, hemisphere, and laterality, indicating a difference in the ERP grammaticality effects for subject/verb and reflexive pronoun number agreement sentences (see Table 2). We describe the grammaticality effects for each sentence type in more detail in Sections 3.5.4 and 3.5.5 below.

Results of the omnibus analysis of ERPs measured 600–900 ms after the onset of the critical words are given in Table 3. As in the previous interval, experimental factors of grammaticality, sentence type, and visual field all interacted with topographic factors, suggesting each of these variables impacted the brain response in this interval. Moreover, the visual field factor also interacted with grammaticality, suggesting presentation field affected the brain response to grammatical vs. ungrammatical sentences (see Table 3). These results are discussed in more detail in Sections 3.5.4 and 3.5.5.

3.5.4. Reflexive pronoun agreement sentences—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 Fig. 4 for a representative subset of electrodes. Analysis of ERPs measured 300–500 ms revealed effects of both grammaticality (Grammaticality, $F(1,35) = 9.99$, $p = .003$; Grammaticality × Hemisphere × Anteriority $F(4,140) = 2.81$, $p = .043$, $\varepsilon = .80$) and visual field (VF × Hemisphere, $F(1,35) = 17.98$, $p = .000$; VF × Hemisphere × Laterality, $F(1,35) = 6.47$, $p = .016$; VF × Hemisphere × Anteriority, $F(4,140) = 13.20$, $p = .001$, $\varepsilon = .35$; VF × Hemisphere × Laterality × Anteriority, $F(4,140) = 12.02$, $p = .000$, $\varepsilon = .62$), that were qualified by higher order interactions with topographic factors (Grammaticality × VF × Laterality, $F(1,35) = 4.53$, $p = .041$).

Analysis reflected a larger negativity to ungrammatical pronouns beginning 300 ms post-onset that 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 medial electrode sites. For LVF presentation, the negativity was more restricted in its distribution, evident over prefrontal and lateral frontal electrodes over the left side of the scalp; moreover, in contrast to the phasic N400-like negativity observed with RVF presentation, the LVF negativity appears to continue until 1500 ms post-onset (see Fig. 4).

In the later part of the epoch (600–900 ms post-onset), ungrammatical pronouns elicited a larger centro-parietal positivity (P600) than did their grammatical counterparts. The grammaticality effect showed up in the analysis as a main effect as well as in interaction with topographic factors (Grammaticality, $F(1,35) = 5.05$, $p = .031$; Grammaticality × Laterality, $F(1,35) = 13.01$, $p = .001$; Grammaticality × Anteriority, $F(4,140) = 6.44$, $p = .$

014, ε = .35; Grammaticality × Laterality × Anteriority, $F(4,140) = 3.05$, $p = .032$, ε = .74). Visual field of presentation also affected ERPs 600–900 ms, consistent with the claim that this manipulation increased the participation of the contralateral hemisphere (VF × Hemisphere, $F(1,35) = 51.76$, $p = .000$; VF × Hemisphere × Anteriority, $F(4,140) = 70.70$, $p = .000$, ε = .47; VF × Hemisphere × Laterality × Anteriority, $F(4,140) = 29.27$, $p = .000$, ε = .82). Moreover, analysis revealed a higher order interaction between the two experimental factors and a topographic one (Grammaticality × VF × Hemisphere, $F(1,35) = 4.83$, $p = .035$).

The grammaticality effect is visualized in Fig. 6 which shows that the difference waves formed by a point by point subtraction of ERPs elicited by grammatical pronouns from those elicited by ungrammatical ones in the LVF and the RVF, respectively. Fig. 6 suggests that the three-way interaction between Grammaticality, VF, and Hemisphere does not reflect differences in P600 amplitude as a function of visual field, but rather slight differences in the scalp distribution consistent with increased participation of the contralateral hemisphere. That is, Fig. 6 reveals similar amplitude P600 with both LVF and RVF presentation; but, for LVF presentation, the positivity was somewhat larger over the RH, whereas for RVF presentation, the positivity was slightly larger over LH.

3.5.5. Subject/verb agreement sentences—ERPs to grammatical and ungrammatical verbs in the subject/verb agreement sentences are shown in Fig. 5, with difference waves presented in Fig. 7. In contrast to the reflexive pronouns described in 3.5.4, grammaticality effects were not evident in ERPs to subject/verb agreement sentences in the 300–500 ms interval. Analysis of ERPs measured 300–500 ms revealed only effects of the visual field manipulation on the topography of the brain response (VF × Hemisphere $F(1,35) = 18.96$, $p = .000$; VF × Hemisphere × Laterality $F(1,35) = 9.53$, $p = .004$; VF × Hemisphere × Anteriority $F(4,140) = 11.83$, $p = .000$, ε = .42; VF × Hemisphere × Laterality × Anteriority $F(4,140) = 12.15$, $p = .000$, ε = .63). Observed effects suggest that the visual field manipulation had a robust impact on the brain regions recruited to process RVF vs. LVF stimuli, but did not impact the brain response to the grammaticality of those stimuli.

Beginning approximately 600 ms after stimulus onset, however, ungrammatical verbs elicited more positive ERPs over posterior scalp with RVF presentation, and more negative ERPs over anterior scalp with LVF presentation (see especially Fig. 7). Analysis of ERPs measured 600–900 ms post-stimulus revealed effects of grammaticality in interaction with topographic factors (Grammaticality × Laterality $F(1,35) = 4.21$, $p = .048$; Grammaticality × Anteriority $F(4,140) = 11.21$, $p = .000$, ε = .42; Grammaticality × Laterality × Anteriority $F(4,140) = 3.13$, $p = .029$, ε = .75), effects of visual field in interaction with topographic factors (VF × Hemisphere $F(1,35)= 48.72$, $p = .000$; VF × Hemisphere × Laterality × Anteriority $F(4,140) = 20.42$, $p = .000$, ε = .76), and higher-order interactions between grammaticality, visual field, and topographic factors (Grammaticality × VF, $F(1,35) = 6.01$, $p = .019$; Grammaticality × VF × Hemisphere × Laterality × Anteriority, $F(4,140) = 3.91$, $p = .024$, ε = .61).

That is, with RVF presentation, ungrammatical verbs elicited a larger centro-parietal positivity (P600) than did their grammatical counterparts. 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. By contrast, no P600 effect whatsoever was observed for LVF presentation of verbs: there was no difference in the response to grammatical vs. ungrammatical items over temporal, parietal, and occipital sites. Rather, ungrammatical verbs presented to the LVF elicited a larger sustained negativity than grammatical verbs over anterior electrodes, especially over the LH. This effect appears to begin approximately 300 ms post-stimulus and remained evident until the end of the epoch (1500 ms post-stimulus). A less pronounced anterior negativity with an onset at about 1000 ms was observed for RVF presentation as well.

3.5.6. Summary of ERP effects—For RVF presentation, ungrammatical reflexives elicited a larger N400-like component 300–500 ms post-onset than grammatical ones, followed by a larger P600. For LVF presentation, ungrammatical reflexives elicited a larger negativity over pre-frontal electrode sites, followed by a larger P600. The overall amplitude of the grammaticality P600 was similar in both VFs, but its scalp distribution differed, presumably due to greater participation by the contralateral hemisphere.

Verbs in subject/verb agreement violations elicited very different ERP effects as a function of visual field. For RVF presentation, relative to grammatical controls, ungrammatical verbs elicited a larger P600 measured 600–900 ms. With LVF presentation, ungrammatical verbs elicited a larger sustained frontal negativity than did grammatical ones, beginning 500 ms and continuing until the end of the epoch.

3.6. Discussion

Experiment 3 investigated 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. 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 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, the ERP response to critical words differed significantly for LVF and RVF presentations. Violations in only 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 1500 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. A less pronounced anterior negativity (slightly larger over LH than RH sites) with an onset at about 1000 ms was observed for RVF presentation as well.

Results for central presentation of these stimuli were reported in Kemmer et al. (2004) which included results for both 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 1300 ms at 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.

4. General discussion

The present study was intended to investigate hemispheric differences in processing grammatical number agreement in neurologically intact individuals using the visual half-field paradigm. As previous research with split brain patients had suggested the isolated RH was more adept at processing number agreement marked lexically than morphologically (Zaidel, 1983b, 1990), stimuli included two sorts of number violations: lexically marked agreement errors between reflexive pronouns and their antecedents ("The grateful niece asked *herself*/**themselves* how she could repay her aunt.") and morphologically marked agreement errors between subjects and verbs ("Industrial scientists *develop*/**develops* many new consumer products"). Consistent with Zaidel's proposal, all three experiments showed greater evidence for hemispheric asymmetry in the detection of morphologically marked subject/verb agreement errors than for lexically marked violations on the reflexives.

In experiment 1, responses to subject/verb sentences were both faster and more accurate with RVF than LVF presentation, suggestive of LH superiority in the detection of morphologically marked number agreement violations. In experiment 2, the duration of the critical word was doubled in order to increase the probability that the RH could read it. While this modification led to better performance for both LVF and RVF presentations relative to that observed in experiment 1, LH superiority in the processing of subject/verb agreement violations was still evident. As in experiment 1, responses in experiment 2 were faster and more accurate with presentation to the RVF than the LVF.

Moreover, the ERP data from experiment 3 revealed a qualitative difference in how our critical words were processed as a function of which hemisphere initially received the stimuli. With RVF/LH presentation, ungrammatical subject/verb materials elicited a larger N400 than grammatical stimuli, followed by a P600 effect that was very similar to that reported by Kemmer et al. (2004) for these same materials presented centrally. With LVF/RH presentation, by contrast, the P600 effect was completely absent, the only effect of grammaticality being a sustained negativity over frontal cortex. These dramatic differences in ERP effects of grammaticality indicate the RH was less able than the LH to appreciate subject/verb number agreement.

Interestingly, our data are somewhat reminiscent of those in an ERP study conducted in stroke patients on the processing of subject/verb agreement violations (Wassenaar et al., 2004). Wassenaar and colleagues recorded ERPs as LH damaged aphasic patients, RH damaged non-aphasic patients, and age-matched controls listened to Dutch sentences that were either grammatical or contained subject/verb agreement violations. Relative to grammatical materials, ungrammatical verbs elicited a larger P600 in healthy controls that was completely absent from ERPs recorded in LH damaged patients (Wassenaar et al., 2004), just as it was absent with LVF presentation in the current study. In RH damaged patients, ungrammatical verbs elicited a larger N400-like response than grammatical, followed by a larger P600 (Wassenaar et al., 2004)—a pattern of results quite similar to that observed with RVF presentation in the current study. These data suggest that when the brunt of morphosyntactic processing is borne by the LH (i.e., with RVF presentation or when the RH has been damaged), compensatory neural activity is recruited during the N400 interval associated with meaning activation and integration processes, but the P600 grammaticality effect is otherwise unchanged. When the RH prevails (with LVF presentation or LHD), P600 grammaticality effects were entirely absent, suggesting a causal role for the intact LH in the elicitation of these effects.

The sustained frontal negativity we observed to subject/verb agreement violations presented to the LVF may be related to bilateral frontal lobe activity previously reported in neuroimaging studies of grammatical processing conducted in healthy adults (Newman et al., 2001). For example, in a study that included agreement violations similar to those employed here, Ni et al. (2000) reported bilateral activity in the inferior frontal and post-central gyri, along with exclusively LH activation in the middle and superior frontal gyri. Indeed, bilateral activation of the inferior frontal gyrus was revealed in a meta-analysis of neuroimaging language studies involving healthy right-handed adults, as syntactic manipulations have often been observed to activate an area in the ventral aspect of the pars triangularis in both the LH and its RH counterpart (Vigneau et al., 2011). But whereas the relevant LH pars triangularis regions activated to both lexical semantic and syntactic manipulations, homotopic activations in the RH were unique to syntax (Vigneau et al., 2011). Vigneau and colleagues argue that while the LH predominates in syntactic processing, inter-hemispheric cooperation can occur between homotopic regions in both frontal and temporal cortex.

In contrast to robust evidence for LH predominance in the processing of subject/verb agreement violations, results of the present study suggested there is far less functional asymmetry in the processing of lexically marked number agreement on reflexive pronouns. In experiment 1, responses to reflexives were no more accurate with RVF than LVF presentation, and only the ungrammatical items showed any evidence of slowing with presentation to the LVF. In experiment 2, responses to *grammatical* reflexives were more accurate with RVF than LVF presentation, but only marginally faster; responses to *ungrammatical* reflexives were reliably faster with RVF presentation, but no more accurate. Perhaps the most revealing, however, were the ERP results in experiment 3 in which we observed very similar P600 grammaticality effects with presentation to the LVF as we did for presentation to the RVF. Taken together, these results suggest the RH had some capacity to detect number agreement violations marked lexically.

4.1. Local vs. global processing preferences

One question of interest is whether the LH advantage for the morphological marking (subject/verb condition) reflects a language-specific difference between the two hemispheres for syntactic processing, or whether it reflects a more general hemispheric difference in perceptual processing. Converging evidence from many fields and methodologies suggests that the hemispheres are differentially dominant at processing local as opposed to global information: the RH is biased for global processing whereas the LH is biased for processing on a local level (Banich and Noll, 1993; Delis et al., 1986; Heinze et al., 1998; Heinze and Münte, 1993; Lamb and Robertson, 1989; Martin, 1979; Martinez et al., 1997; Robertson and Delis, 1986; Robertson and Lamb, 1991; Robertson et al., 1988, 1993; Sergent, 1982; Yovel et al., 2001). In the present study, the morphologically marked number agreement might be considered a local feature, whereas the lexically marked number agreement might be seen as involving more global aspects of these sentences.

Ivry and Robertson's (1998) double filtering by frequency (DFF) theory suggests 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 RH functions like a low-pass filter, while processing in the LH 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 ones. 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.

The RH may have been less likely to pick up on grammatical number marking in the subject/verb sentences than in the reflexive condition because the presence or absence of the/-*s*/is a perceptually less salient feature, the discrimination of which requires higher frequencies. Under a view that the RH 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 RH. 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 (see Fig. 8).

In fact, the English language is such that morphologically marked number agreement is almost always less visually salient than lexically marked number agreement, making it difficult to ascertain whether the observed hemispheric asymmetry is truly linguistic, or reduces to visual processing differences. It is even possible that early differences in visual processing help sculpt the language system such that the LH encodes grammatical information at the morphological level, while both hemispheres encode grammatical information at the lexical level. Future work – perhaps in languages with a richer morphological system than English – should seek to dissociate visual salience from lexical vs. morphological representations.

4.2. Alternative explanations

Observed differences in hemispheric asymmetries in the processing of subject/verb vs. reflexive pronouns might also be related to their differing syntactic properties. In the present stimulus set, subject/verb agreement violations were relatively local, involving dependencies between adjacent words, whereas the pronoun violations involved a dependency that spanned at least one word (e.g., between ‘niece’ and ‘herself’ in ‘niece asked herself’). Neuroimaging research is consistent with dissociations between brain areas supporting local structure building and more complex syntactic processing (Friederici et al., 2003) and suggests that the likelihood of bilateral temporal lobe activations (i.e., including the RH) increases as a function of the distance between dependent items (Roder et al., 2002). On such an account, exclusive LH sensitivity observed in the present study for subject/verb agreement errors would be predicted for any sort of syntactic dependency between adjacent

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words. Moreover, we might expect that subject/verb agreement violations between non-adjacent items (e.g., “Industrial scientists who are good at their jobs *develops many new consumer products,”) would involve more bilateral processing, and, consequently, would elicit more similar ERP effects with presentation to both visual fields.

The two sorts of number agreement violations employed in the present study can also be distinguished in the sorts of rules that generative grammarians invoke to describe them. In particular, the dependencies in the subject/verb sentences can undergo movement, whereas reflexive pronouns are subject to the binding principles (e.g., Lasnik and Uriagereka, 1988, but c.f. Zwart, 2002). Grodzinsky and Santi (2008) have suggested that movement and binding operations are subserved by different networks of brain areas, and further that the movement operations presumed to underlie subject/verb agreement recruit more exclusively LH areas. Our finding of exclusive LH sensitivity to subject/verb agreement violations and bilateral sensitivity to violations on reflexive pronouns are thus in keeping with Santi and Grodzinsky’s (2007) claim that movement operations are subserved by Broca’s area, and binding operations by RH frontal areas.

Finally, it is possible that observed results are related to hemispheric differences in temporal integration that promote LH specialization for phonetic distinctions, and RH specialization for prosodic ones (Poeppel, 2003). Although materials in the present study were visually presented, people often impose prosodic structure during silent reading (Ashby, 2006; Fodor, 2002). Given the importance of prosodic cues for the interpretation of reflexive pronouns in English (Zribi-Hertz, 1989), greater RH sensitivity in the present study to violations in the reflexive pronouns might be related to the importance of that hemisphere for prosodic processing (Friederici and Alter, 2004). Supra-segmental auditory cues are processed in a RH fronto-temporal network that includes counterparts of LH areas presumed important for syntactic processing, such as the frontal operculum and areas in the superior temporal gyrus (Meyer et al., 2002). The bilateral sensitivity observed here to violations in reflexive pronouns would be attributable to different sorts of cues recruited by each hemisphere, syntactic ones in the case of rvf/LH and prosodic ones in the case of LVF/RH. Moreover, the rvf/LH N400 elicited by verb agreement violations might reflect increased processing difficulty that results from the decreased availability of implicit prosody from the RH. Definitive interpretation of these data, however, will require further research.

4.3. Conclusion

The three – one ERP and two behavioral – experiments reported here provide evidence that the RH is better at processing grammatical number marked lexically (reflexive pronoun condition) than marked morphologically (subject/verb condition). Although the data are compatible with a number of plausible interpretations, we speculate that observed differences between the two hemispheres for syntactic processing might be related to hemispheric differences in preferences for global as opposed to local information.

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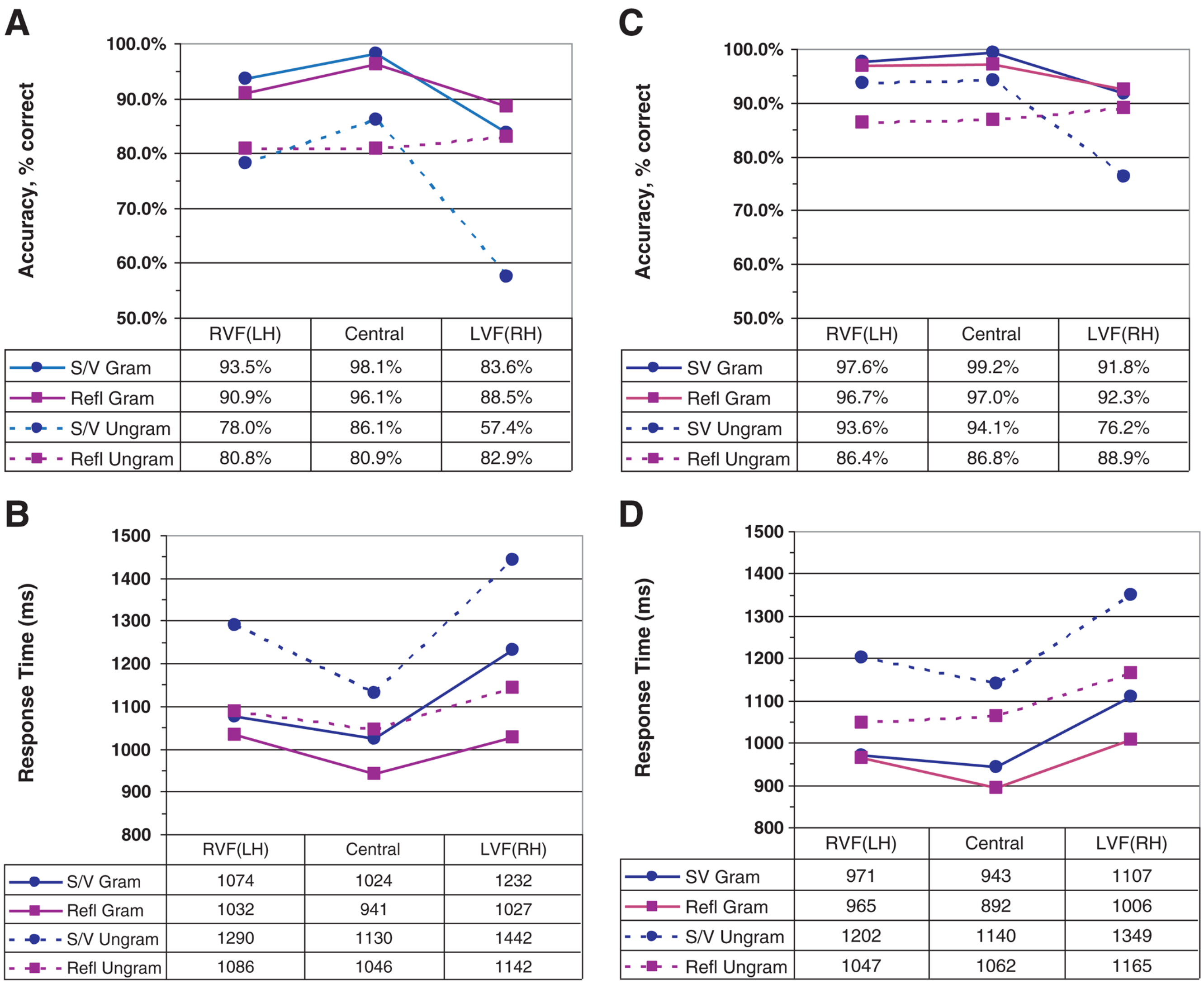

A

	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%

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

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%

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

Fig. 1.

A and B. Accuracy and response time data for experiment 1. Data for the subject/verb condition are shown with round markers; data for the reflexive condition are shown with square markers. Grammatical conditions are shown with solid lines; ungrammatical with dashed lines. A shows the accuracy data; B shows response time data.

C and D. Accuracy and response time data for experiment 2. Data for the subject/verb condition are shown with round markers; data for the reflexive condition are shown with square markers. Grammatical conditions are shown with solid lines; ungrammatical with dashed lines. C shows the accuracy data; D shows response time data.

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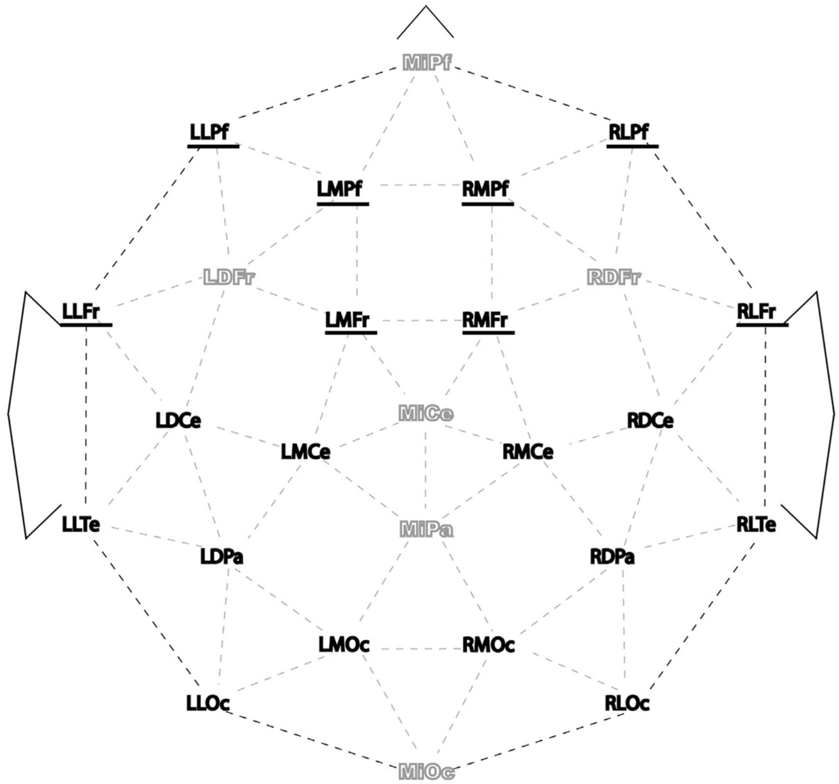


Fig. 2.

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.

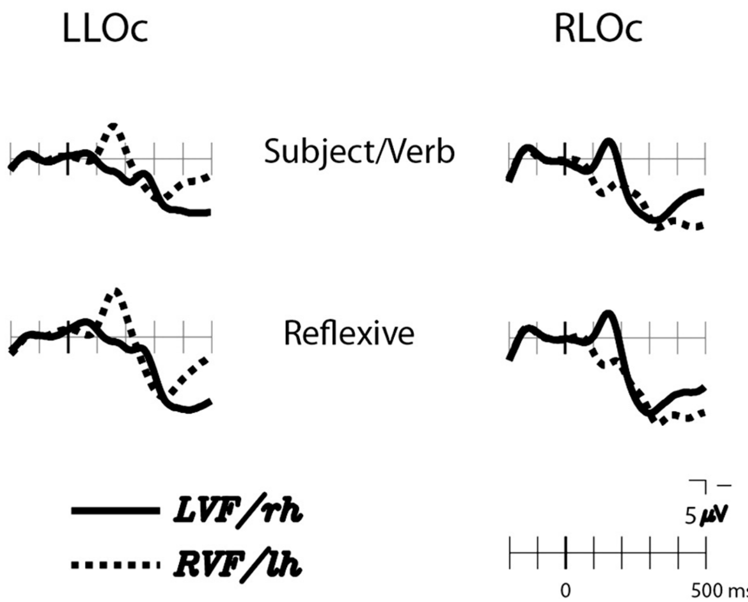


Fig. 3.

Early visual potentials elicited by presentation to the left visual field (LVF/rh; solid line) and the right visual field (RVF/lh; dashed line) 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.

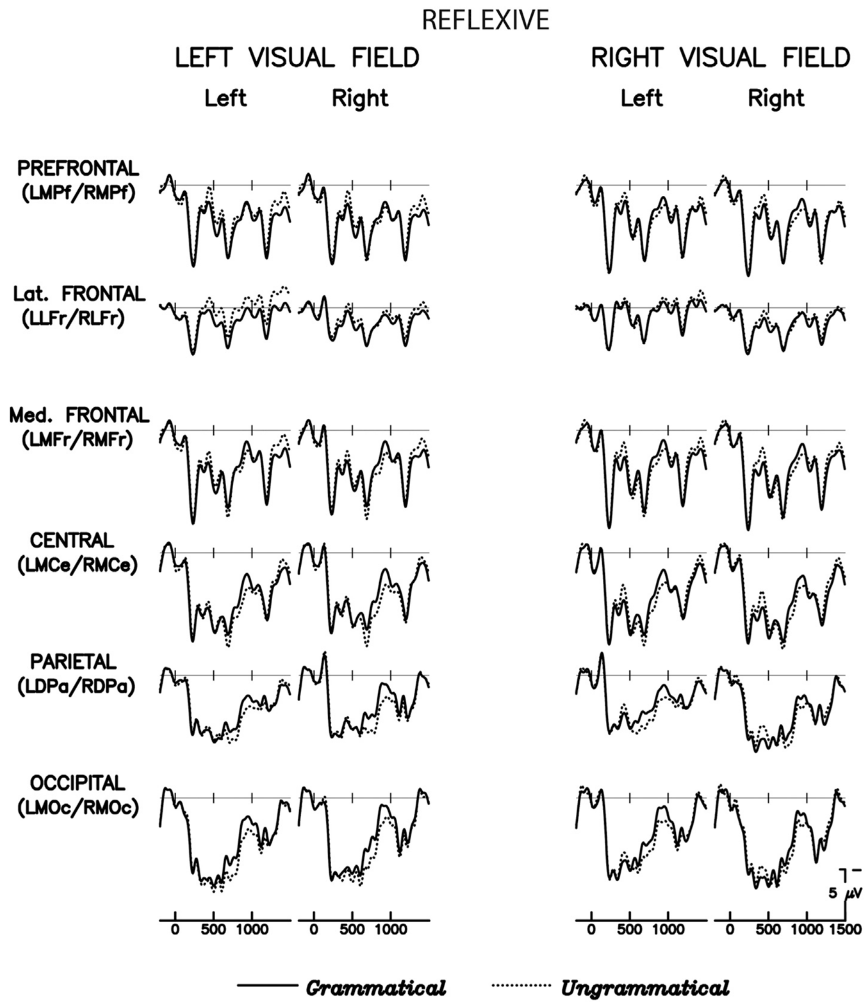


Fig. 4.

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).

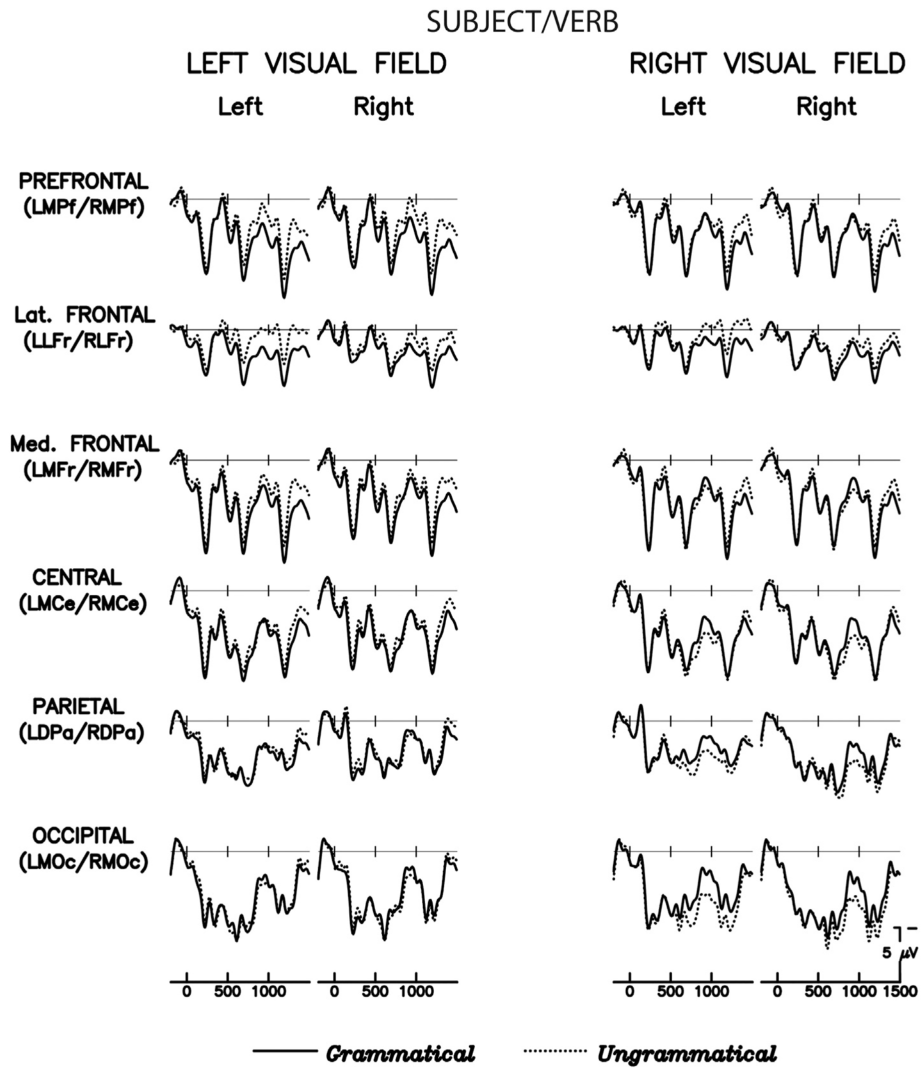


Fig. 5.
Grand average (*N* = 36) ERP waveforms elicited by grammatical number violations (solid line) and corresponding control sentences (dotted line) for subject/verb sentences for LVF and RVF presentation. Electrodes shown are a representative subset, including left and right medial prefrontal electrodes (LMPf, RMPf), lateral frontal (LLFr, RLFr), medial frontal (LMFr, RMFr), mediolateral central (LDCe, RDCe), mediolateral parietal (LDPa, RDPa), and medial occipital (LMOC, RMOc).

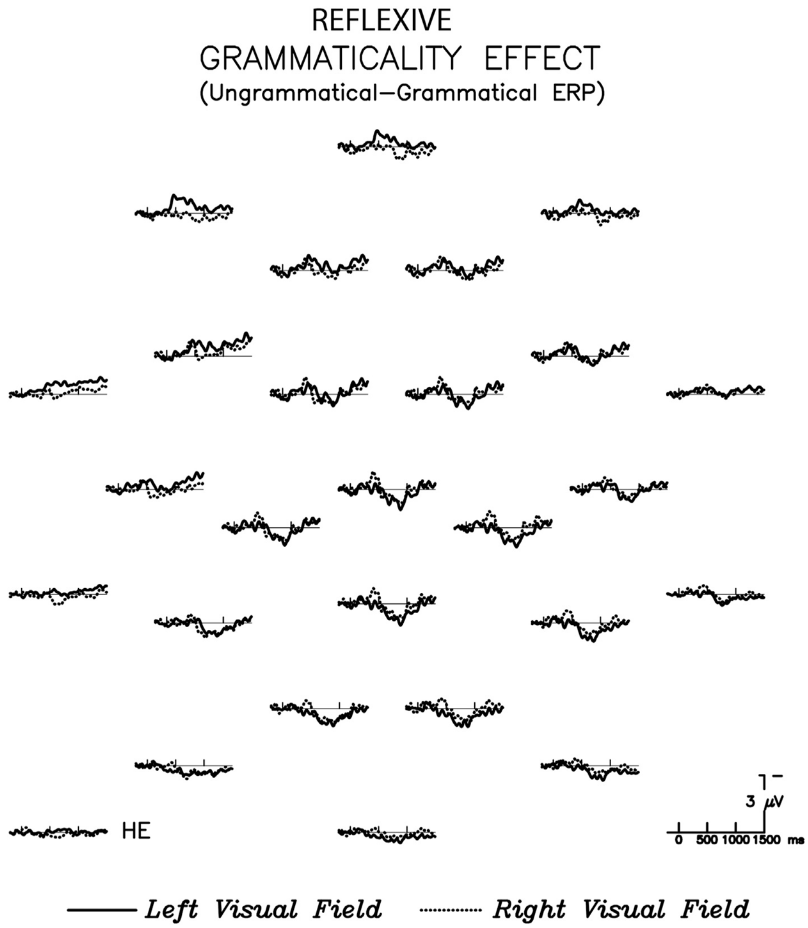


Fig. 6.

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.

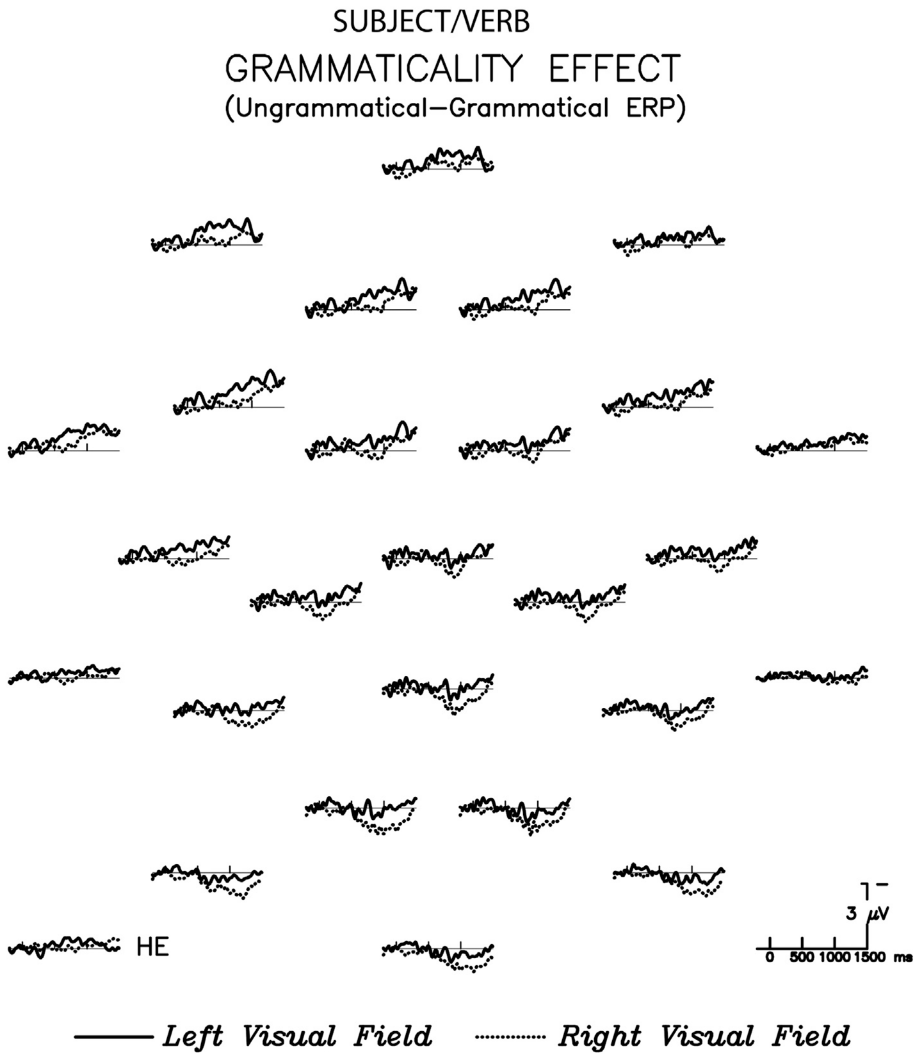
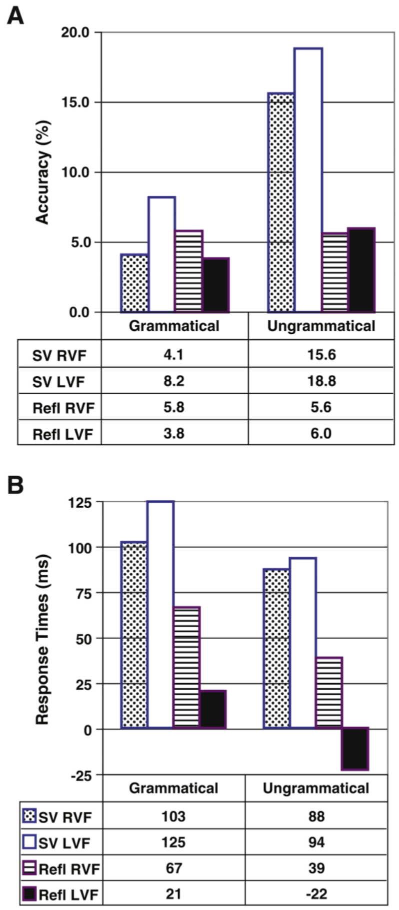


Fig. 7.
Difference ERPs for the subject/verb condition, formed by subtracting grammatical from ungrammatical ERPs, showing the P600 effect for LVF (*N* = 36; solid line) and RVF (*N* = 36; dotted line) presentation.



	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

	Grammatical	Ungrammatical
SV RVF	103	88
SV LVF	125	94
Refl RVF	67	39
Refl LVF	21	-22

Fig. 8.

Performance gain data for accuracy (Fig. 8A) and response time (Fig. 8B) 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 two left bars (dots or solid white) while the data for the reflexive condition is shown in the two right bars (horizontal lines or solid black). For each, the patterned fill represents data for RVF presentation; the solid fill represents data for LVF presentation. Data for grammatical conditions are shown in the left column; ungrammatical in the right column.

Table 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.

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

Table 2

Omnibus analysis of ERP data measured 300–500 ms after the onset of the critical word.

300–500 ms	Factors	F-values	p-values, Epsilon
	Grammaticality	*F*(1,35) = 9.85	*p* = .003
	Grammaticality × Anteriority	*F*(4,140) = 4.30	*p* = .043, ε = .37
	Grammaticality × Hemisphere × Anteriority	*F*(4,140) = 3.10	*p* = .050, ε = .60
	Sentence Type	*F*(1,35) = 41.02	*p* = .000
	Sentence Type × Laterality	*F*(1,35) = 40.54	*p* = .000
	Sentence Type × Anteriority	*F*(4,140) = 10.99	*p* = 002, ε = .37
	Sentence Type × Laterality × Anteriority	*F*(4,140) = 6.22	*p* = .001, ε = .68
	Sentence Type × Hemisphere × Anteriority	*F*(4,140) = 4.75	*p* = .012, ε = .53
	Sentence Type × Hemisphere × Laterality × Anteriority	*F*(4,140) = 8.32	*p* = .000, ε = .90
	Sentence Type × Grammaticality × Hemisphere × Laterality	*F*(1,35) = 4.16	*p* = .049
	Visual Field × Hemisphere	*F*(1,35) = 20.61	*p* = .000
	Visual Field × Hemisphere × Laterality	*F*(1,35) = 11.28	*p* = .002
	Visual Field × Hemisphere × Laterality × Anteriority	*F*(4,140) = 14.78	*p* = .000, ε = .55

Table 3

Omnibus analysis of ERP data measured 600–900 ms after the onset of the critical words in Experiment 3.

600–900 ms	Factors	F-values	p-values, Epsilon
	Grammaticality × Laterality	$F(1,35) = 11.76$	$p = .002$
	Grammaticality × Anteriority	$F(4,140) = 13.39$	$p = .000$, $\varepsilon = .39$
	Grammaticality × Hemisphere × Anteriority	$F(4,140) = 2.97$	$p = .035$, $\varepsilon = .72$
	Grammaticality × Hemisphere × Laterality	$F(1,35) = 4.60$	$p = .039$
	Grammaticality × Laterality × Anteriority	$F(4,140) = 5.38$	$p = .002$, $\varepsilon = .79$
	Sentence Type × Hemisphere × Anteriority	$F(4,140) = 10.29$,	$p = .000$, $\varepsilon = .58$
	Sentence Type × Laterality × Anteriority	$F(4,140) = 3.57$,	$p = .032$, $\varepsilon = .61$
	Sentence Type × Hemisphere × Laterality × Anteriority	$F(4,140) = 9.54$,	$p = .000$, $\varepsilon = .71$
	Visual Field × Hemisphere × Anteriority	$F(4,140) = 82.84$,	$p = .000$, $\varepsilon = .41$
	Visual Field × Grammaticality × Hemisphere	$F(1,35) = 7.66$,	$p = .009$
	Visual Field × Grammaticality × Hemisphere × Laterality	$F(1,35) = 6.69$	$p = .014$
	Visual Field × Grammaticality × Hemisphere × Laterality × Anteriority	$F(4,140) = 2.71$	$p = .049$, e = .74