Psychophysiology, 37 (2000), 179–189. Cambridge University Press. Printed in the USA.

Age-related decline in inhibitory control contributes to the increased Stroop effect observed in older adults

ROBERT WEST AND CLAUDE ALAIN

Rotman Research Institute of Baycrest Centre for Geriatric Care and Department of Psychology, University of Toronto, Canada

Abstract

Past research has demonstrated an age-related increase in the Stroop effect. Some theorists have suggested that this increase results from a decline in the ability to inhibit word information on incongruent trials, whereas others have suggested that the decline reflects general slowing. These two hypotheses were evaluated using event-related brain potentials (ERPs) measured while younger and older adults performed the Stroop task. As expected, the Stroop effect was greater for older than younger adults. The ERP data revealed a selective age-related attenuation of two modulations reflecting the inhibition of word information on incongruent trials. Latency of the P3 wave did not increase to a greater extend for older than younger adults from the congruent to incongruent trials as expected based on the general slowing hypothesis. Taken together, these findings support the inhibitory deficit hypothesis by demonstrating an age-related decline in a conceptual level inhibitory process that supports the suppression of word information in the Stroop task.

Descriptors: Aging, Stroop task, Inhibitory deficit, ERPs, Evoked potentials

The inhibitory deficit hypothesis (Hasher & Zacks, 1988) has been one of the leading models within the field of cognitive aging over the past decade. Within this model, age-related declines across a number of domains of cognition, including attention, retrospective and working memory, and social cognition are proposed to result from an inability to inhibit the influence of task irrelevant information. In comparison, cognitive processes supporting the facilitation or enhancement of task relevant information are proposed to be largely immune to the aging process. A number of studies provide evidence supporting this theory, indicating that age-related declines in inhibitory efficiency contribute to the poor performance of older adults on tasks requiring selective attention (Stoltzfus, Hasher, Zacks, Ulivi, & Goldstein, 1993), controlled memory search (Hartman & Hasher, 1991), and sustained attention (Bunce, Warr, & Cochrane, 1993).

In agreement with these behavioral data, evidence from a number of electrophysiological studies supports the inhibitory deficit hypothesis. For instance, in a study examining the skin conductance orienting response, habituation of the orienting response to a tone was faster for younger adults instructed to ignore the tone than for younger adults instructed to count the number of tones presented (McDowd & Filion, 1992). In comparison, the rate of habituation in older adults was similar in the ignore and attend conditions. This difference suggests that increasing age resulted in a reduced ability to inhibit the processing of task irrelevant information. Complementing this finding, a number of researchers have observed an age-related increase in the amplitude of auditory-evoked potentials including the Pa wave, a middle latency auditory-evoked potential measured between 25 and 35 ms poststimulus onset (Chambers & Griffiths, 1991; Woods & Clayworth, 1986), and the N1 wave, a long latency potential measured between 80 and 120 ms poststimulus onset (Alain & Woods, 1999; Karayanidis, Andrews, Ward, & Michie, 1995; Laffont et al., 1989). Chao and Knight (1997) suggested that this increase in the amplitudes of the Pa and N1 waves results from an age-related decline in inhibitory processes supported by the prefrontal cortex. This proposal is supported by the finding that a similar enhancement of the Pa wave is observed in patients with damage to the prefrontal cortex (Knight, Scabini, & Woods, 1989).

One potential limitation of the current electrophysiological data is that it provides evidence only for age-related decline in inhibitory processes at sensory and perceptual levels. This limitation makes it difficult to determine whether or not declining inhibitory processes in older adults contribute to age-related differences in cognitive efficiency observed at higher conceptual levels of information processing. The potential importance of this limitation becomes apparent when one considers findings from a number of behavioral studies indicating that age-related decline in inhibitory control is not observed universally across tasks reputed to tap inhibitory processing (Burke, 1997; McDowd, 1997). For instance, Connelly and Hasher (1993) reported that age-related declines in inhibitory efficiency were observed in identity but not location-based negative priming. Similarly, in a multivariate study, age-related declines in inhibitory efficiency were observed in a stop

This research was supported by a postdoctoral fellowship sponsored by a grant from the National Institute of Aging (RO1 AG13845-01) awarded to R.W. and a grant from the Medical Research Council of Canada awarded to C.A.

We thank two anonymous reviews for their helpful comments on an earlier version of the paper.

Address reprint requests to: Robert West, 118 Haggar Hall, University of Notre Dame, Notre Dame, IN 46556, USA.

signal paradigm and on the Wisconsin Card Sorting test (Heaton, 1981), but not on a negative priming task, a response compatibility task, or a spatial cueing task (Kramer, Humphrey, Larish, Logan, & Strayer, 1994).

One task that has been used to study age-related declines in conceptual level inhibitory processes is the Stroop task (Stroop, 1935). In this task, individuals are asked to identify the color of a stimulus for congruent (e.g., the word RED presented in the color red), neutral (e.g., XXX presented in the color red), and incongruent (e.g., the word RED presented in the color blue) trials. Response latency for incongruent trials is generally longer than response latency for congruent or neutral trials and this increase in latency on incongruent trials has been termed the *Stroop effect* (MacLeod, 1991). The Stroop effect has been observed when either vocal or manual key press responses are used (MacLeod, 1991) and is greater for older than younger adults in both cases (Spieler, Balota, & Faust, 1996; West & Baylis, 1998). Nearly all existing models propose that interference results from competition between color and word information and the need to suppress word information or facilitate color information to efficiently perform the task (Cohen, Dunbar, & McClelland, 1990; Lindsay & Jacoby, 1994).

A number of studies over the past 30 years have provided evidence that the magnitude of the Stroop effect increases in later adulthood (MacLoed, 1991). Spieler et al. (1996) proposed that this increase in the Stroop effect results from a decline in the efficiency of inhibitory processes in older adults. Using a process dissociation procedure to derive independent estimates of the contribution of color and word information to task performance, these researchers demonstrated that the larger Stroop effect observed in older adults resulted from an increase in the contribution of word information to task performance. Li and Bosman (1996) extended this finding, showing that the age-related increase in the Stroop effect was observed only when competing color and word information were drawn from the same response set. Based on this finding they proposed that older adults have difficulty inhibiting information that competes at the level of response selection and not semantic meaning. Finally, West and Baylis (1998) demonstrated recently that the age-related increase in the Stroop effect was observed in an experimental context that placed a high demand on the utilization of inhibitory processes, when the proportion of incongruent trials was high, and not in an experimental context that placed little demand on the utilization of inhibitory processes, when the proportion of incongruent trials was low.

Although these findings are consistent with the idea of age-related decline in inhibitory processes, a number of researchers have proposed recently that general slowing can also account for the age-related increase in the Stroop effect. In a meta-analysis examining the age-related increase in the Stroop effect, estimates of effect size were found to be of similar magnitude for younger and older adults (Verhaeghen & De Meersman, 1998). Moreover, response latencies for neutral and incongruent trials were found to fall along a single regression line with a negative intercept and a slope greater than one, consistent with the multilayer model of slowing proposed by Cerella (1990). A similar conclusion had been reached in studies examining large samples of individuals where there was little unique age-related variance for incongruent trials, when variance common to neutral trials (Graf, Uttl, & Tuokko, 1995; Uttl & Graf, 1997) or measures of perceptual-motor speed were controlled (Salthouse & Meinz, 1995). Support for the general slowing account is also found in a study examining the event-related potential (ERP) correlates of interference in a flanker response competition task (Zeef & Kok, 1993). In this study, the peak latency of the P3 wave was delayed for incongruent congruent trials and this increase was greater for older than younger adults, consistent with a general slowing model of age-related changes in cognition.

However, there is evidence in the existing literature that questions or at least tempers the general slowing interpretation. First, in those studies using regression methods, a significant relationship between age and performance on incongruent trials remained after controlling for factors common to measures of perceptual speed (Salthouse & Meinz, 1995) or performance on neutral trials (Uttl & Graf, 1997). Second, recent work has demonstrated that general slowing can account for age-related differences in the Stroop effect when task context does not demand the utilization of inhibitory processes, but not when task context places a high demand on the utilization of inhibitory processes (West & Baylis, 1998).

The goal of the current study was to determine whether the age-related increase in the Stroop effect resulted from impaired inhibitory processing or general slowing. Early work examining the ERP correlates of the Stroop effect failed to reveal any modulations differentiating incongruent trials from neutral and congruent trials using either amplitude or latency measures (Duncan-Johnson & Kopell, 1981). However, more recent studies have identified a number of ERP modulations that differentiate incongruent trials from neutral and congruent trials. Rebai, Bernard, and Lannou (1997) reported two ERP modulations differentiating incongruent trials from congruent trials. The first of these modulations was observed between 350 and 450 ms over the midline frontocentral region and reflected an enhanced negativity for incongruent trials. This modulation was proposed to reflect the inhibition of competing word information on incongruent trials. A second modulation was observed between 500 and 750 ms and reflected enhanced positivity over the left parietal region and negativity over the occipital region. West and Alain (1999) also found an increased negativity for incongruent trials over the midline frontocentral region (N500). The N500 was accompanied by a decreased positivity over the left parietal region and decreased negativity over bilateral frontal regions for incongruent trials relative to neutral, congruent, and word identification trials. This pattern of neural activity was proposed to reflect an inhibitory process active on incongruent trials that served to suppress or attenuate the influence of word information upon response selection processes. Following the N500 there was a negative frontocentral slow wave that may reflect response selection processes. There was also an area of enhanced positivity over the left temporoparietal region (700–1,000 ms) that emerged between the response on congruent trials and incongruent trials thought to reflect the processing of perceptual level color information used to guide a response on incongruent trials. These findings indicate that there are definable patterns of electrophysiological activity that reflect the suppression of word information on incongruent trials when competing color and word information is present, and possibly the processing of color information used to guide a response on these trials.

To address the hypothesis that the age-related increase in the Stroop effect resulted from a diminished ability to inhibit word information, we compared the amplitude of ERP modulations in younger and older adults believed to reflect inhibitory attentional processes. An age-related decline in inhibitory processing should result in a reduction in the amplitude of modulations differentiating incongruent trials from neutral and congruent trials over the midline frontocentral region (N500), and left parietal and bilateral

frontal regions. Moreover, if increasing age spares facilitatory attentional processes, then the amplitude of the left temporoparietal modulation (700–1,000 ms), thought to reflect the processing of color information, should be similar for younger and older adults. In comparison, if the age-related increase in the Stroop effect resulted from general slowing, one would expect the amplitude of these modulations to remain intact in older adults, and for the latency of these components to increase in later adulthood, with this slowing to be greatest for incongruent trials.

The Stroop task used in the study included four types of trials (i.e., congruent, neutral, incongruent, and word identification). Word identification trials were presented in light gray and participants were instructed to respond with the identity of the word on these trials. In separate blocks of trials, the proportion of word identification trials was either 25% or 50%. Past research has demonstrated that increasing the proportion of word identification trials makes word information more difficult to ignore on incongruent trials (MacDonald & MacLeod, 1996), especially for older adults (West, 1999). Therefore, by varying the proportion of word identification trials we sought to examine the impact of age-related declines in inhibitory control when task context established either a high or low demand on the need to utilize inhibitory control processes in support of task performance.

Method

Participants

Twelve younger adults ($M = 27.08$ years, $SD = 2.35$ years; 6 women) and 12 older adults ($M = 69.50$ years, $SD = 3.48$ years; 6 women) participated in the study. The younger adults had on average attained more years of formal education ($M = 18.25$ years, $SD = 2.00$ years) than the older adults ($M = 15.92$ years, $SD = 1.83$; $t(22) = 2.97$, $p < .007$). All individuals reported being satisfied with their current health status and no older adult reported any incidence of or was on medication for cardiovascular or neurological disease. Ten of the younger adults reported having a right-hand preference and 2 reported being ambidextrous, all of the older adults reported a right-hand preference. All participants reported normal or corrected to normal visual acuity and were able to clearly distinguish between the five colors used in the Stroop task.

Materials and Procedure

In the Stroop task, participants were asked to identify one of four colors (i.e., red, blue, green, or yellow) or the names of these colors by pressing one of four keys (i.e., V, B, N, or M) on a computer keyboard using the index and middle fingers of the right and left hands. The experiment was divided into a color-to-key acquisition phase, a practice phase, and a test phase. The color-to-key acquisition phase consisted of 100 trials presented in a single block with each of the four colors presented 25 times in a series of Xs equal in length to the color's name. This phase was designed to establish a strong mapping between the stimulus colors and response keys. The practice phase consisted of 40 trials representing the four types of stimuli that would be encountered in the test phase. Thirty of these trials were presented in the color red, blue, green, or yellow. There were 10 congruent (e.g., RED in red), 10 neutral (e.g., XXXX in blue), and 10 incongruent (e.g., GREEN in yellow) trials. For these trials, the participant was instructed to identify the color of the stimulus by pressing the appropriate key. In the 10 remaining trials the words red, blue, green, or yellow were presented in light gray and the individual was instructed to identify the word by pressing the appropriate key.[1]

In the test phase, participants were presented with congruent, neutral, incongruent, and word identification trials. The proportion of word identification trials was varied between blocks. The five 25% word identification blocks consisted of 96 trials. In these blocks, 25% of the trials were presented in light gray and the individual was instructed to press the key identifying the word for these trials. In the remaining trials, equal numbers of congruent, incongruent, and neutral stimuli were presented in the colors red, blue, green, and yellow and the individuals were instructed to press the key corresponding to the color of the stimulus. The five 50% word identification blocks consisted of 144 trials; the additional 48 trials in these blocks were all word identification trials. Presentation of the 25% and 50% word identification blocks was alternated over the course of the experiment, beginning with a 25% word identification block then a 50% word identification block.

At the beginning of each block of trials, a message appeared on the screen instructing the participants to press the space bar to begin the presentation of the stimuli. After the space bar was pressed the screen was blank for 1,000 ms. The stimuli were presented in the center of the screen for 400 ms, followed by a blank screen until 1,000 ms after a response was made. Following this interval, the stimulus for the next trial appeared on the screen. The task was programmed using the MEL Professional 2.0 (MEL) software (Schneider, 1995).

Electroencephalogram (EEG) Recording

The EEG (bandpass 0.05–30 Hz), digitized at 250 Hz, was recorded from an array of 47 electrodes based on the 10/20 system using Neuroscan Synamps and the SCAN 4.0 software. Vertical and horizontal eye movements were recorded from electrodes placed lateral to and below the right and left eyes. During recording all electrodes were referenced to Cz; for data analysis they were rereferenced to an average reference via the brain electrical source analysis (BESA) software (Scherg & Berg, 1991).

ERP Measurement and Analysis

ERP epochs were extracted offline and included 200 ms prestimulus activity and 1,500 ms poststimulus activity. ERPs were averaged for trials associated with a correct response as a function of stimulus type (i.e., congruent, neutral, and incongruent) and proportion of word identification trials (i.e., 25% or 50%). Trials contaminated by excessive eye or movement artifacts were rejected before averaging (peak-to-peak deflections over 200 μV). Eye movements and blinks not removed by the artifact rejection criteria were corrected using an ocular source components approach (Berg & Scherg, 1994) through BESA. Using BESA to correct for ocular activity resulted in a decimation of the data from 425 to 180 points, for a final sampling rate of approximately 105 Hz. All analyses were performed on mean voltage averaged over 100-ms windows in which modulations of interest were observed relative to the mean amplitude of the 200 ms prestimulus baseline activity. Because ERP modulations differentiating incon-

[1] An ANOVA performed on the mean response latency for the four quarters of the practice block (i.e., trials 1–25, 26–50, 51–75, 76–100) revealed significant main effects of age, $F(1,22) = 11.04$, $p < .003$, and quartile, $F(3,66) = 14.48$, $p < .001$. However, these effects did not interact, $F < 1$, indicating that the effect of practice was similar for older and younger adults.

gruent trials from congruent and neutral trials were observed at multiple electrode locations, all analyses were performed on normalized mean voltage measurements permitting a comparison of possible differences in scalp distribution between Stroop trial types, and older and younger adults (McCarthy & Wood, 1985). In addition to permitting a comparison of scalp topographies, this transformation also served to eliminate differences in mean ERPs amplitude between younger and older adults most prominent over the midline frontal region. Original degrees of freedom for all analyses are reported throughout the paper, however, all statistical tests were submitted to a strict Geisser–Greenhouse (1958) correction. For instance, main effects of Stroop trial type including congruent, neutral, and incongruent trials and 24 participants would have (2,44) degrees of freedom and an F-critical of 3.20 at $p < .05$, but be reported as significant with (1,11) degrees of freedom and a F-critical of 4.84 at $p < .05$ under the correction.

Results

Behavioral Data

Average response latency for correct responses to congruent, neutral, incongruent, and word identification trials in the 25% and 50% word identification conditions for younger and older adults are presented in Figure 1. These data were submitted to a 2 (Age) × 2 (Proportion of word identification trials) × 4 (Stroop trial type) analysis of variance (ANOVA). In this analysis each of the main effects was significant, with older adults responding more slowly than younger adults, $F(1,22) = 16.31$, $p < .001$, response latency being faster in the 50% than 25% word identification condition, $F(1,22) = 50.39$, $p < .001$, and response latency increasing from the congruent and neutral trials to the word identification and incongruent trials, $F(3,66) = 97.45$, $p < .001$. Two of the two-way interactions were also significant: Age × Stroop trial type indicating that the Stroop effect was greater for older than younger adults ($F[3,66] = 7.75$, $p < .001$)[2]; and Proportion of word identification trials × Stroop trial type, $F(3,66) = 7.55$, $p < .001$, with the effect of proportion of word identification trials being reliable for the congruent trials, $t(22) = 3.99$, and word identification trials, $t(22) = 6.65$, when tested with a Bonferroni adjustment ($p < .05$ divided by 4 or $p < .0125$). The Age × Stroop trial type × Proportion of word identification trials was not significant ($F < 1$).[3]

To consider the contribution of general slowing to the age-related increase in the Stroop effect, response latency for incongruent trials was compared in younger and older adults using response latency from neutral trials as a covariate in an analysis of covariance (ANCOVA). The effect of the covariate was significant indicating that some of the age-related difference in response latency observed for incongruent trials can be attributed to general slowing, $F(1,21) = 77.29$, $p < .001$. However, the effect of age remained significant after controlling for age-related slowing common to neutral trials, suggesting that age-related decline in some factors (e.g., inhibitory processes) other than general slowing contributed to differences in response latency between younger and older adults on incongruent trials, $F(1,21) = 10.36$, $p < .004$.

A similar ANCOVA was performed with response latency for congruent trials as the dependent variable and with response latency for neutral trials as the covariate. In this analysis the effect of the covariate was again significant, $F(1,21) = 250.66$, $p < .001$, but the effect of age on response latency was no longer significant, $F < 1$. These findings indicate that age-related differences in response latency on congruent trials can be attributed to general slowing unlike response latency on incongruent trials.

An analysis of the proportion of errors committed by younger and older adults for congruent, neutral, incongruent, and word identification trials in the 25% and 50% word identification conditions revealed significant main effects of age, $F(1,22) = 5.99$, $p < .023$, with older adults ($M = .035$) making fewer errors than younger adults ($M = .075$); and Stroop trial type, $F(3,66) = 23.63$, $p < .001$, with more error being made for incongruent trials ($M = .109$) than other trial types (congruent $M = .024$, neutral $M = .036$, word identification $M = .047$). The increased number of errors for incongruent trials reflected the occurrence of word intrusion errors ($M = .082$), in which the individual identified the word instead of the color. The number of nonintrusion errors, in which a key was pressed that did not reflect the color or word for the present trial, was similar to that observed for the other trial types ($M = .027$).

Electrophysiological Data

Figure 2 displays the group average ERPs for younger and older adults elicited in the congruent, neutral, and incongruent trials

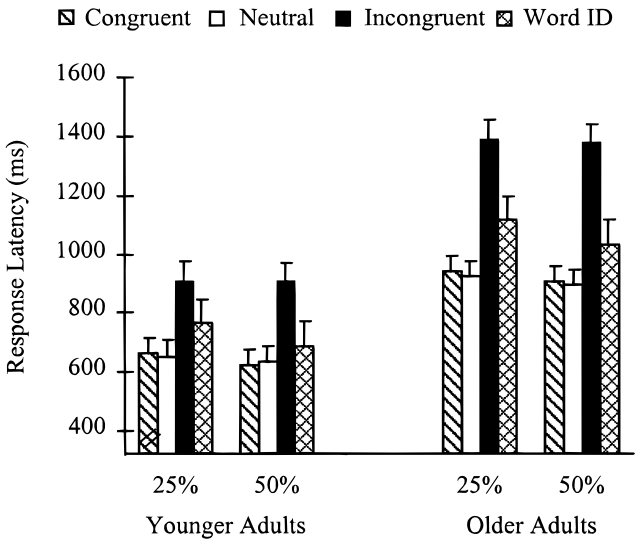

Figure 1. Mean response latency of younger and older adults for congruent, neutral, incongruent, and word identification trials in the 25% and 50% word identification conditions. Bars reflect 1 standard error.

[2] In a specific test of the age-related increase in the Stroop effect, a single degree of freedom interaction contrast was evaluated comparing response latency for older and younger adults on neutral and incongruent trials collapsing across proportion of word identification trials. This contrast was significant, consistent with idea that the magnitude of the Stroop effect increased with age, $F(1,66) = 18.52$, $p < .001$.

[3] The lower levels of education of the older adults could have confounded the effect of age in the behavioral and electrophysiological measures. To address this concern all analyses reported in the paper were also conducted as ANCOVAs using years of education as a covariate. In all cases the effect of the covariate was not significant. Therefore, the F ratios and p values for the ANOVAs are reported. Also, inclusion of the two ambidextrous subjects in the analyses may have complicated the interpretation of the asymmetrical ERP modulations. To address this concern all analyses were conducted with and without these individuals in the data set. In all cases the outcome of both sets of analyses were substantively equivalent. Therefore, the statistical test reported are for the full sample of younger and older adults.

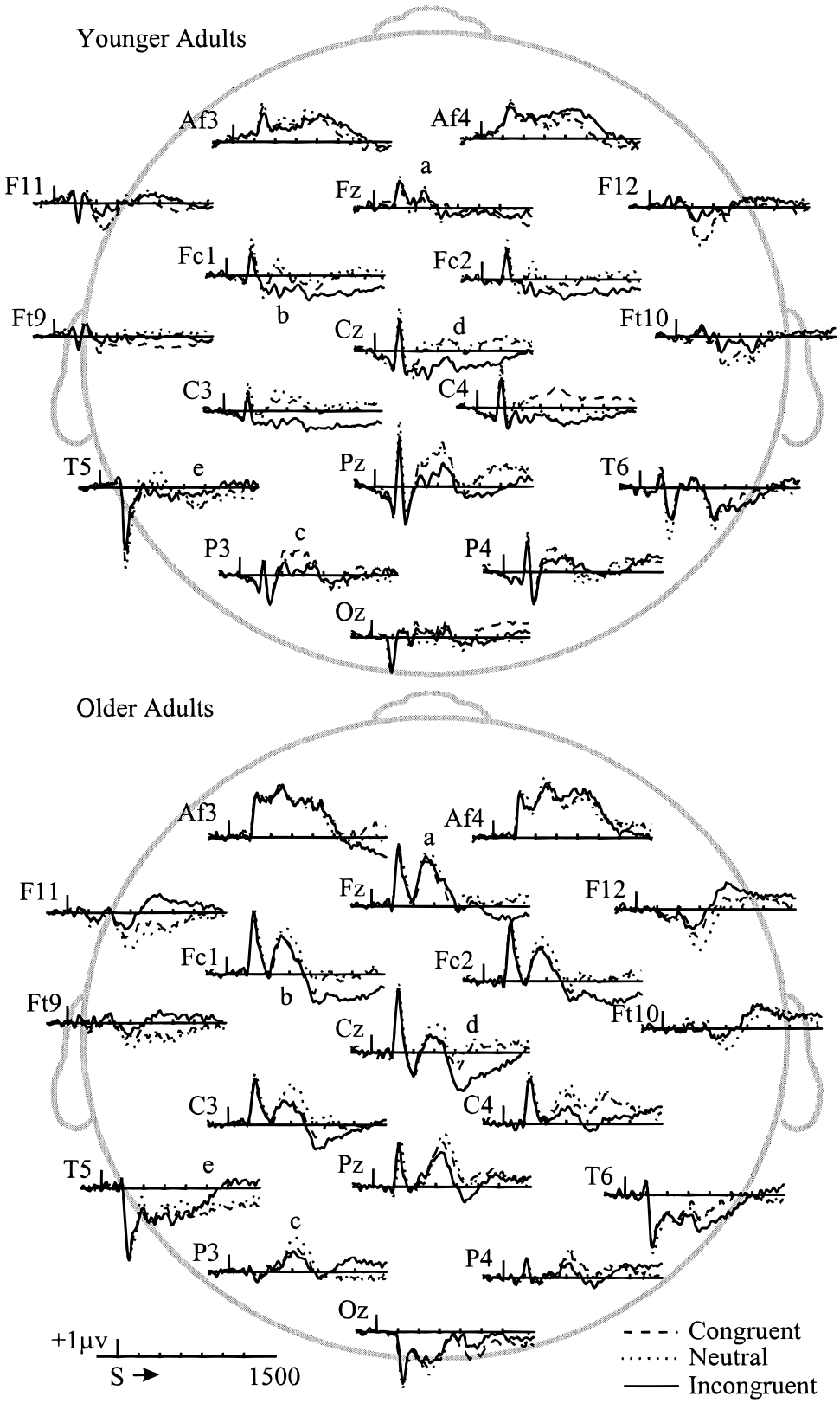

Figure 2. Group-averaged event-related potentials (ERPs) for younger and older adults in congruent, neutral, and incongruent trials measured 200 ms before stimulus onset to 1,500 ms after stimulus onset. The vertical bar indicates stimulus onset and ticks represent 200 ms. (a) Frontal P2 wave that is enhanced in older adults; (b) N500 that is attenuated in the older adults; (c) left parietal negativity for incongruent trials (400–700 ms) that is also attenuated in the older adults; (d) negative frontocentral slow wave; and (e) left temporoparietal positivity.

collapsed over the 25% and 50% word identification conditions.[4] All stimuli elicited a large positive wave peaking at about 240 ms poststimulus, which was maximum over the midline central and parietal regions in younger adults. Consistent with a previous study, there was a marked enhancement of the P2 wave in older adults over the frontal region (e.g., Fz) that inverted over the occipital midline region (e.g., Oz) and was observed for all trial types (Kutas, Iragui, & Hillyard, 1994). There was also a marked increase in the amplitude of a frontal slow wave (e.g., Af3 and Af4) in older adults.

To explore the neurophysiological locus of the increased Stroop effect observed for the older adults, we performed a series of analyses comparing younger and older adults on four ERP modulations specific to the Stroop task observed in our earlier work. The first modulation differentiating incongruent trials from congruent and neutral trials was a phasic negativity (N500) in the younger adults over the midline frontocentral region (see Figures 2 and 3a; e.g., Fc1 and Fc2), confirmed by the significant main effect of condition, $F(2,44) = 13.02$, $p < .001$.[5] As can be seen in Figure 3a, this negativity was greatly attenuated in the older adults relative to the younger adults, Age × Stroop trial type interaction, $F(2,44) = 5.00$, $p < .01$.

The N500 was accompanied over the same period by a decreased positivity over the left parietal region (see Figure 2, e.g., P3) and decreased negativity over bilateral lateral frontal regions (e.g., F11 & F12) for incongruent trials relative to congruent and neutral trials, Stroop trial type, $F(2,44) = 6.83$, $p < .01$.[6] As before, this modulation differentiating incongruent from neutral and congruent trials was greatly attenuated in the older adults (see Figure 3b), Age × Stroop trial type interaction, $F(2,44) = 9.55$, $p < .005$. This attenuation was due to an increase in the amplitude of the ERPs for incongruent trials in older adults.

There was also a negative frontocentral slow wave that differentiated incongruent trials from congruent and neutral trials. This slow wave began at roughly 600 ms, persisted over the remainder of the trial in the younger and older adults (see Figure 3c; e.g., Cz) Stroop trial type $F(2,44) = 5.44$, $p < .008$, and was similar in magnitude for younger and older adults, Age × Stroop trial type interaction, $F < 1$. The age-related stability of the negative frontocentral slow wave coupled with the age-related decline observed in the N500 provides some evidence that different neural generators may contribute to these patterns of activity. To explore this hypothesis further, an analysis was conducted on the normalized mean voltage measurements for incongruent trials in younger adults to determine if the scalp topographies of the N500 and negative frontocentral slow wave differed. In this analysis, the Modulation × Electrode interaction was significant, $F(8,176) = 5.37$, $p < .01$, consistent with the idea that different neural generators contribute to the N500 and the negative frontocentral slow wave.

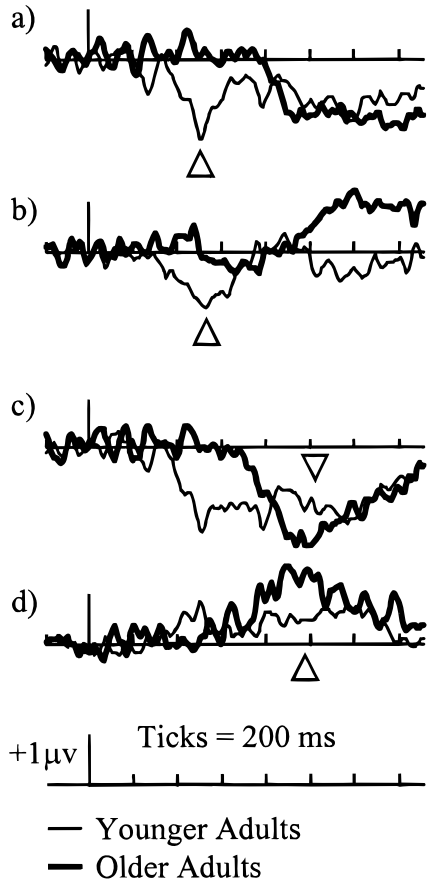

Figure 3. Group-averaged event-related potential (ERP) difference waves (i.e., incongruent − congruent) for younger and older adults showing the four modulations at select scalp locations with triangles marking the interval of interest: (a) frontal midline phasic negativity (N500) at electrode Fc1, notice the marked attenuation of this modulation in the older adults; (b) left parietal negativity and bilateral frontal positivity (400–700 ms) at electrode P3, also greatly attenuated in the older adults; (c) negative frontocentral slow wave at electrode Cz with an onset at approximately 500 ms and persisting until the time of the response in younger and older adults; and (d) left temporoparietal positivity (700–1,200 ms) at electrode T7.

Beginning at approximately the time of the response for congruent trials in younger adults, there was a left temporoparietal positivity that differentiated incongruent trials from congruent trials (see Figures 3d and 4).[7] Mean amplitude of this positivity was measured for younger and older adults over the interval between the response by younger adults on congruent and incongruent trials (i.e., 730–830 ms). The asymmetry of the modulation was confirmed by the Stroop trial type × Hemisphere interaction, $F(2,44) = 6.64$, $p < .003$. The amplitude of the left temporoparietal positivity was similar for older and younger adults at this interval, Age × Stroop trial type interaction, $F < 1$; Age × Stroop trial type × Hemisphere interaction, $F(2,44) = 1.39$, $p > .25$.

As can be seen in Figure 4, the amplitude of this positivity seems to be greater for older than younger adults in the interval

[4] In the analyses of the ERP data the effect of varying the proportion of word identification trails did not interact with the effects of age or Stroop trial type so the data presented in Figures 2, 3, and 4 have been collapsed across this variable.

[5] The frontocentral midline modulations, measured from 450 to 550 ms and from 600 to 700 ms, were evaluated in a 2 (Age) × 2 (proportion of word identification trials) × 3 (Stroop trial type: congruent, neutral, incongruent) × 9 (Electrode: Cz, Fc1, Fc2, C3, C4, Cp1, Cp2, Cp5, Cp6) ANOVA.

[6] The left parietal and bilateral frontal modulation, measured from 450 to 550 ms, was evaluated in a 2 (Age) × 2 (Proportion of word identification trials) × 3 (Stroop trial type) × 8 (Electrode: F11, F12, Ft9, Ft10, Tp9, Tp10, P3, P4) ANOVA.

[7] The left temporoparietal modulation, measured from 730 to 830 ms relative to younger adults and from 1,060 to 1,160 ms relative to older adults, was evaluated in a 2 (Age) × 2 (Proportion of word identification trials) × 3 (Stroop trial type) × 2 (Hemisphere) × 4 (Electrode: Ft9-Ft10, T7-T8, P3-P4, Tp9-Tp10) ANOVA.

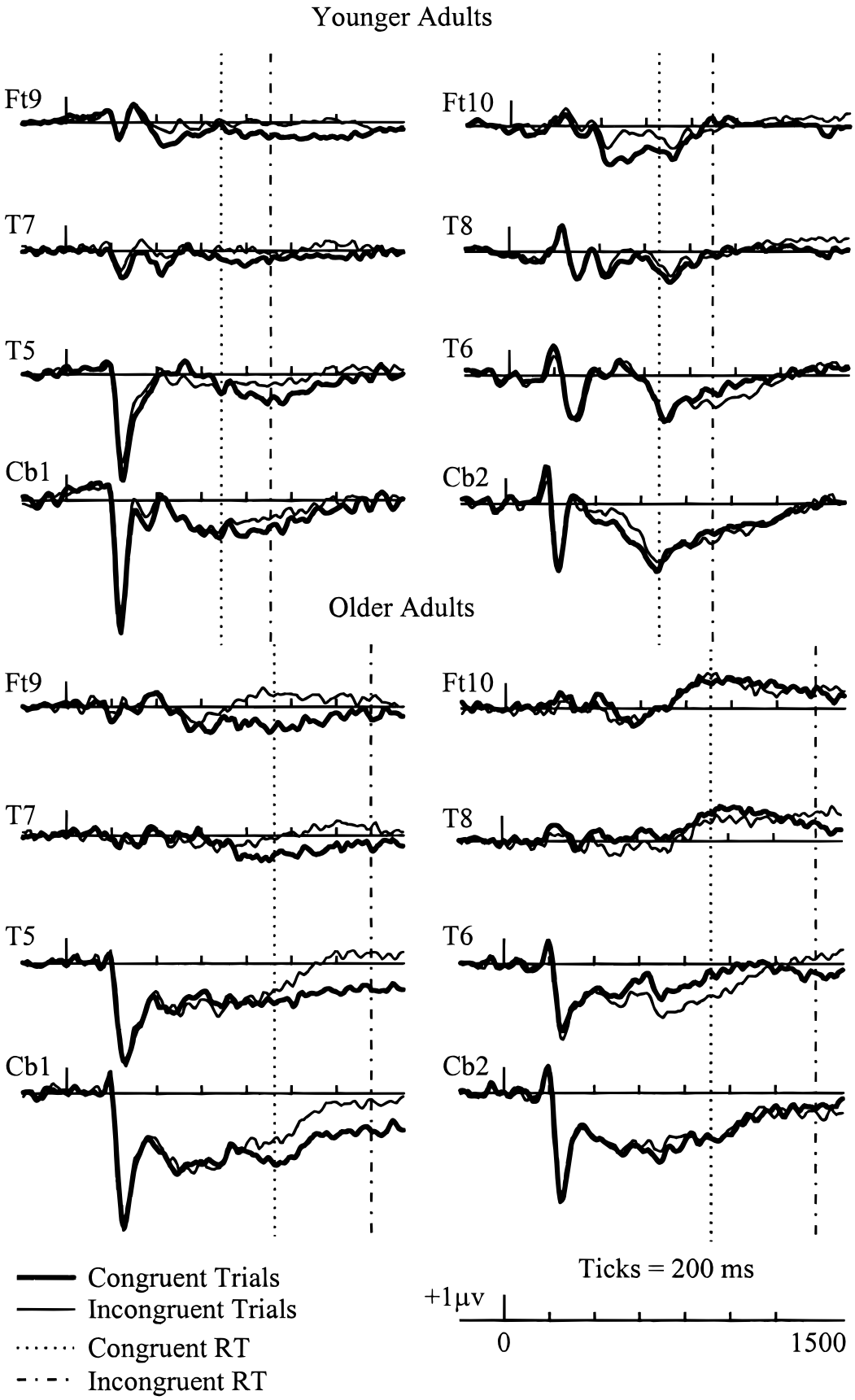

Figure 4. Group-averaged event-related potentials (ERPs) for younger and older adults on congruent and incongruent trials at select electrode locations over the left and right temporoparietal regions. Notice the modulation between congruent and incongruent trials during the interval between a response on congruent and incongruent trials in younger and older adults over the left hemisphere.

between the response on congruent and incongruent trials by older adults. In a test of this idea, mean amplitude measurements taken between 1,060 and 1,160 ms for younger and older adults were analyzed in an ANOVA similar to that reported in the previous paragraph. In this analysis the Stroop trial type × Hemisphere interaction was significant, $F(2,44) = 10.43$, $p < .001$, indicating that the positivity was sustained over this interval. The Age × Stroop trial type interaction was significant under the uncorrected degrees of freedom, $F(2,44) = 3.86$, $p < .03$, but was not significant following the Geisser–Greenhouse correction; and the Age × Stroop trial type × Hemisphere interaction was marginally significant, $F(2,44) = 2.82$, $p = .07$. Although these findings are consistent with the idea that the left temporoparietal positivity was greater for older adults than younger adults over this interval, more evidence remains necessary to support this idea firmly given the marginal significance of these interactions.

The processing reflected in the left temporoparietal positivity may reflect the processing of information in the color pathway once competing information from the word pathway has been inhibited. This possibility was examined by comparing the ERPs elicited in the neutral and word identification trials. If this left temporoparietal activity reflects processing in the color pathway, then a modulation should be observed between the ERPs elicited for neutral and word identification trials over the same region. That is, processing in the color pathway could guide a response on neutral but not word identification trials. There was an enhanced positivity, beginning at approximately 400 ms, for the ERPs elicited on neutral trials relative to those elicited on word identification trials that was greater over the left than right temporoparietal region (see Figure 5). An ANOVA performed on the normalized mean voltages between 400 and 500 ms including the same electrode locations as those used to quantify the left temporoparietal positivity observed between congruent and incongruent trials yielded a significant Stroop trial type × Hemisphere interaction, $F(1,22) = 14.27$, $p < .001$. This modulation was also larger at electrode positions T7 and TP9 than at electrode positions Ft9 and P3, Stroop trial type × Electrode interaction, $F(3,66) = 7.42$, $p < .001$.

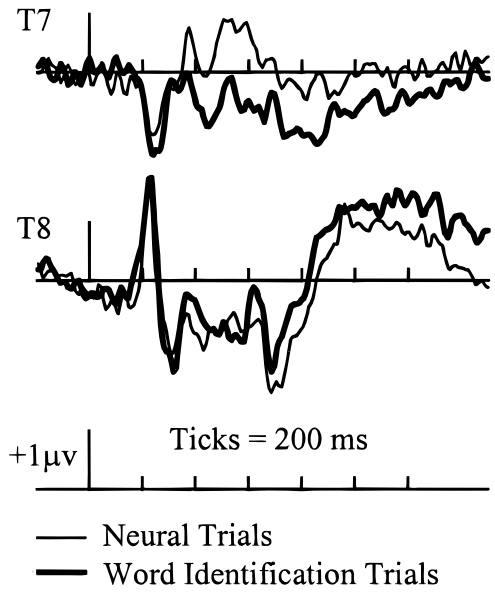

Figure 5. Group-averaged event-related potentials (ERPs) collapsed across younger and older adults demonstrating the left temporoparietal modulation between neutral and word identification trials beginning at approximately (400 ms).

Based on the general slowing account, an Age × Stroop trial type interaction should be observed for latency of the P3 wave over the parietal region. Specifically, latency of the P3 wave should increase from the congruent to incongruent trials to a greater extent for older adults than for younger adults. In a test of this hypothesis, peak latency of the P3 wave defined as the maximum positivity between 550 and 750 ms at the Pz electrode for congruent, neutral, and incongruent trials was taken in younger and older adults. The peak of the P3 was delayed for older adults ($M = 652$) compared with younger adults ($M = 635$), but this slowing did not interact with Stroop trial type and was not significant (F's < 1). This finding is counter to what was expected based on the general slowing hypothesis.

Discussion

Analysis of the response latency data revealed an age-related increase in the magnitude of the Stroop effect in older adults. The effect of age on incongruent trials remained significant after controlling for age-related differences in response latency on neutral trials. This finding indicates that some unique effect of age, beyond that of general slowing, contributed to the larger Stroop effect observed in older adults.

In the electrophysiological data, four temporally and spatially distinct patterns of neural activity that differentiated incongruent trials from congruent and neutral trials were observed in the younger adults. The first of these modulations was a phasic negativity observed in incongruent trials over the midline frontocentral region (N500). The second modulation reflected reduced positivity over the left parietal region and reduced negativity over bilateral frontal regions for incongruent trials. These two modulations seem to reflect the interaction of two neural systems, one most active when competing color and word information is present on incongruent trials and one most active when there is no competition between color and word information on congruent and neutral trials (West & Alain, 1999). The interaction between these two systems seems to result in the suppression of activity over the left parietal and bilateral frontal regions on incongruent trials. Following these modulations a negative frontocentral slow wave was observed for incongruent trials that may reflect neural processing associated with response selection when only color information can guide efficient task performance. A fourth modulation reflecting enhanced positivity for incongruent trials was observed over the left temporoparietal region that seems to reflect the activity of a neural system supporting the processing of color information utilized to guide a response on incongruent trials (West & Alain, 1999). This suggestion was supported by the finding that enhanced positivity was also observed over the left temporoparietal region for the ERPs elicited on neutral trials relative to those elicited on word identification trials. Also, the distribution of this modulation is consistent with the findings of a recent ERP study demonstrating that selective attention to color gives rise to enhanced neural activity over the same region in a different task (Hillyard & Anllo-Vento, 1998).

Analysis of the ERP data revealed a selective effect of increasing age, in which the N500 and left parietal-frontal bilateral modulations were greatly attenuated in older adults. This finding is consistent with predictions based on the inhibitory deficit hypothesis that the age-related increase in the Stroop effect results from a decline in the ability of older adults to inhibit competing word

information on incongruent trials (Spieler et al., 1996). Within the context of dual-process models of the Stroop task (Cohen & Servan-Schreiber, 1992), this age-related decline in the ability of older adults to suppress the influence of word information would increase the time required to activate color information to a level sufficient to guide a correct response. Consistent with this idea, the magnitude of the left temporoparietal positivity was somewhat greater for older than younger adults in the interval between a response in the congruent and incongruent trials. The lack of age effects on the negative frontocentral slow wave and the left temporoparietal positivity is consistent with the proposal that those cognitive processes supporting the processing of task relevant information are not greatly affected by the aging process (Hasher & Zacks, 1988).

Age-related decline in the amplitude of ERP modulations reflecting the suppression of word information at a conceptual level in the Stroop task extends existing electrophysiological data that reveal an inhibitory release in early perceptual processing in older adults (Alain & Woods, 1999; Chao & Knight, 1997). Taken together, these findings indicate that age-related inhibitory deficits can be observed across multiple levels of the neurocognitive system, supporting the idea that increasing age contributes to a decline in the efficiency of inhibitory processes that support performance across a number of domains of cognition (Hasher & Zacks, 1988). However, before this conclusion can be accepted, there are a number of alternative explanations of these data that need to be considered. For instance, one could argue that the greatly enhanced amplitude of the frontal P2 wave obscured the N500 in the older adults. However, evidence for an age-related decline in the efficiency of inhibitory processes can also be seen over the left parietal and lateral frontal regions, where the ERP waveforms were similar for older and younger adults. One could also argue that there was an age-related increase in the degree of temporal jitter present in the data resulting in an attenuation of the N500 in older adults. By examining the ERPs over the left parietal region one can see that this possibility is unlikely because the decrease in the magnitude of the modulation between incongruent and congruent and neutral trials resulted from an increase in the amplitude of the ERPs elicited in the incongruent trials. This pattern is the opposite of what would be expected if temporal jitter contributed to the observed age-related declines, where the amplitude of the averaged ERPs would be reduced in older adults.

The failure to find an age-related increase in the latency of the P3 wave was surprising given numerous other studies that have found such an effect (for a review see, Bashore, Osman, & Heffley, 1989). For instance, the increase in the latency of the P3 wave (.40 ms/year) in the current study was roughly half that reported in a recent large-scale study using auditory stimulation (.92 ms/year) (Anderer, Semlitsch, & Saletu, 1996). However, there are a number of factors that may have contributed to differences between these studies. In a meta-analysis of 32 studies examining age-related differences in the latency of the P3 wave in odd-ball type tasks, Polich (1996) reported that age differences were greater for auditory than visual stimuli. Also, age-related differences were found to decrease when the number of stimuli increased from two to three and when a key press response was made relative to counting the number of oddball stimuli. Given these findings, the use of a key press response, visual simulation, and 24 different stimuli in the current study may account for the failure to find a significant age-related increase in the latency of the P3 wave.

Recent cerebral blood flow studies of the neuroanatomical network supporting performance of the Stroop task have identified a number of regions within the prefrontal cortex that are activated during performance of the Stroop task. These studies have demonstrated consistently that the anterior cingulate is more active during incongruent trials than neutral or congruent trials (Carter, Mintun, & Cohen, 1995; Pardo, Pardo, Janer, & Raichle, 1990). In addition, a number of other cortical regions including the left inferior frontal region (Taylor, Kornblum, Lauber, Minoshima, & Koeppe, 1997) and the inferior and superior parietal regions (Bench et al., 1993) are more active during incongruent trials than neutral or congruent trials. These findings are relevant to the current study given the growing body of literature suggesting that cognitive processes supported by the prefrontal cortex are particularly vulnerable to the effects of increasing age (for reviews see; Albert & Kaplan, 1980; West, 1996). For the Stroop effect, evidence consistent with this hypothesis has been revealed in a recent study in which increased cortical activation over frontal and parietal regions, measured as alpha suppression in the EEG, was observed for older adults on incongruent trials relative to congruent trials when color and word information were integrated at the same spatial location and not when color and word were spatially separated (West & Bell, 1997). In comparison, levels of cortical activation were similar for younger adults on incongruent trials and congruent trials regardless of whether color and word were integrated or separated. These findings are consistent with a proposal by Hartley (1993) suggesting that the prefrontal cortex will be recruited only to support task performance when color and word are integrated and spatial attention cannot serve to protect the information processing system from the conflict arising when competing color and word information are presented.

In the current study two modulations were observed over the frontocentral region that may reflect the activity of neural generators within the prefrontal cortex identified in previous positron emission tomography (PET) studies. Only one of these modulations, the N500 reflecting the activity of a neural system participating in the suppression of word information, was sensitive to the aging process. The negative frontocentral slow wave reflecting selection based on color information was intact in older adults. Assuming that both modulations reflect the activity of neural generators within the prefrontal cortex, these data call for a refinement of the frontal lobe hypothesis of aging that has until now postulated a general decline in cognitive processes supported by the prefrontal cortex (West, 1996). Evidence consistent with the idea that increasing age may differentially affect cognitive processes supported by the prefrontal cortex has been presented in a recent study using PET. In this study, activation of the left prefrontal cortex during memory encoding was greatly attenuated in older adults compared with younger adults, whereas similar levels of activation were observed in younger and older adults within the right prefrontal region during a recognition memory task (Grady et al., 1995). Based on these findings, it seems that future investigations of the frontal lobe hypothesis of aging should seek to identify those cognitive processes supported by the prefrontal cortex that are and are not influenced by the aging process and the boundary conditions under which tasks recruiting these processes reveal age-related decrements.

In summary, the findings of the current study reveal the age-related attenuation of ERP modulations reflecting the activity of a neural system supporting the suppression of word information on incongruent trials in the Stroop task. In comparison, ERP modulations reflecting the processing of color information and selection processes were intact in older adults. These findings are consistent with the proposal that an age-related decline in the efficiency of inhibi-

tion processes contributes to the increased Stroop effect observed in older adults (Spieler et al., 1996). Within current models of the Stroop task, this inability to suppress the influence of competing word information would lengthen the time required to activate color information to a level sufficient to guide a correct response, giving rise to the increased Stroop effect observed in older adults.

REFERENCES

Alain, C., & Woods, D. L. (1999). Age-related changes in processing auditory stimuli during visual attention: Evidence for deficits in inhibitory controls and sensory memory. *Psychology and Aging, 14,* 507–519.

Albert, M. S., & Kaplan, E. (1980). Organic implications of neuropsychological deficits in the elderly. In L. W. Poon (Ed.), *New directions in memory and aging: Proceedings of the George A. Talland memorial conference* (pp. 403–432). Hillsdale, NJ: Erlbaum.

Anderer, P., Semlitsch, H. V., & Saletu, B. (1996). Multichannel auditory event-related brain potentials: effects of normal aging on the scalp distribution of N1, P2, N2, and P300 latencies and amplitudes. *Electroencephalography and Clinical Neurophysiology, 99,* 458–472.

Bashore, T. R., Osman, A., & Heffley, E. F. (1989). Mental slowing in elderly persons: A cognitive psychophysiological analysis. *Psychology and Aging, 4,* 235–244.

Bench, C. J., Frith, C. D., Grasby, P. M., Friston, K. J., Paulesu, E., Frackowiak, R. S. J., & Dolan, R. J. (1993). Investigations of the functional anatomy of attention using the Stroop task. *Neuropsychologia, 31,* 907–922.

Berg, P., & Scherg, M. A. (1994). A multiple source approach to the correction of eye artifacts. *Electroencephalography and Clinical Neurophysiology, 90,* 229–241.

Bunce, D. J., Warr, P. B., & Cochrane, T. (1993). Blocks in choice responding as a function of age and physical fitness. *Psychology and Aging, 8,* 26–33.

Burke, D. M. (1997). Language, aging, and inhibitory deficits: Evaluation of a theory. *Journal of Gerontology: Psychological Sciences, 52B,* P254–P264.

Carter, C. S., Mintum, M., & Cohen, J. D. (1995). Interference and facilitation effects during selective attention: An H2150 PET study of Stroop task performance. *Neuroimage, 2,* 264–272.

Cerella, J. (1990). Aging and information processing rate. In J. E. Birren & K. W. Schaie (Eds.), *Handbook of the psychology of aging* (3rd ed, pp. 201–221). San Diego, CA: Academic Press.

Chambers, R. D., & Griffiths, S. K. (1991). Effects of age on the auditory middle latency response. *Hearing Research, 51,* 1–10.

Chao, L. L., & Knight, R. T. (1997). Prefrontal deficits in attention and inhibitory control with aging. *Cerebral Cortex, 7,* 63–69.

Cohen, J. D., Dunbar, K., & McClelland, J. L. (1990). On the control of automatic processes: A parallel distributed processing account of the Stroop effect. *Psychological Review, 97,* 332–361.

Cohen, J. D., & Servan-Schreiber, D. (1992). Context, cortex, and dopamine: A connectionist approach to behavior and biology in Schizophrenia. *Psychological Review, 99,* 45–77.

Connelly, S. L., & Hasher, L. (1993). Aging and the inhibition of spatial location. *Journal of Experimental Psychology: Human Perception and Performance, 19,* 1238–1250.

Duncan-Johnson, C. C., & Kopell, B. S. (1981). The Stroop effect: Brain potentials localize the source of interference. *Science, 214,* 938–940.

Geisser, S., & Greenhouse, S. W. (1958). An extension of Box's results on the use of the *F* distribution in multivariate analysis. *Annals of Mathematical Statistics, 29,* 885–891.

Grady, C. L., McIntosh, A. R., Horwitz, B., Maisog, J. M., Ungerleider, L. G., Mentis, M. J., Pietrini, P., Schapiro, M. B., & Hazby, J. V. (1995). Age-related reductions in human recognition memory due to impaired encoding. *Science, 269,* 218–221.

Graf, P., Uttl, B., & Tuokko, H. (1995). Color- and picture-word Stroop tests: Performance changes in old age. *Journal of Clinical and Experimental Neuropsychology, 17,* 390–415.

Hartley, A. A. (1993). Evidence for the selective preservation of spatial attention in older adults. *Psychology and Aging, 8,* 371–379.

Hartman, M., & Hasher, L. (1991). Aging and suppression: Memory for previously relevant information. *Psychology and Aging, 6,* 587–594.

Hasher, L., & Zacks, R. T. (1988). Working memory, comprehension, and aging: A review and a new view. *The Psychology of Learning and Motivation, 22,* 122–149.

Heaton, W. C. (1981). *Wisconsin Card Sorting Test.* Odessa, TX: Psychological Assessment Resources.

Hillyard, S. A., & Anllo-Vento, L. (1998). Event-related brain potentials in the study of visual selective attention. *Proceedings of the National Academy of Science USA, 95,* 781–787.

Karayanidis, F., Andrews, S., Ward, P. B., & Michie, P. T. (1995). ERP indices of auditory selective attention in aging and Parkinson's disease. *Psychophysiology, 32,* 335–350.

Knight, R. T., Scabini, D., & Woods, D. L. (1989). Prefrontal cortex gating of auditory transmission in humans. *Brain Research, 504,* 338–342.

Kramer, A. F., Humphrey, D. G., Larish, J. F., Logan, G. D., & Strayer, D. L. (1994). Aging and inhibition: Beyond a unitary view of inhibitory processing in attention. *Psychology and Aging, 9,* 491–512.

Kutas, M., Iragui, V., & Hillyard, S. A. (1994). Effects of aging on event-related brain potential (ERPs) in a visual detection task. *Electroencephalography and Clinical Neurophysiology, 92,* 126–139.

Laffont, F., Bruneau, N., Roux, S., Agar, N., Minz, M., & Cathala, H. P. (1989). Effect of age on auditory evoked responses (AER) and augmenting-reducing. *Neurophysiology Clinical, 19,* 15–23.

Li, K. Z. H., & Bosman, E. A. (1996). Age differences in Stroop-like interference as a function of semantic relatedness. *Aging, Neuropsychology, and Cognition, 3,* 272–284.

Lindsay, D. S., & Jacoby, L. L. (1994). Stroop process dissociations: The relationship between facilitation and interference. *Journal of Experimental Psychology: Human Perception and Performance, 20,* 219–234.

MacDonald, P. A., & MacLeod, C. M. (1996, November). *Further evidence that facilitation in the Stroop task is illusory.* Poster session at the annual meeting of the Psychonomic Society, Chicago, IL.

MacLeod, C. M. (1991). Half a century of research on the Stroop effect: An integrative review. *Psychological Bulletin, 109,* 163–203.

McCarthy, G., & Wood, C. C. (1985). Scalp distributions of event-related potentials: an ambiguity associated with analysis of variance models. *Electroencephalography and Clinical Neurophysiology, 62,* 203–208.

McDowd, J. M. (1997). Inhibition in attention and aging. *Journal of Gerontology: Psychological Sciences, 52B,* P265–P273.

McDowd, J. M., & Filion, D. L. (1992). Aging, selective attention, and inhibitory processes: A psychophysiological approach. *Psychology and Aging, 7,* 65–71.

Pardo, J. V., Pardo, J. P., Janer, K. W., & Raichle, M. E. (1990). The anterior cingulate cortex mediates processing selection in the Stroop attentional conflict paradigm. *Proceedings of the National Academy of Science, 87,* 256–259.

Polich, J. (1996). Meta-analysis of P300 normative aging studies. *Psychophysiology, 33,* 334–353.

Rebai, M., Bernard, C., & Lannou, J. (1997). The Stroop's test evokes a negative brain potential, the N400. *International Journal of Neuroscience, 91,* 85–94.

Salthouse, T. A., & Meinz, E. J. (1995). Aging, inhibition, working memory, and speed. *Journal of Gerontology: Psychological Sciences and Social Sciences, 50B,* P297–P306.

Scherg, M., & Berg, P. (1991). *Brain electric source analysis* (Version 2.0) [Computer software]. Munich: Authors.

Schneider, W. (1995). *MEL professional* (Version 2.0) [Computer software]. Pittsburgh, PA: Psychology Software Tools, Inc.

Spieler, D. H., Balota, D. A., & Faust, M. E. (1996). Stroop performance in healthy younger and older adults and in individuals with dementia of the Alzheimer's type. *Journal of Experimental Psychology: Human Perception and Performance, 22,* 461–479.

Stoltzfus, E. R., Hasher, L., Zacks, R. T., Ulivi, M. S., & Goldstein, D. (1993). Investigations of inhibition and interference in younger and old adults. *Journal of Gerontology: Psychological Science, 48,* P179–P188.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology, 18,* 643–661.

Taylor, S. F., Kornblum, S., Lauber, E. J., Minoshima, S., & Koeppe, R. A. (1997). Isolation of specific interference processing in the Stroop task: PET activation studies. *Neuroimage, 6,* 81–92.

Uttl, B., & Graf, P. (1997). Color-word Stroop test performance across the adult life span. *Journal of Clinical and Experimental Neuropsychology, 19,* 405–420.

Verhaeghen, P., & De Meersman, L. D. (1998). Aging and the Stroop effect: A meta-analysis. *Psychology and Aging, 13*, 120–126.
West, R. (1999). Age differences in lapses of intention in the Stroop task. *Journal of Gerontology: Psychological Science, 54B*, P34–P43.
West, R. L. (1996). An application of prefrontal cortex function theory to cognitive aging. *Psychological Bulletin, 120*, 272–292.
West, R., & Alain, C. (1999). Event-related brain activity associated with the Stroop task. *Brain Research: Cognitive Brain Research, 8*, 157–164.
West, R., & Baylis, G. C. (1998). Effect of increased response dominance and contextual disintegration on the Stroop interference effect in older adults. *Psychology and Aging, 13*, 206–217.
West, R., & Bell, M. A. (1997). Stroop color-word interference and electroencephalogram activation: Evidence for age-related decline in the anterior attention system. *Neuropsychology, 11*, 421–427.
Woods, D. L., & Clayworth, C. C. (1986). Age-related changes in human middle latency auditory evoked potential. *Electroencephalography and Clinical Neurophysiology, 64*, 297–303.
Zeef, E. J., & Kok, A. (1993). Age-related differences in the timing of stimulus and response processes during visual selective attention: Performance and psychophysiological analyses. *Psychophysiology, 30*, 138–151.

(Received August 14, 1998; Accepted April 25, 1999)