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Syntactic processing with aging: An event-related potential study

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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, is 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 change in speed of processing.

Descriptors: Event-related potentials, Syntax, Language, Aging, P600, Generalized slowing

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 adults, "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 the 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) that affect a large number (although not all) of the cognitive processes as well as some localized components that 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

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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, & Muente, 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 between 200 and 500 ms post stimulus onset, 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 0.05–0.09 μV per year and reliable linear increase in peak latency of the N400 effect of 1.5–2.1 ms/year (spanning six decades from 20 s to 70 s). 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 propositional 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, and 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, 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 function words, 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 70 s and 80 s (relative to those in their 50 s and 60 s) 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; Muente, 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 given 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.

Methods

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 1 for sample experimental sentences).

Table 1. *Sample Sentences from Each Condition*

Subject-verb number 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.

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 & 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 coreferenced 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.

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 that includes both verbal and nonverbal tests; all of our older subjects 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.

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 midbreak until participants were accustomed to the hand mapping switch.

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 rereferenced 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.

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 rereferenced off-line 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 that 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 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 violation 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.

Results

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, $F(1,30) = 27.32$,

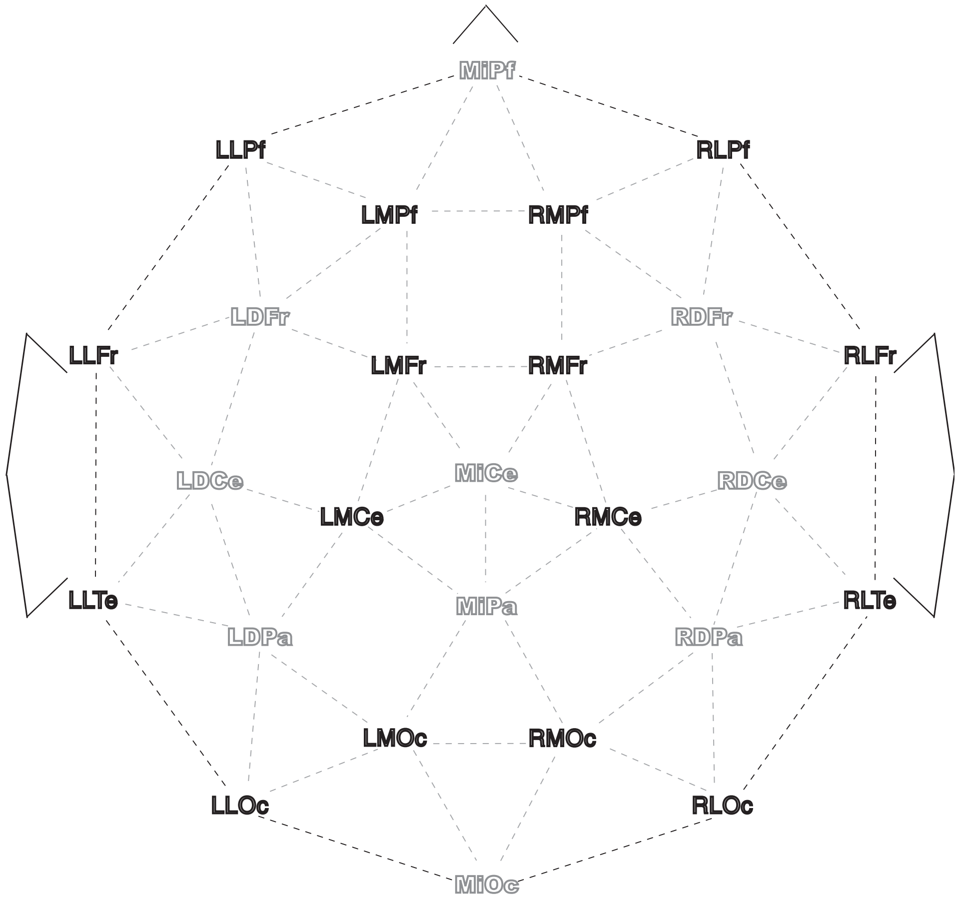

Figure 1. Schematic diagram of the locations of the 26 scalp electrodes, all of which were used for the full statistical analysis. The distributional analysis was restricted to the 16 electrodes with labels shown in bold print.

$p = .000$. Younger participants were both more accurate (90% vs. 82%) and faster (994 ms vs. 1,675 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 speed, $F(1,30) = 24.27$, $p = .000$. 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 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, $F(1,30) = 0.76$, $p = .390$, whereas 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 ($\beta = .72$) but not to subject/verbs ($\beta = 1.03$; a β of 1.0 represents no bias at all).

Table 2. *Accuracy Data*

	Grammatical (hits)	Ungrammatical (correct rejects)	Misses	False alarms
Younger adults				
Subject/Verb	96.4 (0.7)	83.6 (3.3)	3.6 (0.7)	16.4 (3.2)
Reflexives	96.0 (0.6)	82.3 (3.8)	4.0 (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, $F(1,15) = 13.35$, $p = .002$.

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.

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 ($0.80\,\mu V$) than those in the subject/verb condition ($0.33\,\mu V$); 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 ($3.11\,\mu V$) than those of the older ($0.84\,\mu V$) ones, 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.

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 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.

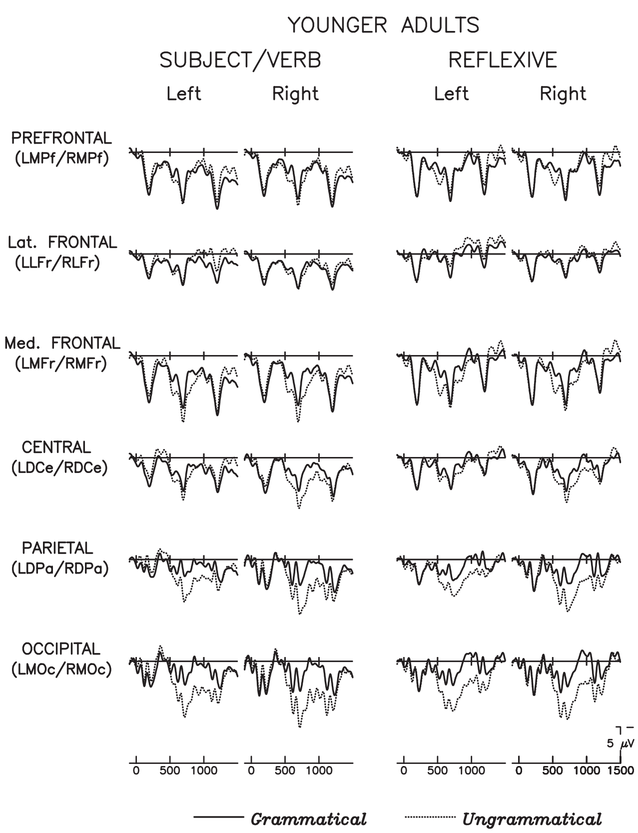

Figure 2. Grand average ($N = 16$) ERP waveforms elicited by grammatical number violations (solid line) and corresponding control sentences (dotted line) in younger adults for each sentence type. Electrodes shown are a representative subset, including left and right medial prefrontal electrodes (LMPf, RMPf), lateral frontal (LLFr, RLFr), medial frontal (LMFr, RMFr), mediolateral central (LDCe, RDCe), mediolateral parietal (LDPa, RDPa), and medial occipital (LMOC, RMOc).

Analyses of mean amplitude: 300–500 ms. The hemispheric analysis (all electrodes except the four midline), with factors of Sentence Type, Grammaticality, and Hemisphere, showed a significant Type × Grammaticality × 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 × Laterality and Type × Anteriority interactions that were modulated by a three-way interaction of Sentence Type × Laterality × 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.

Analyses of mean amplitude: 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, $F(1,15) = 5.960$, $p = .028$, though more so by about 0.5 μV for ungrammatical than grammatical items, Grammaticality × Hemisphere, $F(1,15) = 6.95$, $p = .019$.

Grammaticality effects were larger at medial than lateral sites, especially over posterior sites, Grammaticality × Laterality × 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 × Anteriority, $F(3,45) = 9.15$, $p = .007$, $\varepsilon = .45$; Sentence Type × Laterality × 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 × 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 × Anteriority, $F(3,45) = 6.62$, $p = .020$, $\varepsilon = .36$.

Analyses of mean amplitude: 250–400 ms. Between 250 and 400 ms, there was no sign of difference between grammatical and ungrammatical items for the 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 × Hemisphere, $F(1,15) = 3.81$, $p = .070$. The same analysis for the reflexive condition revealed no significant main effects or interactions.

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 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.

Analyses of mean amplitude: 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, $F(1,15) = 0.09$, $p = .768$.

Analyses of mean amplitude: 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 the difference in the ungrammatical items (1.32 vs. 2.14 μV, grammatical = − 0.04 vs. − 0.08 μV; Sentence Type × 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 × Laterality, $F(1,15) = 12.90$, $p = .003$, Sentence Type × Hemisphere × Anteriority, $F(1,15) = 6.90$, $p = .003$; Sentence Type × Laterality × Anteriority, $F(1,15) = 3.71$, $p = .035$; Sentence Type × Grammaticality × Laterality × Anteriority, $F(3,45) = 4.06$, $p = .029$, $\varepsilon = .60$; Sentence Type × Hemisphere × Laterality × Anteriority, $F(3,45) = 4.28$, $p = .024$, $\varepsilon = .65$; and Grammaticality × Hemisphere × Laterality × 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 × 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.

Analyses of mean amplitude: 250–400. There were no reliable effects of interest in this window.

Between–Groups Comparison: Young versus 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 N1 s, 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.

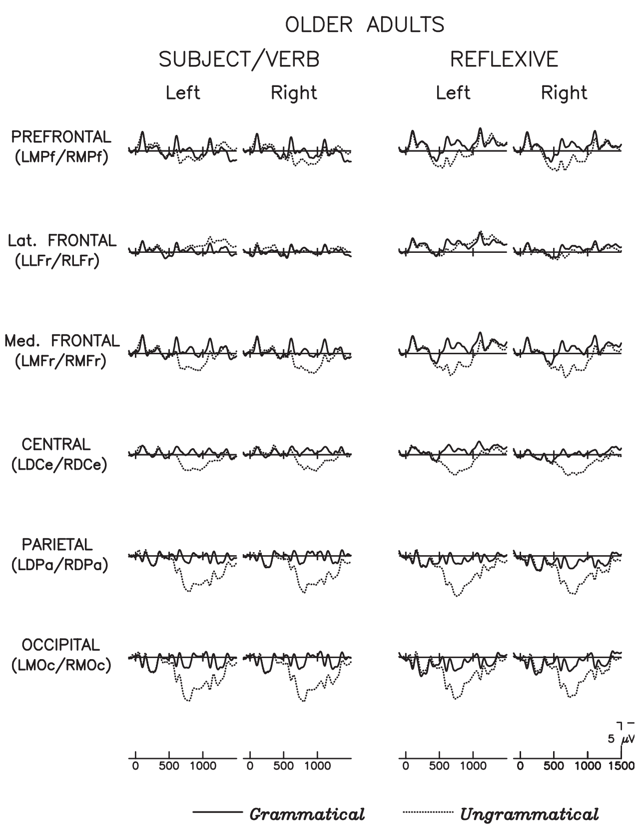

Figure 3. Grand average ($N = 16$) ERP waveforms elicited by grammatical number violations (solid line) and corresponding control sentences (dotted line) in older adults for each sentence type. Electrodes shown are a representative subset, including left and right medial prefrontal electrodes (LMPf, RMPf), lateral frontal (LLFr, RLFr), medial frontal (LMFr, RMFr), mediolateral central (LDCe, RDCe), mediolateral parietal (LDPa, RDPa), and medial occipital (LMOC, RMOc).

[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).

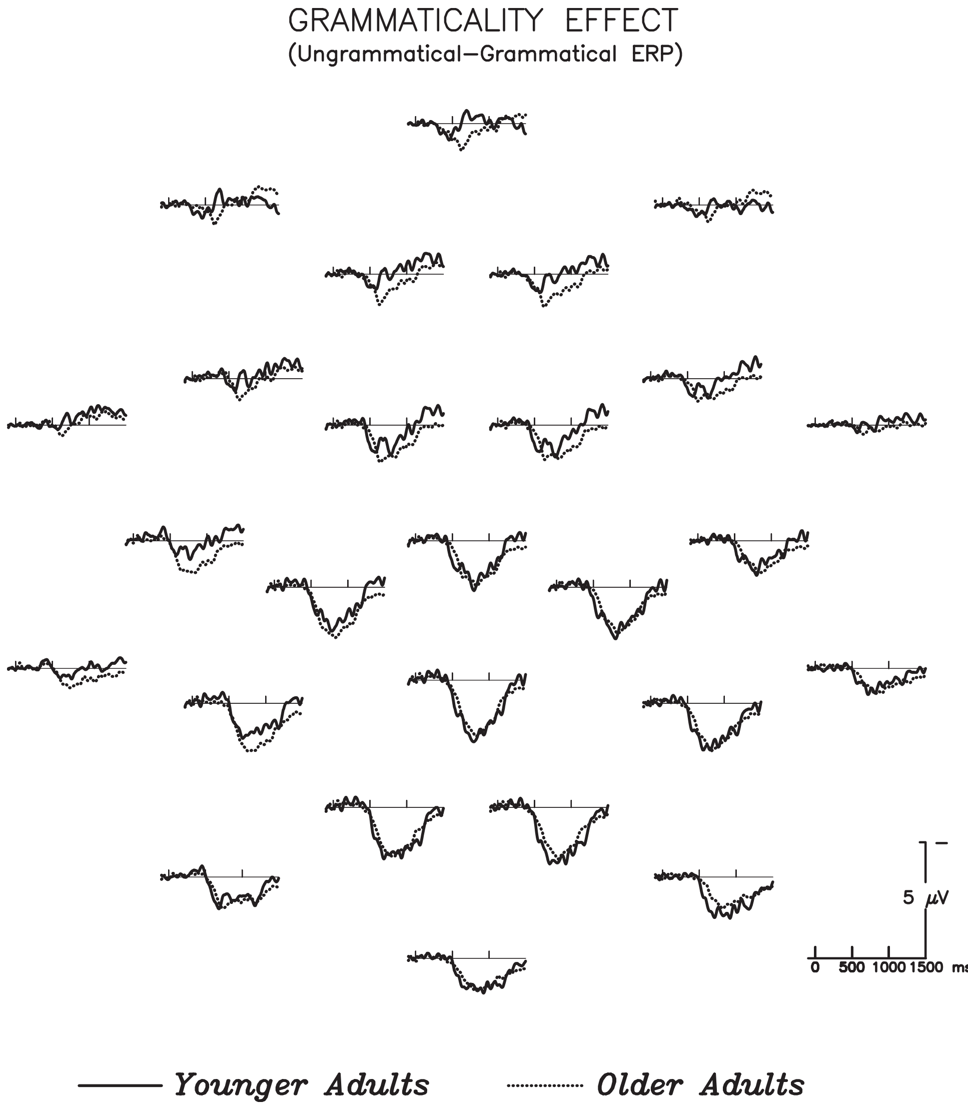

Figure 4. Difference ERPs, formed by subtracting grammatical from ungrammatical ERPs, showing the P600 effect for younger ($N = 16$; solid line) and older ($N = 16$; dotted line) adults.

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 4).

Analyses of mean amplitude in difference ERPs: 300–500 ms. There were no reliable age-related effects between 300 and 500 ms.

Analyses of mean amplitude in difference ERPs: 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 × 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 × 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 × Grammaticality × Hemisphere, $F(1,30) = 7.20$, $p = .012$. See Figure 5 for voltage maps showing the scalp distribution for the 500–800-ms time window.

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 violations, 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

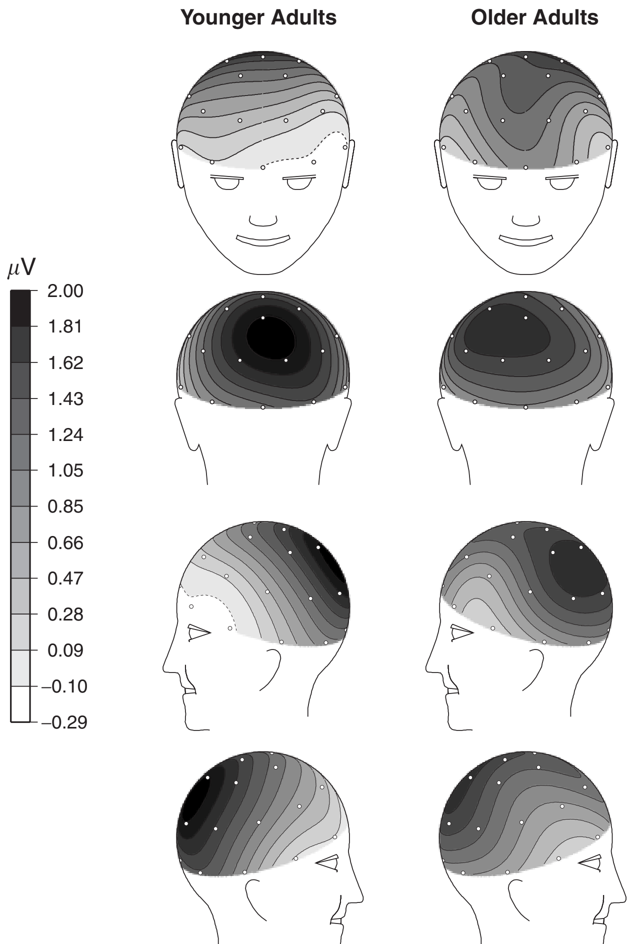

Figure 5. Voltage maps showing the scalp distribution of the P600 effect (mean amplitude in 500–800-ms time window) in younger adults and older adults.

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: Muente 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).[2] 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 5).[3]

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, preresponse cognitive processes (Bashore & Smulders, 1995; Ford et al., 1979; Hartley, 2001; Madden, Pierce, & Allen, 1993). However, because 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]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.

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 reanalysis 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). Muente 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 reprocessing, 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.

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).

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 responses 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 of 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).

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