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Accounting for Cognitive Aging: Context Processing, Inhibition or Processing Speed?

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ABSTRACT

Age-related deficits in context processing were examined in relationship to two predominant theories of cognitive aging (the Inhibitory Deficit and Processing Speed Models). Older and younger adults completed a measure of context processing (AX Continuous Performance Test (CPT) task) as well as a computerized battery of inhibitory tasks: Stroop, garden path sentences, go no-go, and the stop-signal paradigm. Participants also completed a simple processing speed task. After controlling for baseline differences in processing speed, age effects were detected on the AX-CPT. Smaller, but significant age effects were noted on the Stroop and stop-signal tasks, but no significant age effects were found on the garden path sentence and go no-go tasks. Intertask correlations were weak, providing little evidence for a homogenous or uniform construct of inhibition. The sensitivity of the AX-CPT to cognitive aging is discussed in the context of existing theories of cognitive aging. The authors suggest that deficits in context processing and utilization may underlie cognitive aging phenomena.

The goal of much research on cognitive aging is to identify the core cognitive processes that show age-related changes. In our prior research, we found significant age differences on an AX version of the Continuous Performance Test (AX-CPT) (Braver et al., 2001) which we interpreted as reflecting age-related changes in context processing. However, task demands on the AX-CPT are multifactorial, and it is possible that age-related changes in AX-CPT task performance primarily reflect cognitive mechanisms other than context processing. In particular, although the AX-CPT is a task of context processing, successful performance also depends on inhibitory control and processing speed efficiency. The goal of the current study was to determine the extent to

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which age differences in context processing may be related to, or explained by, age-related changes in either inhibitory function or processing speed. Below, we first review our theory regarding context processing in cognitive aging, and prior experimental work in testing this theory using the AX-CPT. Next, we discuss alternative accounts of cognitive aging: the Inhibitory Deficit (ID) account and the Processing Speed (PS) account. We then describe the current study, in which we test these various accounts in terms of their respective abilities in accounting for age-related changes in task performance.

Context Processing

Context processing is integral to cognitive control as it allows individuals to internally represent patterns of environmental cues such that these cues can be used to exert control over thoughts and behavioral responses. Context processing involves the formation of an internal representation of context, maintenance of context information over time, and continuous updating of context representations to accurately represent changes in environmental cues (Braver & Cohen, 1999; 2000; 2001; Braver et al., 2002; O'Reilly et al., 1999). Internal representations of context can be generated from the presentation of a specific prior stimulus, as a result of earlier processing, or from task instructions. Context representations appear to be particularly important to cognitive control in situations where there is strong response competition. As such, context can be helpful for guiding behavior when the appropriate response is infrequent or when a dominant response is no longer appropriate (Barch, Racine, & Braver, submitted).

The AX-CPT was specifically designed to examine different aspects of context processing. In the AX-CPT, participants see a continuous stream of single letters, presented in cue-probe pairs. Participants are instructed to make a "target" response when they see the letter "X," but only if it follows an "A" cue; a "nontarget" response should be made with any other cue-probe pairing. As such, the cue (A or non-A) serves as the context that determines how one should respond to an "X" probe. Seventy percent of AX-CPT trials are target (AX) trials. The remaining 30% are nontarget trials, with 10% "A–Y (Y = any probe other than X), 10% B–X (B = any cue other than A), and 10% B–Y trials. This creates a bias for individuals to respond with a target response to X probes because this is the correct response on the majority of trials. Thus, on BX trials, context must be used to *inhibit* or override a prepotent response tendency. A second bias is also created by the high frequency of target trials. Healthy individuals will have a bias to make a target response after seeing "A" cues, given that the majority of the time they see an "A," it is followed by an "X." Thus, on AY trials context actually causes individuals to false alarm, or respond inappropriately to a probe based on cue information. As such, individuals with intact context representations are likely to demonstrate slowing and elevated rates of error in AY trials relative to BX

trials because context representations will hurt AY performance, but aid BX performance. Conversely, individuals with poor context representations are likely to demonstrate slowing and elevated rates of errors in BX trials relative to AY trials, because poor context representations will not allow them to override prepotent responses in BX trials, and will not cause them to false alarm on AY trials.

Empirical support for age differences in context processing between young and old adults comes from Braver et al. (2001), Braver, Satpute, Rush, Racine, & Barch (2005), and Barch et al., (submitted). These previous studies revealed that young adults are able to maintain the context of the A cue, as they demonstrated a characteristic slowing of responses in AY trials relative to BX trials as well as greater errors on AY compared to BX trials. In contrast, older adults did not seem able to use the context of the A cue. The most consistent finding is of disproportionately slower RTs on BX trials compared to younger adults (Braver et al., 2001; Barch et al., submitted), and an absence of the typical slowing of RTs on correct AY trials. In addition, one study also found that older adults showed as many (or more) BX than AY errors (Barch et al., submitted). These results suggest that older adults have a subtle, but impaired ability to engage inhibitory mechanisms particularly when they are required to endogenously maintain the context for appropriate behavioral responding. In addition, Braver et al. (2001) found that when context maintenance demands are further raised (by introducing interference information between cue and probe information) older adults demonstrate reliable overt errors in responding as well as consistent patterns of slowing. Thus, characteristic age-related patterns of performance on the AX-CPT for AY and BX trials may surface in response slowing and/or overt response errors, depending on the relative demand for context representation, processing, and maintenance in the task situation. Nevertheless, there are at least two possible alternative interpretations of the data regarding age-related performance changes in AX-CPT performance that are based on existing theories of cognitive aging—the ID and PS models.

The ID Account

It is important to consider whether an ID account of cognitive aging can explain performance differences between young and old adults on the AX-CPT. Hasher and Zacks (1988) proposed that many age-related deficits observed across cognitive domains (including selective attention, language, and episodic memory) can be explained by a single common mechanism—declining efficiency in inhibitory function with increased age. According to this model of cognitive aging, older adults (as compared to younger cohorts) cannot appropriately filter incoming information, cannot efficiently and accurately delete irrelevant information from cognitive representations of current task demands, and cannot accurately restrain prepotent tendencies

under changing contextual contingencies. Given these general inhibitory deficits, older adults can appear more challenged across cognitive tasks relative to younger adults. A substantial amount of empirical support for the ID model has amassed, coming from a variety of cognitive tasks including directed forgetting paradigms (Zacks et al., 1996), the garden path sentence paradigm (Hartman & Hasher, 1991), and Stroop tasks (Daigenault et al., 1992). Nevertheless, several studies have suggested that the relation between age and inhibition may not be so clear (e.g., Connelly & Hasher, 1993; Sullivan & Faust, 1993; Sullivan et al., 1995). Further, in a large study comparing age-related changes on a variety of inhibitory tasks, including negative priming, response compatibility, the stop-signal paradigm, and the Wisconsin Card Sort Test, Kramer et al. (1994) showed that age-related inhibitory deficits were only present on some of the tested tasks.

As previously described, the AX-CPT involves inhibitory control because individuals must use context information to override prepotent response tendencies. On the basis of age-related deficits in inhibition, the ID model may predict that old adults (as compared to young adults) show elevated rates of error and disproportionate slowing on BX trials since this trial type requires individuals to overcome prepotent response tendencies. Data from previous studies on the AX-CPT and aging reveal this pattern of deficit on BX trials for old adults, but also demonstrate that old adults show relative improvements in performance (compared to young adults) on AY trials. Although the ID model can account for the pattern of age effects on BX trials, it cannot account for a counterintuitive improvement in performance (relative to young adults) on AY trials. Nonetheless, BX trials do appear to tap into the inhibitory construct that Hasher and Zacks posit to be impaired in older adults. Thus, one useful way to examine this issue further would be to compare performance on the AX- CPT to performances on other measures of inhibitory function to better understand the constructs represented by the AX-CPT. As such, one of the goals of the current study will be to compare AX-CPT performance to performance on a range of inhibitory control tasks.

The PS Account

The AX-CPT is a task that requires speeded responses. For this reason, it is also important to consider whether a PS account of cognitive aging could also account for performance differences between young and old adults on the AX-CPT. Salthouse (1996) proposed a uniquely parsimonious explanation for age-related deficits in cognition. He suggested that age differences in simple processing speed decrease general information processing efficiency across a variety of cognitive tasks including those of attention, working memory, and episodic memory; the decreased efficiency results in age-related deficits. Several studies support this model (e.g., Cerella, 1990, 1991; Cerella & Hale, 1994; Cerella et al., 1993; Sliwinski & Buschke, 1999).

In addition, there is now evidence that the effects of generalized slowing with increased age are more pronounced as task complexity increases (Cerella, 1990; Cerella et al., 1980; Hale et al., 1991; Salthouse, 1995). Although this evidence suggests that age differences in processing speed might account for age-related deficits in cognitive functions such as context processing, other studies have suggested that significant age-related variance in cognition remains after adequately controlling for baseline differences in processing speed (e.g., Keys & White, 2000). In previous studies of age differences on the AX-CPT (Braver, Barch, Keys, Carter, et al., 2001; Braver, et al., 2005), age differences on the AX-CPT remained significant after controlling for baseline processing speed differences, suggesting that the PS model of cognitive aging does not adequately account for age-related deficits on the AX-CPT. However, these previous studies did not include a separate measure of simple processing speed that could be used to prospectively address the influence of processing speed on AX-CPT task performance.

Overview of the Current Study

The current study was designed to replicate previous findings of age differences on the AX-CPT and to further investigate the extent to which age effects on the AX-CPT relate to the ID and PS models of cognitive aging. In order to examine this issue, we recruited a large sample of healthy older and younger adults to complete a test battery that included the AX-CPT, as well as other commonly used tasks of inhibitory control (the Stroop task, go no-go paradigm, garden path sentence task, and the stop-signal paradigm). The following a priori predictions were made:

1. If age differences in AX-CPT performance are simply due to age-related deficits in inhibitory control, then older adults should show elevated error rates and/or disproportionate slowing in BX trials as this condition requires inhibitory control. In addition, age-related effects on BX trials should be highly correlated with age-related Stroop effects, and the ability to withhold prepotent responses on the garden path sentence, go no-go, and stop-signal tasks. A high degree of intercorrelation between tasks would suggest convergent validity for an age-related inefficiency on a common ability construct (such as inhibition) across tasks.
2. If age differences in AX-CPT performance are due to baseline differences in processing speed, then age effects on BX and/or AY trials of the AX-CPT should no longer be significant after statistically controlling for simple motor speed.
3. If age differences in AX-CPT performance are uniquely due to age-related deficits in context processing, then older adults should not

only show elevated errors and disproportionate slowing in BX trials, but also demonstrate a relative improvement in performance on AY trials, as revealed by a decreased rate of errors and/or decreased slowing on AY trials relative to young adults. In addition, older adult performance on AY and BX trials should be weakly correlated with performances on the Stroop, garden path sentence, go no-go, and stop-signal paradigms, indicating that the context processing construct is not identical to that of inhibition.

METHOD

Participants

Fifty-one healthy younger adults (35 women and 16 men, mean age = 19.8 years) and 56 healthy older adults (39 women and 17 men, mean age = 74.8 years) with no history of neurological compromise were recruited. This sample comprises a subset of participants recruited for a larger study on cognitive aging. AX-CPT data from the larger study, which includes data from the subsample reported here, has been published in Braver, Gray et al. (2005). Participants in the young group were recruited from the Washington University community; older participants were recruited from the older adult volunteer pool in Washington University's Department of Psychology. Informed consent was obtained from all individuals prior to beginning participation in the investigation following guidelines set forth by the Washington University Standing Committee on the Use of Human Subjects. Participants were told that they could withdraw consent and discontinue the study at any time. Participants were offered $15 remuneration for their participation.

Individuals with medical disorders, neurological disorders, psychiatric disorders, or medication histories that could contribute to cognitive dysfunction were excluded from the study. All participants were asked health status screening questions during initial telephone contact. Individuals with a positive history of neurological disorder, cerebrovascular accident, head injury, learning disability, and/or recent drug use were not included in this study. All older adult individuals were administered the Blessed Orientation-Memory-Concentration (BOMC) (Katzman et al., 1983) over the telephone in addition to the health status questions. Individuals obtaining five or more errors were not included in this study. Among older adult participants included in this study, the mean BOMC score was 1.14 (SD = 1.33).

All participants were administered the vocabulary subtest from the Wechsler Adult Intelligence Scale—Third Edition (WAIS-III) (Wechsler, 1997) to provide an estimate of general intellectual function in the two age groups. In addition, because depression may affect psychomotor speed and general cognitive performance (White et al., 1997), all participants were

administered the Beck Depression Inventory (BDI) (Beck et al., 1961). Individuals with a score of 10 or higher on the BDI were excluded from all analyses.

Materials

AX Version of the Continuous Performance Test (AX-CPT)

Materials for the AX-CPT are those developed by Braver et al. (1999). In this paradigm, participants are instructed to make a target response when provided the sequence of an A, immediately followed by the letter X. In all other cases, participants are instructed to make a nontarget response. The paradigm provides a sequence of letters that cue a target response on 70% of the trials (AX trials), priming the cognitive and motor systems to be predisposed towards a target response. The remaining 30% of trials provide cues to make nontarget responses (10% AY trials, 10% BX trials, 10% BY trials). Inhibitory control is examined by examining error rates in AY and BX conditions. Specifically, this paradigm examines how individuals' respond when provided with an "A" cue followed by a non-X probe (e.g., AY trials) and how they will respond when provided with a non-A cue followed by an X probe (e.g., BX trials). Visual stimuli were a series of letters presented in the middle of a computer-controlled display in 48-point Geneva font subtending a visual angle of approximately 3 degrees. One hundred trials were presented for each participant. There was a 5000-ms delay between cue and probe and a 1000-ms intertrial interval between the probe and the next cue. Dependent variables for this task were median numbers of errors and reaction times for the trials of primary interest (e.g., AY and BX trials).

Stroop

Participants were required to name the ink color of a printed word as quickly as possible. Because word reading is automatic, inhibitory control is though to be required to override this prepotent cognitive processing. Incongruent trials were composed of color word names (e.g., red, blue, green) that were presented in a color different from the color associated with the word name (e.g., the word red presented in blue ink). Congruent trials were composed of word names in which the word name is a color different from the ink color in which the word is printed. In congruent trials, the word and ink color are the same. Neutral trials consisted of noncolor word names within a single semantic category (e.g., animals: monkey, tiger, bear, cat). Materials for this task and task procedure were similar to those used by Barch et al. (1999) and consisted of 90 trials, 30 congruent trials, 30 incongruent trials, and 30 neutral trials. Voice reaction times were recorded via a voice key connected to the computer. Sensitivity of the voice key to participants' vocal responses was adjusted prior to the onset of task administration. Participants' responses were entered into a keypad on the computer during task

administration in order to record accuracy. The inhibitory effects of the paradigm were examined by comparing performance in the incongruent condition to the performance in the congruent condition (Spieler, 1996). This form of Stroop analysis is typically referred to as the "total" Stroop effect (inhibition minus facilitation). The total Stroop effect may be more likely to reveal inhibitory deficits due to the fact a failure to inhibit attention to the word can lead to slow RTs on incongruent trials, but could actually speed performance on congruent trials, leading to a more pronounced difference in performance between the incongruent and congruent conditions (Barch et al., 1999).

The dependent variables for this task were median errors and RTs in the congruent and incongruent conditions. For regression analyses of age effects, we formed two residual scores—one for errors and one for RT. Each residual score reflected performance in the incongruent condition adjusted for an individual's performance in the congruent condition. In other words, residual scores captured the difference between predicted and observed performance in the incongruent condition. Residuals were used instead of difference scores to take into account baseline differences in speed of processing.

Garden Path Sentences

The garden path sentence task is a measure of implicit memory that examines the ability to abandon prepotent or automatic responses when instructed to do so. The garden path sentence task was developed as a task that taps into the ability to inhibit information from memory. In contrast to other commonly used inhibitory tasks (i.e., Stroop, stop-signal), the garden path sentence task does not require a speeded response. As such, it is thought to represent a more pure measure of inhibitory function in cognition. Materials for the sentence completion task and task procedure are those developed by Hartman and Hasher (1991). The learning phase consisted of presentation of 28 sentences with highly predictable endings (approximate cloze values = .85; e.g., "Before you go to bed, turn off the *light*"). For each of these sentences a low probability ending (e.g., *stove* for this example) is also available. For half of the 28 sentence frames presented, participants were instructed to "abandon" the own high probability ending in favor of the low probability ending; participant-generated endings were confirmed for the remaining 14 sentences confirmed the participant-generated endings for the remaining 14 sentences. After a 5-minute delay, participants were given a "memory" test. They were instructed to read 56 moderate-cloze sentence frames (approximate cloze values = .50) as they appeared on the computer screen and to complete the sentences with the first word that came to mind that made sense. Target word completions were defined as responses from the learning phase that participants were instructed to abandon. Control word completions were defined as responses to sentence frames that were

never presented during the learning phase. The dependent variable of interest in the garden path task was calculated from target and control word completions. The primary variable of interest was a residual score reflecting performance in the target condition adjusted for an individual's performance in the control condition. As such, the residual score created captured the difference between observed and predicted performance in the target condition. That is, target word completions were predicted on the basis of one's ability to produce control word completions. A residual score was used instead of a difference score to take into account baseline differences in sentence completion.

Go No-Go

The go no-go is a classic task of inhibitory function that is widely used in the clinical and cognitive neuroscience literatures, including a recent brain imaging study of older adults (Nielson et al., 2000). The task indexes the ability to suppress responding to a low-frequency target stimulus. Materials for this go no-go task and procedure employed here were similar to those used by Casey et al. (1997). Participants were presented with a sequence of single stimuli (letters) in size 48 font one at a time at the center of the computer screen. Participants were instructed to respond by pressing a button with the index finger of their dominant hand to any sequentially presented stimulus except the number 5. Stimuli were presented for 500 ms with an interstimulus interval of 1000 ms. The number 5 occurred in 25% of the trials. The dependent variable for this task was the number of errors in withholding a respond to the 5 stimulus.

Stop-Signal

The stop-signal task is similar to the go no-go in that it probes the ability to intermittently suppress responding when instructed. A critical difference is that stop-signal onset times are manipulated in order to estimate the exact time required to stop a given response once it had been initiated. The materials and procedure for the stop-signal task used here were similar to those employed by Williams et al. (1999). The go task was a simple reaction-time task that had the same stimulus and presentation parameters as the simple processing speed task described in the following section. Participants were told that occasionally an auditory tone (stop-signal) would occur; when they heard the tone, they were not to respond on that trial (e.g., withhold key press). The stop-signal was a 10-ms, 1000-Hz tone generated by the computer. Participants were told that the stop-signal would occur at different times on each trial and that they should not wait for the stop-signal because it would occur randomly and infrequently. The 256 trials were divided into eight blocks of 32 trials each. The stop-signal was presented randomly on 25% of the trials in each block. Stop-signal trials were presented in a different random order for each block of the task. Participants initiated the onset

of each trial by pressing the space bar to begin. Participants received a block of 12 practice trials (including four stop trials) to ensure they understood the task instructions.

The stop-signal task was administered using an adaptive procedure that adjusted stop-signal delays in a fashion to achieve a target stop-signal error rate of 50%. At this level of performance, the average stop-signal delay provides an index of inhibitory control. The following procedure was used. Stop-signal delay was initially set at 125 ms (i.e., the presentation of the auditory tone occurred 125 ms following the onset of the go stimulus). If the participant successfully inhibited the motor response, the stop-signal delay was increased by 25 ms on the next stop trial, effectively making it harder to inhibit the motor response. Conversely, if the participant failed to inhibit responding, the stop-signal delay was reduced by 25 ms on the next stop trial.

During the first two task blocks the stop-signal value fluctuated towards asymptotic values. Consequently, these blocks were excluded from analyses. The median stop-signal delay interval was then calculated for each participant from the 48 stop-signal trials occurring in Blocks 3 through 8. If the tracking procedure functioned effectively, the error rate for the trials on which the median stop-signal delay interval was calculated should be 50% (i.e., the person inhibits the motor response on half of the stop-signal trials and fails to inhibit on the other half). Based on 48 trials, the 95% confidence interval for an error rate of 50% would be 35% to 65% errors. Only three participants were excluded from analyses due to error rates outside of this confidence interval. For young adults, there was an average of 47% errors; the average was 55% in old adults.

The dependent variable used in this task was a residual score. The residual score captured the median stop-signal delay adjusted for an individual's go-signal reaction time. The residual was the difference between the predicted and observed median stop-signal delay. A residual score in place of a difference score in order to account for baseline differences in processing speed.

Simple reaction time (SRT)

A SRT task was administered in order to account for age-related differences in performance that are related to motor slowing. This method has been used in previous studies (e.g., Keys & White, 2000) to identify the unique contribution of age to variability in performance on a specified task of interest.

Participants were presented with a fixation point (+) of size 48 at the center of a computer screen followed by a black square of size 96 font on a white background. Once the square appeared on the screen, it remained until the participant made a response. Participants used the index finger of their dominant hand to press a designated button on a button box interfaced with PsyScope software (http:psyscope.psy.cmu.edu) as quickly and as accurately as they could when the stimulus appeared. The onset of the next trial was initiated by pressing the spacebar on the computer keyboard. Participants

received five practice trials in order to ensure comprehension of task instructions. The preparatory interval between the fixation onset and stimulus onset varied randomly between 1000 and 2000 ms in units of 250 ms (1000, 1250, 1500, 1750, 2000 ms) so that the onset time of the stimulus would be difficult to predict. Ten trials with each stimulus onset delay were presented. The dependent variable from this task was median reaction time from 50 trials for each participant.

Procedure

Participants completed all experimental measures and laboratory tasks in a single, 2-hour testing session. The order of task administration was counterbalanced across participants within each group, with the exception that the simple processing speed task always immediately preceded the stop-signal task. All testing was conducted in testing rooms specifically designed to provide appropriate lighting and to minimize potential auditory and visual distraction. Participants were informed of their opportunity to request short breaks between tasks at any time during a given testing session. On all tasks, participants were encouraged to respond as quickly as possible without sacrificing accuracy to performance. The tasks were administered on an Apple Macintosh computer using PsyScope software (http:psyscope.psy.cmu.edu) for stimulus presentation and data collection (Cohen et al., 1993). For all tasks but the Stroop, participants responded to computer tasks by pressing response buttons located on a specifically constructed box connected to the computer, which recorded both response choice and reaction time with 1 ms accuracy. Responses to the targets were made with the index finger of the dominant hand. Responses to the nontargets on the AX-CPT task were made with the adjacent middle finger of the dominant hand.

RESULTS

An alpha level of .05 was used for all statistical tests

Means and standard deviations for age, education, WAIS vocabulary, and the BDI are presented in Table 1. Younger adults were slightly less educated than older adult participants, $t(105) = 2.81$, $p < .01$; younger adult participants had slightly higher WAIS vocabulary scores than older participants, $t(105) = 3.05$, $p < .01$; and younger adults had slightly lower BDI scores than older adult participants, $t(105) = 3.85$, $p < .01$. It is important to note that, despite slight group differences on the BDI, both groups obtained scores well within the "not depressed" range of the normative sample (i.e., a score of 10 or higher is considered mildly depressed).

Table 2 includes means, standard deviations, and independent *t*-test results for all dependent measures included in the study. Results from

TABLE 1. Participant Demographics

	Younger Adults		Older Adults		
	n = 51		*n* = 56		
	Mean	SD	Mean	SD	t
Age	19.8	1.9	74.8	4.3	
Education	13.9	1.5	14.9	2.3	2.81**
WAIS Vocabulary	54.7	4.9	50.1	10.0	3.05**
Beck Depression Inventory	2.7	2.7	4.7	2.7	3.85**

**$p < .01$.

TABLE 2. Means and Standard Deviations for All Dependent Variables

	Young		Old			
Variables	Mean	SD	Mean	SD	t	*p*-Value
AX-CPT errors—AX trials (%)	4.00	8.00	3.00	3.00	–1.12	NS
AX-CPT errors—BY trials (%)	1.00	2.00	0.00	1.00	–1.11	NS
AX-CPT errors—AY trials (%)	13.00	15.00	4.00	7.00	–4.20	.0001
AX-CPT errors—BX trials (%)	6.00	11.00	4.00	11.00	–0.83	NS
AX-CPT reaction time—AY trials (ms)	554.29	108.81	624.82	80.75	3.83	.0001
AX-CPT reaction time—BX trials (ms)	374.63	112.02	576.37	206.66	6.35	.0001
Stroop errors—congruent (%)	1.00	2.00	1.00	3.00	0.97	NS
Stroop errors—neutral (%)	1.00	2.00	1.00	4.00	1.21	NS
Strop errors—incongruent (%)	3.00	6.00	4.00	6.00	1.15	NS
Stroop reaction time—congruent (ms)	610.53	81.80	777.23	160.90	6.84	.0001
Stroop reaction time—neutral (ms)	642.75	71.93	837.96	136.07	9.39	.0001
Stroop reaction time—incongruent (ms)	735.00	102.55	956.62	174.53	8.09	.0001
Garden path—target items (# recalled)	7.67	2.28	7.96	2.06	0.71	NS
Garden path—control items (# recalled)	7.00	2.01	6.96	2.10	–0.09	NS
Go no go—nontarget errors (%)	14.00	14.00	13.00	16.00	–0.37	NS
Go no go—target errors (%)	0.00	0.00	1.00	7.00	1.11	NS
Stop-signal—errors stopping (%)	47.00	11.00	55.00	14.00	3.34	.001
Stop-signal—stop-signal delay (ms)	180.36	118.92	362.45	187.46	5.93	.0001
Simple reaction time (ms)	243.64	41.43	319.26	65.30	7.22	.0001

NS = Non-significant.

independent samples *t*-tests are provided in order to document age differences on the various tasks administered. Arcsine transformations were performed on all raw accuracy data before these data were subjected to statistical analysis. *T*-test results reveal that younger adults made more errors on AY trials than older adults. Compared to young adults, old adults were generally slower across all tasks and they produced greater errors in withholding a prepotent response on the stop-signal task. In order to test specific

a priori theoretical hypotheses regarding differential aging effects across task conditions, multiple analysis of variance (MANOVA) and hierarchical regression procedures were conducted; the results of finer-grained analyses are presented for each task.

A/X Version of the Continuous Performance Test (A/X CPT)

A priori hypotheses were tested using a mixed model analysis of variance (ANOVA) for errors, with age group (young vs. older) as a between-subject independent variable and trial type (AY, BX) as a within-subject independent variable. Figures 1A and 1B reveal AX-CPT error and reaction time data across trial types and facilitate a comparison of current results with previously published data on cognitive aging and AX-CPT performance. Analyses of error rates revealed that younger adults produced more errors than older adults, $F(1, 105) = 12.29$, $p < .05$, and participants made more AY than BX errors, $F(1, 105) = 5.34$, $p < .05$. Finally, a significant interaction between age group and trial type was found, $F(1, 105) = 7.77$, $p < .05$.

Consistent with prediction, simple effect analyses revealed that younger adults produced more AY errors than BX errors, $F(1, 105) = 12.42$, $p < .0001$. Thus, the context of an A cue appeared to cause young adults to a false alarm on trials that should have resulted in a nontarget response. In

FIGURE 1A. AX-CPT errors by trial type

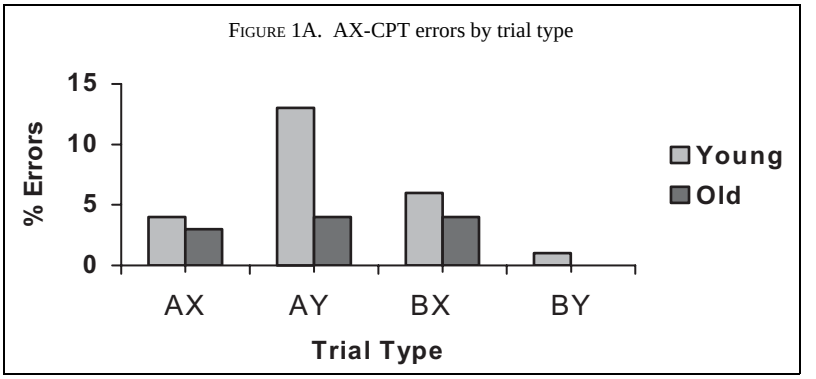
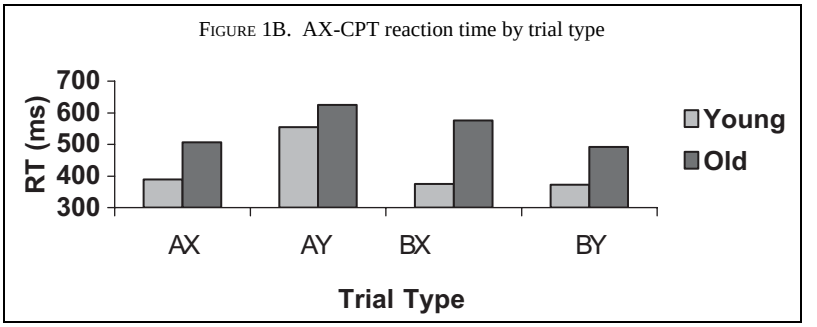


FIGURE 1B. AX-CPT reaction time by trial type



contrast, simple effect analyses revealed that older adults produced approximately equivalent amounts of errors in AY and BX conditions, $F(1, 105) = .12$, $p > .05$; further, the age group X trial-type interaction was also driven at least in part by the fact that younger adults produced substantially more AY errors than older adults $F(1, 105) = 20.47$, $p < .0001$, whereas, there was no significant group difference in BX errors, $F(1, 105) = .79$, $p > .05$. These results suggest that as predicted, the presence of context resulted in greater errors for younger than older adults, whereas older adult performance appeared less dependent on the context of the cue (A or non-A) provided. However, we did not find the predicted increase in BX errors among older adults.

Reaction Time (RT) analyses revealed that older adults were generally slower than younger adults, $F(1, 105) = 55.48$, $p < .01$. A main effect of trial type was found, $F(1, 105) = 62.25$, $p < .01$, as well as a group trial type interaction, $F(1, 105) = 24.04$, $p < .01$. Simple effects analyses revealed that young, $F(1, 105) = 78.18$, $p < .0001$, and older adults, $F(1, 105) = 4.68$, $p < .05$, were slower in AY relative to BX trials. Thus, both groups demonstrated RT slowing on trials during which they received the A cue (context information). Older adults were slower than younger adults on both AY trials, $F(1, 105) = 33.45$, $p < .0001$, and BX trials, $F(1, 105) = 51.08$, $p < .0001$. However, comparison of the effect sizes for group differences on these two trial types indicated that age differences in RT were disproportionately greater on BX trials relative to AY trials. Although old adults did not demonstrate the predicted elevation of overt errors on BX trials, RT data provide evidence that older adults were less able to use the context provided by the cue to override prepotent response tendencies.

In order to determine that confirmed age effects on the AX-CPT were not simply due to motor slowing, hierarchical regressions were conducted with statistical control for SRT. After controlling for motor slowing, the unique effect of age on AY error performance, $R^2 = .14$, $\beta = -.46$, $F(1, 104) = 17.77$, $p < .01$, and BX RT performance remained significant, $R^2 = .04$, $\beta = .23$, $F(1, 104) = 7.05$, $p < .01$. Interestingly, the effect of age on AY RT was no longer significant after controlling for simple processing speed, suggesting that the initially detected relationship was likely related to age differences in cognitive efficiency.

Stroop

Hierarchical regression was used to examine age differences on the total Stroop effect. Performance in the incongruent condition was the dependent variable. Performance in the congruent condition was entered as the independent variable on the first step; age was entered at the second step of the analyses. After entering error performance in the congruent condition first, the effect of age on error performance in the incongruent condition was not significant, $R^2 = .02$, $\beta = .13$, $F(1, 104) = 1.88$, $p > .05$. After entering RT performance in the

congruent condition first, the effect of age on RT performance in the incongruent condition was significant, $R^2 = .03$, $\beta = .19$, $F (1, 104) = 13.97$, $p < .05$. Therefore, the Stroop effect increased with increased age. Even after accounting for motor slowing first (with the SRT task), the Stroop effect increased with increased age, $R^2 = .01$, $\beta = .15$, $F (1, 103) = 7.09$, $p < .05$.

Garden path sentences

Table 2 shows no significant group differences on any garden path variables. Further analyses with hierarchical regression were conducted to examine the unique relation between age and target completion performance over and beyond the ability to provide control completions. Target completions were prorated based on a person's tendency to produce anticipated critical endings during the learning phase (e.g., number of critical items from the learning phase that a participant actually generated and were disconfirmed by the experimenter that were expected to be generated as high-cloze endings). In the hierarchical regression, the prorated number of target completions was entered as the dependent variable. The total number of control completions was entered as the independent variable in the first step of the analysis; age was entered as the independent variable in the second step. After entering control completions first, the effect of age on critical completions was not significant, $R^2 = .00$, $\beta = .10$, $F (1, 104) = 0.46$, $p > .05$; increased age was not associated with a greater recall of target items during the test phase. Additional analyses indicated that there was no age difference in raw target completion performance (i.e., performance before prorating) during the learning phase of this task, $t (105) = 1.10$, $p > .05$.

Go No-Go

No significant group differences were found on any of the go no-go dependent variables when evaluated by *t*-tests or hierarchical regression. There were no significant effects of age on the percentage of errors in the no-go condition, $R^2 = .00$, $\beta = –.02$, $F (1, 105) = 0.06$, $p > .05$, or in the go condition, $R^2 = .03$, $\beta = .17$, $F (1, 105) = 3.03$, $p > .05$.

Stop-Signal

Hierarchical regression was used to determine if there were age effects in the mean time needed to respond accurately to the stop-signal. Mean stop-signal delay was entered as the dependent variable. Median go-signal reaction time was entered as the independent variable on the first step of the analysis; age was entered as the independent variable on the second step. As predicted, stop-signal reaction time increased with age, $R^2 = .01$, $\beta = –.14$, $F (1, 104) = 11.31$, $p < .01$. Despite age-related slowing effects, increased age appears to result in the need for a decreased stop-signal delay, $R^2 = .01$, $\beta = –.13$, $F (1, 103) = 8.27$, $p < .01$.

SRT

A significant positive correlation between age and SRT was confirmed, $r = .57$, $p < .01$, providing evidence for motor slowing with increased age. Unilateral ANOVA confirmed significant group differences in speed, F (1, 107) = 50.03, $p < .0001$ (partial eta-squared = .36).

Comparison of cognitive aging effects across tasks

The magnitude of cognitive aging effects across tasks, after controlling for processing speed, is summarized and presented in Table 3. As shown, the magnitude of the beta weights suggests that the largest age-related effects were found in the two AX-CPT measures. This numerical effect was more directly examined using the Z-test of correlated correlation coefficients (Meng, Rosenthal, & Rubin, 1992). This approach takes into account the degree to which performance on one task may be correlated with performance on a second task. Z-test results revealed that the unique age effect yielded by AY errors on the AX-CPT was significantly greater than unique age effects yielded by BX errors on the AX-CPT, Z (107) = 3.32, $p < .01$, and by Stroop reaction times, Z (107) = 3.32, $p < .01$. The unique age effect yielded by AY errors on the AX-CPT was not significantly greater than age effects yielded on the stop-signal task, Z (107) = .70, $p > .01$. The unique age effect yielded by BX RT on the AX-CPT was not significantly greater than age effects yielded by the Stroop, Z (107) = .10, $p > .01$, or stop-signal tasks, Z (107) = .07, $p > .01$. Finally, the unique age effected yielded by the Stroop task was not significantly greater than age effects yielded by the stop-signal task, Z (107) = .03, $p > .01$.

Correlations Between Tasks

Correlations were computed in each age group to examine the degree to which performance across tasks was related. In the older adult group, AY errors significantly correlated with BX errors (r = .30, $p < .05$) and Stroop

TABLE 3. Unique Correlation of Age with Dependent Variables Partialing Out Processing Speed

Variables	Correlation with Age (sr^2)	β
1. AX-CPT—AY errors	.14**	–.46**
2. AX-CPT –BX RT	.04**	.23**
2 . Stroop RT (total Stroop effect)	.01**	.15**
3. Garden path (target items recalled)	.01	.10
4. Go no-go (non-target errors)	.00	–.02
5. Stop-signal (stop-signal delay)	.01**	–.13**

**$p < .01$.

RT (r = –.32, $p < .05$). BX RT significantly correlated with BX errors (r = .32, $p < .05$), AY RT (r = .40, $p < .01$), and median SRT (r = .56, $p < .01$). AY RT significantly correlated with SRT (r = .35, $p < .01$). All other intertask correlations were not significant. In the younger adult group, go no-go performance was significantly correlated with AY errors (r = .31, $p < .05$), Stroop errors (r = .44, $p < .01$), stop-signal (r = –.35, $p < .05$), and SRT (r = –.33, $p < .05$). BX RT significantly correlated with AY RT (r = .53, $p < .01$) and SRT (r = .40, $p < .01$). AY RT significantly correlated with Stroop RT (r = –.36, $p < .01$). All other intertask correlations were not significant.

Effects of WAIS Vocabulary and BDI Scores

Age differences were not anticipated for WAIS Vocabulary or the BDI. In order to examine the potential influence of these group differences, all analyses were repeated separately controlling for vocabulary and BDI performances. Results of these subsequent analyses did not significantly change the reported findings. Specifically, there were no significant correlations between vocabulary and any dependent measure and there were no significant correlations between BDI Depression score and any other measure.

DISCUSSION

The results of the current study replicate previous findings of age differences in performance on the AX-CPT (Barch et al., submitted; Braver et al., 2001, 2005). Older adults demonstrated a significantly greater challenge making use of context information than younger adults. Compared to young adults, old adults made fewer errors on AY trials and demonstrated disproportionate slowing relative to young adults on BX trials. Although old adults did not demonstrate a higher rate of errors in BX trials relative to AY trials, the disproportionate slowing in BX trials relative to AY trials suggests, at a minimum, that there was a qualitative difference in how young and old adults processed contextual information on BX trials. Age effects on the AX-CPT in the current study remained significant after controlling for baseline differences in motor slowing. Age effects were additionally identified on the Stroop and stop-signal tasks, although the magnitude of these effects was smaller than that found on the AX-CPT. Age effects were not found for the garden path sentence and go no-go tasks. Despite the presence of some moderate intertask correlations in the young group, intertask correlations in the old group were few and weak, questioning the uniformity of an inhibitory construct of aging. The implications for understanding these results with regard to larger theories of cognitive aging are discussed further below.

The goal of this study was to determine the extent to which age differences on the AX-CPT were related to two predominant theories of cognitive aging. Study findings are poorly explained by the PS and ID theories of

cognitive aging. Contrary to predictions of PS theories (e.g., Salthouse, 1996), age differences in AY errors and BX RT on the AX-CPT remained significant after controlling for age-related motor slowing. It could be argued that the SRT measure used in the current study does not accurately represent "the speed with which many elementary cognitive operations can be performed" (Salthouse, 1996). This is somewhat of a controversial point of discussion since "elementary cognitive operations" has never been specifically defined. Many researchers have favored choice reaction time (CRT) tasks over SRT (e.g., Salthouse, 1998; Salthouse & Berish, 2005; Verhaeghen et al., 2003) on the presumption that CRT accounts for more age-related variance in cognitive tasks of interest than SRT. We acknowledge the possibility that SRT insufficiently accounts for age-related variance in many cognitive tasks; however, when hierarchical regression analyses were repeated using BY RT as an alternative to SRT, the unique relation between age and AX-CPT performance (at least for AY errors) remained significant. Given that BY trials presumably have greater processing requirements than our SRT task, BY RT should have accounted for a greater proportion of age-related variance in task performance than SRT. This was not the case, suggesting convergent validity to the conclusion that age differences on the AX-CPT are not solely due to processing speed and motor slowing.

Perhaps one of the most fascinating aspects of the AX-CPT paradigm is that predicted age-related effects surface as weaknesses on BX trials, but counterintuitive improvements on AY trials. The ID model of cognitive aging (e.g., Hasher & Zacks, 1988) can predict age effects on BX trials, but is not capable of explaining why older adults demonstrate lower error rates on AY trials than younger adults. Further, the ID model suggests that age-related deficits are general and observable in many situations, a supposition that was unsupported by the findings of the current study. Age effects were not uniformly detected across tasks of inhibition administered, and intertask correlations within the old and young groups failed to provide robust evidence for a unified construct of inhibition. Importantly, our findings replicate previous studies (Kramer et al., 1994; Shilling et al., 2002), and corroborate continued questioning of the ID account of cognitive aging.

It would be natural to question whether the tasks administered were reliable enough to detect individual differences in cognitive function, as it is often presumed that tasks with strong reliability should demonstrate the greatest cognitive aging effects. We examined available reliability data for the tasks administered in order to determine if differential task correlations with age were a reflection of differential reliability. Unpublished AX-CPT data for 168 young adults revealed the following test-retest reliabilities: BX errors ($r = .53$); BX RT ($r = .67$); AY errors ($r = .43$); AY RT ($r = .72$). Split-half reliability data for the Stroop (Barch & Carter, 1998) ranged from low average (error interference: $r = .26$) to above average (RT interference: $r = .70$).

Internal consistency data computed from the current sample was excellent for the go no-go (r = .95). To our knowledge, there is no published reliability data for the garden path sentence and stop-signal tasks and acknowledge the potential impact that the absence of this data has on interpreting current findings. Based on available reliability data, however, our data do not support the argument that differential correlations with age across tasks are a function of differential task reliability. For example, the measure with the lowest test-retest reliability (AY errors) has the strongest independent correlation with age. BX RT (which has moderate test-retest reliability) is also strongly correlated with age. We only have internal consistency as an estimate of reliability for the go no-go task (which may not be as optimal as test-retest reliability). Nonetheless, it is intriguing to note that while its reliability was very high, the measure still did not show a significant correlation with age. Thus, it does not appear that tasks with high reliability always have the greatest power to detect individual differences in cognitive (and specifically, inhibitory) function, nor do tasks with lower reliability show reduced power to detect age-related differences in cognitive function.

In contrast to PS and ID models of cognitive aging, deficits in context processing seem to fully explain the pattern of age effects characteristically observed on the AX-CPT. Older adults appear to have greater difficulty using context information, an impairment that "saves" them from making the same rate of false alarms on AY trials as younger adults, but makes them slower to override prepotent response tendencies on BX trials. In contrast, younger adults' reliance on context information results in a high rate of false alarms on AY trials and reduced errors on BX trials. There are several possible explanations for age-associated deficits in context processing but some hypotheses seem more probable than others.

Older adults seem to have little difficulty making an association between the cue and probe. If associative learning deficits were the underlying reason for age effects, then older adults should demonstrate high rates of errors across all trial types of the AX-CPT, but this is not the case; high rates of errors and disproportionate slowing seem to be specific to BX trials. With that said, it is possible, as suggested by Rogers and Gilbert (1997) that older adults are less apt than younger adults in developing efficient automatic processing of task-relevant context information, particularly following new learning. Thus, age-related deficits in associative binding (Chalfonte & Johnson, 1996) may account for deficits in context processing on the AX-CPT. Based on this assumption, although contextual associations between cue and probe stimuli may exist for older adults, the newly learned information may be more fragile within the cognitive system of the older adult, influencing task performance on the AX-CPT.

A closer look at contrasting patterns of performance between the age groups reveals that older adults appear to pay more attention to probe

information (the presence or absence of an X probe), whereas younger adults appear to pay more attention to cue information (the presence of absence of an A cue). It is possible that the processing of cue information requires a greater allocation of attentional resources than the processing of probe information. This is certainly supported by the work of Naveh-Benjamin et al. (1998) who suggested that retrieval and recognition processes requires less attentional resource for execution than encoding processes. On the AX-CPT, older adults may unconsciously hone in on probe information as a result of implicit learning (70% of AX-CPT trials are AX target trials) and unconscious economization of declining attentional resources, whereas young adults may be more likely to process cue information because they are not yet experiencing the same age-related decline in attentional resources.

On the other hand, it is possible that age differences in AX-CPT performance reflect strategic differences between old and young adults in how contextual information is put to use. As discussed in detail in Braver, Gray, and Burgess (in press), healthy young adults appear to rely on proactive control in many difficult cognitive tasks. However, under certain conditions, or for individuals for which there is a breakdown in proactive control mechanisms, performance might default to reactive cognitive control mechanisms. AX-CPT data from the current study suggest that younger adults used the context of cue information (i.e., A or non-A cue) proactively to prime the selection of a target or nontarget response. In contrast to the proactive style of younger adults, one might argue that older adult performance use a reactive control strategy, due to their reduced ability to use context information to prepare their response to probe stimuli. Instead, the reactive control strategy used by older adults, may involve a decision to initiate target or nontarget responses based on a process of referring back to context information once incoming probe information was presented. Therefore it is possible that age differences in strategy use underlie age-related context processing deficits on the AX-CPT.

As reviewed, age effects on the AX-CPT appear related to age differences in context processing. Recent reports confirm that cognitive aging effects appear dependent on context processing demands (e.g., West, 2004), but further research is needed before a context processing theory of cognitive aging can be accepted. First, it will be important to understand the factors that contribute to context processing deficits and to determine if context processing deficits create age effects on tasks of selective attention, episodic memory, and inhibition. Evidence from the current study provides inconsistent evidence of a correlation between AX-CPT performance and performance on other inhibitory tasks, but it would be important to establish convergent and divergent validity between the AX-CPT and other tasks involving episodic memory or selective attention that vary in context processing demands. Second, it will be important to compare the magnitude of

the age effect on the AX-CPT with the magnitude of age effects on other tasks thought to be exquisitely sensitive to aging to further establish evidence of relative convergent and divergent validity.

In summary, the current study introduces an exciting new hypothesis by which to further explore and understand cognitive aging. Future research is needed to address how deficits in context processing relate to age-related deficits detected by tasks of attention, inhibition, language, and long-term memory. Importantly, context processing theories of cognitive aging may improve upon previously predominant theories, by proposing a single cognitive mechanism that is capable of accounting for a broader range of cognitive aging phenomena.

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