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The Effects of Aging on Controlled Attention and Conflict Processing in the Stroop Task

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Abstract

Recent computational modeling and behavioral work indicate that age-related declines in the ability to represent task context may contribute to disruptions of working memory and selective attention in older adults. However, it is unclear whether age-related declines in context processing arise from a disruption of the encoding or maintenance of task context and how age-related declines in context processing interact with mechanisms supporting conflict detection and resolution processes contributing to efficient selection of task-relevant information. This study examines the effects of aging on neural correlates of context and conflict processing in the Stroop task using event-related brain potentials (ERPs). Age-related differences in the time course of modulations of the ERPs associated with encoding (P3) and maintaining (slow wave) task context were observed. There were also age-related differences in the N450, conflict SP, and ERN associated with conflict processing that interacted with task context. These data indicate that aging is associated with declines in the efficiency of those neural mechanisms supporting both context and conflict processing, and that the effects of aging are not pervasive but rather interact with task context.

INTRODUCTION

The concept of controlled or supervisory attention has a rich history in the areas of cognitive psychology (Baddeley, 1996), neuropsychology (Norman & Shallice, 1980), and computational neuroscience (Cohen, Dunbar, & McCelland, 1990). Within each of these domains controlled attention is thought to orchestrate the functional efficiency of lower-level or domain-specific neural systems devoted to fundamental aspects of information processing and action control in contexts that are novel, involve distracting information, or when multiple sources of information compete for a response (Norman & Shallice, 1980). The Stroop color–word task has been used extensively in studies of controlled attention (MacLeod, 1991; Stroop, 1935). In this task, individuals are asked to name the color of color–word stimuli when these two sources of information are congruent (e.g., RED—presented in red) or incongruent (e.g., RED—presented in blue). Word information generally interferes with color naming, leading to an increase in response time and error rate on incongruent trials relative to congruent trials, whereas color information typically has little effect on word reading (Stroop, 1935). This asymmetry in the interference effect is thought to arise from differences in the degree of automaticity or prior experience with word reading relative to color naming in literate adults (MacLeod, 1991). Controlled attention is thought to support performance of the Stroop task by biasing the information-processing system toward the goal-compatible stimulus dimension (i.e., color; Cohen et al., 1990) or away from the goal-incompatible stimulus dimension (i.e., word; Lindsay & Jacoby, 1994).

Several investigators have suggested that age-related declines in the efficiency of controlled attention may contribute to the poor performance of older adults across various domains of cognition including selective attention (Spieler, Balota, & Faust, 1996) and working memory (West, 1999a). Braver et al. (2001) have recently tested this idea within a computational framework wherein age-related declines in the ability to represent task context gives rise to working memory deficits in older adults. Furthermore, these and other authors (West & Baylis, 1998) have suggested that a reduction in the efficiency of representing task context may contribute to age-related declines in the efficiency of selective attention. Consistent with this prediction, West and Baylis (1998) observed that the Stroop effect was similar for younger and older adults in a task condition requiring minimal controlled attention (i.e., when trials were mostly congruent) and was greater for older adults in a task condition requiring a high degree of controlled attention (i.e., when trials were mostly incongruent). West (1999b) also provided evidence for this idea in demonstrating that older adults are more susceptible to intrusion errors in the Stroop task (i.e., reading the word instead of naming the color) than are younger adults, presumably resulting from fluctuations in the representation of task context during task performance.

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One limitation of those studies examining age-related differences in the influence of task context on the efficiency of controlled attention in the Stroop task is the inability to determine whether aging is associated with a reduced ability to encode or update task context or a reduced ability to maintain task context. The present study was designed to address this limitation using the cueing version of the Stroop task that requires updating of task context on a trial-by-trial basis. This method was employed in concert with event-related brain potentials (ERPs), which allowed an independent assessment of the neural correlates of those processes supporting encoding and maintenance of task context and conflict processing. The particular interest was related to the effects of aging on modulations of the ERPs associated with encoding task context (P3), maintenance of task context (slow wave), and conflict processing (N450, conflict sustained potential [SP], error-related negativity [ERN]).

In the cueing version of the Stroop task the stimulus dimension that is relevant for a given trial is cued before onset of the Stroop stimulus (MacDonald, Cohen, Stenger, & Carter, 2000). The temporal dissociation of the dimension cue and Stroop stimulus has allowed researchers to tease apart the functional neuroanatomy of controlled attention and conflict processing in the Stroop task. MacDonald et al. (2000) found that controlled attention was associated with left prefrontal cortex activation following the presentation of a dimension cue that was greater for color naming than word reading; these researchers also found that conflict processing (i.e., greater activation for incongruent than congruent trials) was associated with anterior cingulate activation (Carter et al., 2000; Pardo, Pardo, Janer, & Raichle, 1990). West (2003) used trial-by-trial cueing in the Stroop and digit-location tasks to examine the time course of controlled attention and conflict processing using ERPs. In this study, controlled attention was associated with a slow wave over the occipital–parietal region following presentation of the dimension cue, and conflict processing was associated with an N450 and conflict SP following presentation of the Stroop or digit-location stimuli.

The relationship between conflict processing and the N450 and conflict SP has been examined in a number of studies (Liotti, Woldorff, Perez, & Mayberg, 2000; West & Alain, 2000a). The N450 reflects a phasic negativity over the frontal–central–parietal region that reverses polarity over the lateral frontal and frontal polar regions. The N450 is elicited in the Stroop, digit-location, and counting tasks (West, Jakubek, Wymbs, & Perry, 2002), is generated when either color or word identification is required in the Stroop task (West, 2003), and is elicited by correct responses and intrusion errors (West & Alain, 2000b). The amplitude of the N450 covaries with the magnitude of the interference effect, being greater when the interference effect is largest, indicating that it is sensitive to variation in the allocation of controlled attention (West & Alain, 2000a). The results of spatiotemporal source analysis indicate that the neural generator of the N450 may lie within the anterior cingulate cortex (Liotti et al., 2000). Together these findings lead to the suggestion that the N450 reflects the activity of a neural generator that supports conflict detection rather than selection (West, 2003; van Veen & Carter, 2002). The amplitude of the N450 is severely attenuated in older adults (West & Alain, 2000c), indicating that aging is associated with a functional impairment of conflict detection processes supported by the anterior cingulate. Consistent with this proposal other recent evidence indicates that the amplitude of the ERN is attenuated in older adults (Nieuwenhuis et al., 2002; Flakenstein, Hoormann, & Hohnsbein, 2001). The ERN is associated with the detection of conflict between an intended and performed action (Gehring, Goss, Coles, Meyer, & Donchin, 1993) and is thought to reflect the activity of an anterior cingulate generator (Holroyd & Coles, 2002; van Veen & Carter, 2002).

The conflict SP reflects a sustained positivity over the parietal region that reverses polarity over the lateral frontal regions. Similar to the N450, the conflict SP is elicited in a variety of tasks (West et al., 2002) and its amplitude varies with the allocation of controlled attention (West & Alain, 2000a). The topography of the conflict SP differs depending on whether the dominant or nondominant stimulus dimension is relevant for a response, being similar in amplitude for the dominant and nondominant stimulus dimension over the left lateral frontal region and greater in amplitude for the nondominant stimulus dimension over the right lateral frontal region (West, 2003). In the Stroop task the amplitude of the conflict SP is also greater for correct incongruent trials than intrusion errors over the right frontal region when color identification is required (West, 2003). These findings lead to the suggestion that the conflict SP arises from the activity of a neural system that supports selection or conflict resolution following conflict detection in the Stroop task (West, 2003).

In summary, this study was designed to examine the effects of aging on modulations of the ERPs associated with encoding and maintaining task context (i.e., P3 and cue slow wave) and conflict processing (i.e., N450, conflict SP, and ERN). The allocation of controlled attention was varied between stimulus dimensions (i.e., color or word) and the relevant stimulus dimension was cued in a blocked or trial-by-trial manner. For blocked cueing, participants were instructed that for the next series of trials they should always respond based on the color or the word. For trial-by-trial cueing, the relevant dimension (color or word) varied randomly across trials and was cued before onset of the Stroop stimuli. A dimension cue was also presented before the Stroop stimuli in the blocked conditions to equate the perceptual characteristics of the display across condi-
tions; however, this cue could be considered irrelevant, as it was constant across trials (e.g., it was always the word COLOR for color-identification blocks). If age-related declines in the efficiency of controlled attention result from a reduction in the ability of older adults to encode task context, age-related differences were expected in modulations of the ERPs associated with stimulus encoding or working memory updating (i.e., P3) associated with presentation of the dimension cue in the trial-by-trial condition. In contrast, if age-related differences in controlled attention result from a reduction in the ability of older adults to maintain task context, one would expect to observe age-related differences in the amplitude of the cue slow wave. If there are age-related declines in the efficiency of those neural mechanisms supporting conflict processing, one would expect to observe age-related differences in the amplitudes of the N450, conflict SP, and ERN.

RESULTS

Behavioral Data: RT and Accuracy

The mean response time and response accuracy data were analyzed in a set of mixed model ANOVAs. For the response time data, the Stroop effect was larger for trial-by-trial than blocked cueing, $F(1,26) = 35.44, p < .001$, and was larger for color than word identification, $F(1,26) = 21.80, p < .001$. The Stroop effect was larger for older than younger adults, $F(1,26) = 10.42, p < .01$, and this effect was modulated by whether color or word identification was required, $F(1,26) = 14.22, p < .001$, being similar in younger and older adults for word identification and greater in older than younger adults for color identification (Figure 1A). For the response accuracy data, the Stroop effect was larger for trial-by-trial than blocked cueing, $F(1,26) = 35.83, p < .001$, and for color than word identification, $F(1,26) = 25.15, p < .001$. The Stroop effect was larger in older than in younger adults, $F(1,26) = 11.86, p < .01$. The age-related increase in the Stroop effect interacted with both the relevant dimension, $F(1,26) = 18.37, p < .001$, being greater for the color identification condition (Figure 1B), and cueing method, $F(1,26) = 7.51, p < .05$, being greater for trial-by-trial cueing (Figure 1C).

ERPs: Controlled Attention, N1, P3, Slow Wave

Examination of the ERPs elicited by the presentation of the dimension cue revealed three modulations that differentiated blocked from trial-by-trial cueing (i.e., N1, P3, and slow wave). The amplitude of the occipital–parietal N1 was greater for trial-by-trial cueing, $M = -1.87 \mu V$, than for blocked cueing, $M = -1.09 \mu V$, $F(1,26) = 5.99, p < .03$ (Figure 2A). This finding is consistent with extensive research demonstrating that the amplitude of the N1 is greater for attended stimuli than for ignored stimuli (see Mangun & Hillyard, 1995). The effect of cueing on the N1 interacted with age and dimension, $F(1,26) = 4.74, p < .04$, reflecting a significant effect of cueing in the younger adults, $F(1,13) = 7.82, p < .02$, but not in the older adults, $F < 1$.

A parietally distributed P3 wave was elicited for trial-by-trial, but not blocked, cueing that was similar in amplitude for younger and older adults. Figure 2B
reveals that the duration of the P3 was somewhat longer in older than younger adults. Therefore, the P3 was quantified in two measurements reflecting the peak of the P3 for younger adults, 250 to 350 msec, and for older adults, 400 to 500 msec. In both of these epochs the effect of cueing was significant, $F(1,26) = 21.83, p < .001$, and $F(1,26) = 17.10, p < .001$, with the amplitude of the P3 being greater for trial-by-trial cueing ($M = 1.73 \mu V, M = 1.32 \mu V$) than blocked cueing ($M = .81 \mu V, M = .28 \mu V$). For the epoch reflecting the peak of the P3 for younger adults the effect of age was not significant, $F < 1$; in contrast, in the epoch reflecting the peak of the P3 for older adults the main effect of age, $F(1,26) = 6.61, p < .02$, and the Age $\times$ Electrode interaction, $F(5,130) = 5.77, p < .002, \epsilon = .56$, were significant. These findings indicate that updating working memory based on the dimension cue was prolonged in the older adults.

The slow wave onset was approximately 600 msec after presentation of the cue and reflected greater negativity over the occipital–parietal region and positivity over the anterior frontal region for trial-by-trial relative to blocked cueing (Figure 2C). The effect of age on the slow wave differed between 600 msec after onset of the cue and just before onset of the Stroop stimuli. Therefore, the slow wave was quantified in two epochs reflecting the early, 800 to 1000 msec, and later, 1000 to 1500 msec, portions of this modulation. For the early epoch, the effect of cueing was significant for the occipital–parietal, $F(1,26) = 7.11, p < .02$, and anterior frontal, $F(1,26) = 11.98, p < .002$, regions. In the later slow wave epoch, the effect of cueing remained significant for the anterior frontal region, $F(1,26) = 5.48, p < .03$; over the occipital–parietal region the effect of cueing was maintained in younger but not older adults, $F(3,78) = 2.80, p < .05, \epsilon = .98$. This finding indicates that older adults demonstrated a reduced ability to maintain task context until onset of the Stroop stimuli (Braver et al., 2001; West & Baylis, 1998).

**ERPs: Conflict Processing, N450, Conflict SP, ERN**

The polarity of the N450 reversed from the central parietal region to the lateral frontal and frontal polar regions, $F(6,156) = 4.43, p < .006, \epsilon = .51$ (Figures 3 and 4). The effect of age on the amplitude of the N450 interacted with cueing methods and relevant dimension, $F(1,26) = 4.95, p < .04$. This interaction reflected the tendency for the N450 in younger adults to be independent of cueing method and dimension, and for the N450 to be reliable in the older adults for trial-by-trial, $F(1,13) = 3.47, p < .03, \epsilon = .55$, but not blocked,

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Figure 2. Grand average ERPs for younger and older adults demonstrating the effect of aging on the (A) N1, (B) P3, and (C) cue slow wave.

Figure 3. Grand average ERPs for younger and older adults for congruent and incongruent stimuli for the color and word identification conditions. Note the attenuation of the N450 in older adults.
This finding indicates that in older adults the N450 was only reliable when conflict was highest. For the conflict SP separate analyses were conducted for electrodes over the parietal and lateral frontal regions, as previous research has revealed that there are functional differences in the characteristics of this modulation over these two regions (West, 2003). The analysis for the parietal region revealed that the ERPs were more positive for incongruent, \( M = .56 \mu V \), than congruent trials, \( M = -.11 \mu V, F(1,26) = 13.50, p < .001 \), and that this effect interacted with age, \( F(1,26) = 11.13, p < .003 \), and age and dimension, \( F(1,26) = 11.25, p < .002 \) (Figure 5). To understand the nature of the three-way interaction separate analyses were performed for the color and word conditions. For the color condition the amplitude of the conflict SP was greater for younger than older adults, \( F(1,26) = 27.83, p < .001 \); in contrast, for the word condition the amplitude of the conflict SP did not differ between younger and older adults, \( F < 1 \). Analysis of the conflict SP for the lateral frontal region revealed that the conflict SP was attenuated in older adults and that this effect interacted with stimulus dimension, \( F(1,26) = 9.70, p < .004 \), and stimulus dimension and hemisphere, \( F(5,130) = 4.20, p < .003, \epsilon = .85 \) (Figure 6). To understand the nature of the four-way interaction separate analyses were performed for the color and word conditions. For the word condition the amplitude of the conflict SP did not differ between younger and older adults, \( F < 1 \). For the color condition the

**Figure 4.** ERP difference waves (incongruent – congruent) for younger and older adults demonstrating the attenuation of the N450 in older adults. The asterisk marks the N450 for color and word trials.

**Figure 5.** Grand average ERPs and ERP difference waves (incongruent – congruent) for younger and older adults for color and word identification trials demonstrating the effects of aging on the conflict SP over the parietal region.

**Figure 6.** Grand average ERPs and ERP difference waves (incongruent – congruent) for younger and older adults for color and word identification demonstrating the effects of aging on the conflict SP over the lateral frontal regions.
amplitude of the conflict SP was attenuated in older adults, \( F(3,130) = 5.26, p < .003, \eta^2 = .49 \), and this effect was significant over the right, \( F(1,26) = 9.15, p < .006 \), but not left hemisphere, \( F < 1 \).

In addition to the conflict SP, a second sustained potential was observed in the older adults that reflected greater parietal negativity and frontal positivity for color incongruent trials than color congruent or word trials that started around 700 msec after presentation of the Stroop stimuli, \( F(1,26) = 10.33, p < .003 \) (Figure 7). This finding may indicate that there is some degree of functional reorganization of those neural mechanisms supporting conflict processing in older adults (Milham et al., 2002).

The effect of aging on the ERN was examined in an analysis including ERPs elicited by correct incongruent trials and intrusion errors for the trial-by-trial cueing condition. The data for one younger adult were not included in this analysis, as the younger adult committed a single intrusion error in the word condition. For the ERN, the main effect of trial, \( F(1,25) = 16.90, p < .001 \), and the Age \( \times \) Trial interaction, \( F(1,25) = 7.59, p < .02 \), were significant (Figure 8), indicating that the amplitude of this modulation was attenuated in older adults.

**DISCUSSION**

This study was designed to examine the neural correlates of age-related declines in controlled attention and conflict processing and to determine the degree that the effects of aging interact with variations in task context. The behavioral data revealed that Stroop interference was greater for older than younger adults, in terms of both response time and accuracy. The age-related increase in the Stroop effect was modulated by stimulus dimension, reflecting greater interference in older adults for color, but not word, identification trials; and cueing method, being greater for trial-by-trial than blocked cueing in the accuracy data. These data indicate that age-related differences in the Stroop effect are modulated by task demands (West & Baylis, 1998) and are inconsistent with the idea that age-related differences in the Stroop effect result solely from general slowing (Verhaeghen & De Meersman, 1998). The physiological data revealed age-related differences in ERPs elicited by dimension cues, Stroop stimuli, and errant responses. These findings indicate that aging is associated with a decline in the efficiency of those neural mechanisms supporting both context processing and conflict detection and resolution (Nieuwenhuis et al., 2002; Braver et al., 2001; West & Alain, 2000c).

**Cue-Related ERPs**

Age-related differences in processing the dimension cues were observed as early as the N1 component. For younger adults the amplitude of the N1 was greater...
for trial-by-trial than blocked cueing. This finding indicates that the younger adults devoted greater attention to the cues in the trial-by-trial than blocked condition (see Mangun & Hillyard, 1995). The amplitude of the N1 was greater in older than younger adults, although this difference was not significant, consistent with extensive literature revealing age-related increases in the amplitude of ERP components associated with sensory processing. This increase in the amplitude of early visual components has been associated with a reduction in the efficiency of inhibitory control processes in later adulthood (Alain & Woods, 1999). For older adults there was no effect of cueing method on the amplitude of the N1. This finding may indicate that older adults were either unable to suppress processing of the cues in the blocked condition or that they relied on this information to bolster a degraded representation of task context in this condition. This later alternative seems somewhat unlikely since the P3 was limited to the trial-by-trial condition in both older and younger adults.

The age-related difference in the cueing effect on the N1 may be somewhat surprising given prior research demonstrating similar endogenous cueing effects in younger and older adults in both visual and auditory attention tasks (Curran, Hills, Patterson, & Strauss, 2001; Ford et al., 1979). However, there are substantial differences between the eliciting conditions of the cueing effect observed in the current study and those observed in studies of spatial attention. In the current study, the cueing effect arises from differences in stimulus relevance between the trial-by-trial and blocked cueing conditions; in contrast, in studies of spatial attention cueing effects arise from the enhanced processing of attended versus unattended locations. Together these findings may indicate that aging has a negative effect on the efficiency of an attentional system that limits the processing of irrelevant stimuli (Alain & Woods, 1999) and has relatively little effect on the efficiency of those neural systems supporting spatial attention (West & Bell, 1997; Hartley, 1993).

A P3 was observed for cues in the trial-by-trial cueing condition; in contrast, for the blocked cueing condition the P3 was small or absent. This finding indicates that individuals devoted relatively little attention to the cues in the blocked condition. The amplitude of the P3 in the trial-by-trial condition was similar in younger and older adults, indicating that both groups were using the cues to update a representation of the relevant dimension in this condition (Donchin & Coles, 1988). The time course of the P3 was prolonged in older adults, indicating that encoding task context required extended processing with increasing age. This finding reveals that age-related differences in the updating function of working memory reflected in the P3 (Polich, 1996) contribute to declines in the implementation of controlled attention in older adults.

A slow wave was observed that reflected greater negativity over the occipital–parietal region and positivity over the anterior frontal region for the trial-by-trial cueing condition relative to the blocked cueing condition. The effect of age on the cue slow wave varied from the early to late portions of this modulation. Between 800 and 1000 msec the amplitude of the slow wave did not differ between younger and older adults; in contrast, between 1000 and 1500 msec the difference between trial-by-trial and blocked cueing remained significant for younger, but not older, adults. This finding indicates that older adults have a reduced ability to maintain task context when this information changes frequently during task performance. Together these findings indicate that aging is associated with a decline in the efficiency that task context is encoded into and maintained within working memory (Braver et al., 2001).

**Stroop Stimulus and Response-Related ERPs**

There were age-related differences in the amplitudes of the N450, conflict SP, and ERN, consistent with the prediction that aging is associated with a disruption of those neural mechanisms supporting conflict processing. In addition, a sustained potential was observed in older adults that reflected greater parietal negativity and frontal positivity for color incongruent trials relative to color congruent trials and word trials. In younger adults, the N450 was not influenced by cueing method or stimulus dimension (West, 2003). The amplitude of the N450 was attenuated in older adults (West & Alain, 2000c) and was only reliable for color trials using trial-by-trial cueing where conflict was greatest. Like the N450, the amplitude of the ERN was also attenuated in older adults for color and word intrusion errors. Source analysis has revealed that the neural generators of the N450 (Liotti et al., 2000; McNeely et al., 2002) and ERN (van Veen & Carter, 2002) may lie within the anterior cingulate. This finding, together with the observation of an age-related attenuation in the amplitudes of the N450 (West & Alain, 2000c) and ERN (Nieuwenhuis et al., 2002), may indicate that there is a general age-related decline in the efficiency of those neural mechanisms supporting conflict detection that involve the recruitment of the anterior cingulate cortex (Milham et al., 2002).

For younger adults the pattern of data observed for the conflict SP was consistent with previous research (Liotti et al., 2000; West & Alain, 2000a). Over the parietal and left lateral frontal regions the conflict SP was similar in amplitude for color and word incongruent trials, whereas over the right lateral frontal region the amplitude of the conflict SP was greater for color incongruent trials than word incongruent trials. This finding indicates that there is a hemispheric asymmetry in the neural generators that give rise to the conflict SP, with the generator of the conflict SP over the right
lateral frontal region being particularly sensitive to conflict arising from the dominant dimension (i.e., word information) in the Stroop task (West, 2003). Similar findings have been reported in recent studies using fMRI to examine the functional neuroanatomy of conflict processing in the Stroop task (Banich et al., 2000). For instance, Milham et al. (2001) found that response-related interference in the Stroop task was associated with activation in both the left and right middle frontal gyrus, whereas stimulus-related interference was associated with activation in the left, but not right, middle frontal gyrus. However, in the present data the hemispheric asymmetry was driven by the relevant dimension rather than the nature of the interference, indicating that multiple factors contribute to differences in the recruitment of left and right lateral frontal cortex in the Stroop task.

The effect of aging on the conflict SP interacted with the processing demands of the task. When word identification was required, age-related differences in the amplitude of the conflict SP were not significant, mirroring the behavioral data wherein the Stroop effect did not differ in younger and older adults for word identification. In contrast, when color identification was required, the amplitude of the conflict SP was attenuated in older adults over the parietal and right lateral frontal regions.

Interactions between contextual variables and the effects of aging on the Stroop task have been observed in other studies using behavioral and electrophysiological methods. West and Bell (1997) observed that age-related differences in the degree of EEG alpha suppression for incongruent relative to congruent trials were significant when the color and word were integrated, but not when color and word were spatially separated. Consistent with this finding, data from a number of studies have revealed that the magnitude of the interference effect is greater for older adults when color and word information is integrated, but not separated (West & Bell, 1997; Hartley, 1993). West and Baylis (1998) also observed that the proportion of congruent trials modulated age-related differences in the Stroop effect, with interference being greater for older adults when trials were mostly incongruent, and similar for younger and older adults when trials were mostly congruent. These interactions between aging and contextual variables in the Stroop task indicate that age-related differences in the neural mechanisms supporting conflict processing may arise from rather specific changes in the functional integrity of the anterior cingulate and prefrontal cortex, rather than from more global effects such as general slowing (Verhaeghen & De Meersman, 1998).

The effects of aging upon behavioral and electrophysiological indices of conflict processing in the Stroop task are highly similar to the effects of schizophrenia. Like the older adults in the present study, patients with schizophrenia demonstrate a pronounced increase in error rate for color incongruent trials relative to word incongruent trials when required to switch between color naming and word reading during the task (Cohen, Barch, Carter, & Servan-Schreiber, 1999). Also, other work indicates that the amplitudes of the N450, conflict SP, and ERN are attenuated in patients with schizophrenia during performance of the Stroop task (McNeely, Christensen, West, & Alain, in press; Alain, McNeely, Yu, Christensen, & West, 2002). These findings are consistent with the proposal that nonoptimal dopaminergic function contributes to both age- and disease-related impairments in tasks requiring context processing and conflict detection and resolution (Braver et al., 2001; Braver & Cohen, 1999).

**Conclusions**

Age-related differences were observed in modulations of the ERPs related to the encoding and maintenance of task context (i.e., P3, slow wave) and conflict processing (i.e., N450, conflict SP, ERN). Age-related differences in the time course of the P3 indicate that there are differences in the efficiency that younger and older adults encode or represent task context, whereas age-related differences in the slow wave between 1000 and 1500 msec indicate that aging is also associated with a reduced ability to maintain task context. These findings are consistent with the idea that age-related differences in the ability to represent task context contribute to age-related declines in the efficiency of working memory (Braver et al., 2001) and selective attention (West & Baylis, 1998). Age-related differences in the N450 and ERN indicate that aging is associated with a functional impairment of the anterior cingulate leading to disruption of conflict detection in older adults. Age-related differences in the conflict SP and the magnitude of the interference effect in the response time data indicate that there are interactions between the effects of aging and task demands on the efficiency of those neural mechanisms supporting conflict processing.

**METHODS**

**Participants**

Fourteen younger adults, 6 women, $M = 21.36$ years of age, and 14 older adults, 10 women, $M = 72.21$ years of age, participated in the study. The younger adults were recruited from the undergraduate and graduate populations of the University of Notre Dame and the older adults were recruited from a pool of retired faculty and staff representing individuals who had been engaged in academic, professional, and service positions. All individuals received $20.00 for participation in the study. The groups did not differ in years of formal education, younger $M = 14.86$, older $M = 15.86$, $F < 1$, vocabulary, younger $M = .66$, older $M = .71$, $F < 1$, or self-reported health status, younger $M = 1.50$, older $M = 1.57$, $F < 1$. 

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Performance on a measure of processing speed revealed that the older adults, $M = 24.36$ sec, were slower than the younger adults, $M = 13.33$ sec, $F(1,26) = 27.95$, $p < .001$.

**Materials and Procedure**

At the beginning of the testing session all participants completed a brief biographical questionnaire including items related to years of education, occupation, and health status; the Mill Hill vocabulary test; and a speed of processing task. The speed of processing task included 16 items presented on two 8.5 × 11 in. pieces of paper. For each item, individuals were to match a target design to one of four alternatives by placing a mark through the alternative matching the target. A vertical line divided the targets and alternatives; targets were presented to the left of the line and alternatives were presented to the right of the line. The number of seconds required to complete the 16 items served as the dependent measure for this task.

The Stroop task included a color-to-key acquisition phase and a test phase. The color-to-key acquisition phase included 100 trials and was designed to acquaint participants with the response key mapping that was used in the task (i.e., red—v key, blue—b, green—n, yellow—m). In this phase, each of the colors was presented equally often in a random order in a string of X's until a response was made and individuals were to press the key associated with the color. Accuracy rather than speed was stressed in this phase.

The test phase included three sets of trials (i.e., blocked color cueing, blocked word cueing, and trial-by-trial cueing). The color and word sets included six blocks of 48 trials (1 practice and 5 tests) and the trial-by-trial set included 11 blocks of 48 trials (1 practice and 10 tests). Each trial included two displays: a dimension cue and the Stroop stimulus. The dimension cues were the words COLOR or WORD and indicated whether the color or word was relevant for that trial; the Stroop stimuli were the words (RED, BLUE, GREEN, YELLOW) presented in one of these four colors and could be either congruent (e.g., RED in red) or incongruent (e.g., RED in blue). There were 24 congruent and 24 incongruent stimuli in each block. The dimension cue was presented for 500 msec followed by a blank screen for 1000 msec and then the Stroop stimulus until a response was made. For the color blocks, individuals were instructed that color was always the relevant dimension for the block of trials and the dimension cue was always the word COLOR; for the word blocks individuals were instructed that the word was always the relevant dimension for the block of trials and the dimension cue was always the word WORD. For the trial-by-trial blocks the relevant dimension was randomly cued for each trial and individuals were instructed to respond to the stimulus dimension that was indicated by the cue (e.g., COLOR → RED in blue, respond blue). In the trial-by-trial blocks, there were 24 color and 24 word identification trials.

**Electrophysiological recording and analysis**

The EEG (band pass .01–100 Hz, digitized at 512 Hz, gain 2500, 12-bit A/D converter) was recorded from an array of 45 tin electrodes (Fpz, Fz, Pz, Oz, Iz, Fp1, Fp2, AF3, AF4, F3, F4, F7, F8, F9, F10, FC1, FC2, FC5, FC6, FT9, FT10, C3, C4, T7, T8, Cp1, Cp2, Cp5, Cp6, P3, P4, P7, P8, O1, O2, Po9, Po10, M1, M2, Lo1, Lo2, Io1, Io2) sewn into an Electro-cap or affixed to the skin with an adhesive patch. 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 electrode Cz; for data analysis, they were re-referenced to an average reference, electrode Cz was reinstated (Picton et al., 2000), and a 12-Hz low-pass filter was applied.

ERP epochs were extracted off-line for three different events (i.e., cue-related activity, Stroop stimulus-related activity, and response-related activity). Cue-related activity was measured from 200 msec before onset of the dimension cue to onset of the Stroop stimulus; Stroop stimulus-related activity was measured from 200 msec before onset of the Stroop stimulus to 1200 msec after onset of this stimulus; and response-related activity was measured from 200 msec before the response to 300 msec after the response. Ocular artifacts associated with blinks were removed from the data using a covariance-based technique including empirically derived estimates of the EEG associated with artifact and artifact-free data. Trials contaminated by other artifacts, peak-to-peak deflections over 100 µV, were rejected before averaging. ERPs elicited by dimension cues and Stroop stimuli were averaged for correct congruent and incongruent trials in the color, word, and trial-by-trial cueing blocks in younger and older adults. ERPs elicited by the response to the Stroop stimuli were averaged for correct and incorrect incongruent color and word trials in the trial-by-trial cueing condition for younger and older adults.

All statistical tests were performed on mean voltages using the univariate $F$ ratio at the $p < .05$ level of significance and Huynh–Feldt adjusted degrees of freedom. Throughout the paper, the adjusted $p$ values are reported with the unadjusted degrees of freedom and epsilon value for tests including more than one degree of freedom in the numerator. In the cue-related epoch, three modulations were of interest (i.e., N1, P3, and slow wave). The N1 was measured between 125 and 150 msec and the analysis of this component included electrodes Po9–Po10, O1–O2, and Oz; the P3 was measured between 250 and 350 and 400 and 500 msec and the analysis included electrodes P3–P4, Pz, C1–C2, and Cz; the slow wave was measured between 800 and 1000 and 1000 to 1500 msec and the analysis
included electrodes O1–O2, Pz–Po4 for the occipital–parietal region and A3–A4 and Fp1–Fp2 for the anterior frontal region. In the Stroop stimulus-related epoch three modulations were of interest. The N450 was measured between 475 and 525 msec and the analysis included electrodes P3–P4, C3–C4, and Pz, and Po3–Po4 for the parietal region and electrodes F7–F8, F9–F10, and F7–F10 for the lateral frontal region. The analysis of the stimulus-related sustained potential observed in older adults included electrodes Fz and Pz. The ERN was measured between 50 and 100 msec, and the analysis included electrode Cz.

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