Psychology and Aging
2005, Vol. 20, No. 1, 33–46

0882-7974/05/$12.00 DOI: 10.1037/0882-7974.20.1.33

Context Processing and Context Maintenance in Healthy Aging and Early Stage Dementia of the Alzheimer's Type

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Declines in the ability to process context information may represent a fundamental mechanism of age-related cognitive changes. Two components of context processing—activation/updating and maintenance—were examined in a sample of healthy younger and older adults, along with individuals suffering from early stage dementia of the Alzheimer's type (DAT). All older adult groups showed context activation/updating impairments, whereas context maintenance was only impaired in the oldest adults (age > 75 years) and was further exacerbated in DAT individuals. The results suggest that context processing may be composed of functionally dissociable components and point to the utility of this construct in understanding the timecourse of cognitive decline in healthy and pathological aging.

One of the areas in which age-related cognitive changes seems to be most pronounced is in tasks or situations that require a high degree of cognitive control, such as when attention must be endogenously and intensely focused, especially in the face of distraction or interference (e.g., Duchek, Balota, & Thessing, 1998), when inappropriate response tendencies must be inhibited (e.g., May, Zacks, Hasher, & Multhaup, 1999; Spieler, Balota, & Faust, 1996; West & Bell, 1997; Zacks, Hasher, & Radvansky, 1996), or when information must be maintained in an easily accessible form within working memory (e.g., Craik, Morris, & Gick, 1990; Daigneault & Braun, 1993; Salthouse, 1990). A number of theorists have developed hypotheses about the fundamental mechanisms that might lead to age-related deficits in such task conditions. These hypotheses include generalized slowing (Cerella, 1985; Myerson, Hale, Wagstaff, Poon, & Smith, 1990; Salthouse, 1996), reduced processing resources (Craik & Byrd, 1982), reduced working-memory capacity (Park, 2000; Salthouse, 1990), inhibitory deficits (Hasher & Zacks, 1988), and disturbed attentional control (Balota, Dolan, & Duchek, 2000).

In our own work, we have put forth the hypothesis that one of the fundamental mechanisms that leads to age-related cognitive changes is a deficit in the ability to process context information (Braver & Barch, 2002; Braver, Barch, Keys, et al., 2001). The current study describes a further test of the context-processing hypothesis in cognitive aging, in which we examine whether distinct components of context processing are differentially affected by advancing age. Before turning to the study, we first describe the context-processing hypothesis in greater detail and the experimental paradigm we have developed as a means of conducting focused investigations of context-processing functions in different populations. We then review our previous findings of age-related changes in context processing and discuss how these findings provide motivation for the current study.

Context Processing

Context processing seems to be a central component of cognitive control. Internal, active representations of context can serve as a cue for attention, guide inhibitory processes, and structure the encoding, maintenance, and retrieval of information in memory (Braver, Cohen, & Barch, 2002). We consider context representations to be those that code task-relevant information in a manner that enables modulation of processing in the pathways responsible for task performance. Context representations can be thought of as similar to goal representations, which tend to exert influence on planning and overt behavior. We use the more general term *context*, however, to include representations that may have their effect earlier in the processing stream, on interpretive or attentional processes. For example, in the Stroop task, the context provided by the task instructions must be actively represented and maintained to bias attentional allocation and response selection toward the ink color dimension of a visually presented word. Thus, context representations may include information generated from processing a specific prior stimulus or a sequence of stimuli (e.g., a sentence), as well as task instructions or a particular intended action. Representations of context are particularly important for situations in

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This work was supported by Grants RO3 AG18138 and P50 AG05681 from the National Institute on Aging (to Todd S. Braver and Deanna M. Barch). David Balota and Martha Storandt provided helpful guidance, support and comments on this study. Additionally, we thank the staff and participants of the Alzheimer's Disease Research Center for their support and help in making this study possible.

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which there is strong competition for response selection. These situations may arise when the appropriate response is one that is relatively infrequent or when the inappropriate response is dominant and must be inhibited (such as the word name in the Stroop task).

In working-memory tasks, activating a context representation is an operation (though not an obligatory one) that helps transform the information held in working memory into a plan for how to optimally prepare and respond to upcoming stimuli. For example, in a Sternberg item recognition task, a context representation may take the items “A, B” presented as a memory set and transform this information into a representation of the form “if the probe item is ‘A’ or ‘B,’ press the target button, otherwise press the nontarget button.” By activating and then maintaining such context representations over the delay interval, the cognitive system can optimally prepare for the upcoming probe. It is important, however, to note that activation of context representations is not required for performance of some working-memory tasks. In tasks such as the Sternberg, responses could be based on other representations of the task-relevant information (i.e., stimulus information represented in a phonological/articulatory code that is held within the phonological loop). Nevertheless, in many difficult cognitive tasks, context representations are actively maintained over extended intervals to appropriately bias processing in task-specific pathways. Consequently, context can be thought of as one component of working memory. Specifically, context can be viewed as the subset of representations within working memory that are specifically engaged in the service of cognitive control. In this manner, context representations simultaneously subserve both mnemonic and control functions. This aspect of our theory differentiates it from the classic model of working memory, developed by Alan Baddeley (e.g., Baddeley, 1986), which postulates a strict separation of representations for storage versus control. However, more recent formulations of even the Baddeley model have acknowledged that almost all working-memory representations can be seen to be serving attentional-control functions (Baddeley, 1993) and that the central executive may include a storage component (Baddeley, 2003).

The *AX*-CPT Task

In previous research, we have used a version of the classic Continuous Performance Test (CPT; Rosvold et al., 1956) that was specifically modified to assess context-processing functions (Servan-Schreiber, Cohen, & Steingard, 1996). In this task, hereafter referred to as the AX-CPT, sequences of letters are presented one at a time, as a series of cue–probe pairs. The object of the task is to make a target response to an *X* (the probe) but only when it follows an *A* (the cue), and to make a nontarget response in all other cases (hence the prefix “*AX*”). Performance in this task relies on the successful activation and updating of context information on a trial-by-trial basis, insofar as the correct response to *X* depends on the cue stimulus (*A* or non-*A*). It is important to note that the *AX*-CPT provides a number of measures for examining different aspects of context processing. Context information serves both inhibitory and attentional functions in the *AX*-CPT. Target (*AX*) trials occur with high frequency (70%) in the task. This induces two types of biases in participants. The first is a bias to make a target response to the occurrence of an *X* probe. On those trials in which such a target response would be incorrect (i.e., “*BX*” trials, where *B* refers to any non-*A* cue), context information must be used in an inhibitory fashion to override the tendency to false alarm. The second bias that occurs in the *AX*-CPT is an expectancy to make a target response following the occurrence of an *A* cue. In this case, the context provided by the cue serves a predictive function that directs attention to a particular response (i.e., attention to action; Allport, 1989; Norman & Shallice, 1986). On those trials in which the cue is an invalid predictor of the response (i.e., *AY* trials, where *Y* refers to any non-*X* probe), this attentional function of context creates the tendency to false alarm. This type of cue validity effect is similar to others that have been well studied in the attentional literature (e.g., Posner, 1980). Thus, nontarget performance, and specifically the relationship of performance on *AY* versus *BX* trials, provides an index of one component of context processing that we refer to as *context activation/updating*. In particular, it might be predicted that with an intact context-processing system, performance would be poorer on *AY* than on *BX* trials. Indeed, this is what we have regularly observed in studies with healthy college-aged adults (Braver & Cohen, 2001; Braver et al., 2002).

A second component of context processing, called *context maintenance*, reflects the working-memory functions of context and can also be examined in the *AX*-CPT through a manipulation of the cue–probe delay duration. When there is a long cue–probe delay (e.g., 5–10 s), context information must not only be properly activated/updated, but it must also be actively sustained over an extended period to be available to optimally bias processing of the probe. Thus, under long-delay conditions in the *AX*-CPT, the demand on context maintenance is high. The effect of delay on *AY* and *BX* performance provides an index of the integrity of context maintenance. If context maintenance is intact, then the strength of context representations should either remain constant or increase with delay (i.e., if it takes some period of time for context representations to reach full activation strength). Consequently, *BX* performance should remain constant or improve at long delays, whereas *AY* performance should remain constant or worsen with delay. Conversely, if context maintenance is impaired, then context representations should lose strength over time. This should lead to a worsening of *BX* performance with a delay but a counterintuitive improvement in *AY* performance. Again, in studies with healthy college-aged populations, our typical finding is that *AY* performance worsens with delay, whereas *BX* performance stays constant (Braver & Cohen, 2001; Braver et al., 2002).

To more concretely examine the mechanisms of context processing within the *AX*-CPT task, we have developed and implemented a computational model of this task (Braver, Barch, & Cohen, 1999; Braver & Cohen, 2000, 2001). Although detailed descriptions of this modeling work and simulation results are beyond the scope of this article, some of the principles developed from working with the model are instructive with respect to context representation, to context-processing dynamics in the *AX*-CPT, and to how such mechanisms could lead to specific patterns of task performance. In the model, presentation of the cue stimulus leads to the activation of one of two distinct context representations in the context-processing module (which is thought to correspond to the functions of dorsolateral prefrontal cortex). These two different representations, when active, serve as a top-down bias on stimulus–response association pathways. One context representation biases units that activate the target response for an *X* probe. This context representation can be interpreted as corresponding to a working-memory representation of the *A* cue, or alternatively as something like an if/then goal (i.e., if probe is *X*, then press target button). The other context representation, when active, serves to bias units that activate a nontarget response for either type of probe. This second context representation can be interpreted as either a working-memory representation of the *B* (or non-*A*) cue or of a different type of goal (i.e., if probe is *X* or *Y*, then press nontarget button).

Under normal conditions in the model, context representations get updated with each new cue stimulus and then they are actively maintained over delay periods, through self-sustaining recirculation of activation. These actively maintained context representations thus serve as a top-down source of bias (or priming) on response activation. However, bottom-up sources of bias also exist. In particular, the association strength between the *X* probe and the target response is greater than the association strength between *X* and then the nontarget response. Likewise, there is a strong association between *Y* probes and nontarget responses. Thus, under conditions in which context information either fails to update or decays in strength during the delay period then responding will be more strongly weighted toward these preexisting associations than to cue-driven contextual biases. It is important to note that although other types of conceptual schemes are logically possible, in terms of the mechanisms and nature of context representation and activation, our hypothesized mechanisms have been found to be sufficient to successfully capture a great deal of data regarding normal behavioral-performance patterns in the *AX*-CPT task, specifically the relationship of *AY* to *BX* performance and the interaction with delay (Braver et al., 1999, 2002). Likewise, in simulations exploring the consequences of disruptions to the context-processing module, the model behaves in ways that are similar to what we observed empirically in older adults (Braver & Barch, 2002; Braver, Barch, Keys, et al., 2001). These experimental results are discussed next.

Age-Related Changes in Context Processing

In a prior study, we used several variants of the *AX*-CPT to examine context processing in older adults compared with younger adults (Braver, Barch, Keys, et al., 2001). Specifically, we used the standard version of the *AX*-CPT (as just described) as well as an "interference" version. The interference condition had distracting letters in a different color presented during the delay period, and as such it was predicted to place an even greater demand on context-processing functions. We observed a pattern of performance in the older adults that was indicative of a selective deficit in context processing. Healthy older adults performed more poorly on *BX* trials (i.e., the nontarget trial type in which context representations are needed to prevent errors) in terms of both accuracy and reaction times (RTs) compared with younger adults. At the same time, older adults actually performed better on *AY* trials (i.e., the nontarget trial type in which intact context representations lead to worse performance). These findings with *AY* trials were particularly compelling, because they represent one of the few cases in the cognitive aging literature in which older adults actually performed both more accurately and as quickly as younger adults. These performance differences between older and younger adults were further enhanced in the interference version of the task, which placed an even greater demand on context-processing functions. In contrast, in a third control condition, increasing the difficulty of the *AX*-CPT in a context-independent manner, through stimulus degradation, did not affect age differences in *AX*-CPT performance.

These initial data are consistent with the hypothesis that context-processing impairments may be a fundamental source of age-related declines in cognitive control; however, several questions remain. First, do older adults have deficits in multiple components of context processing (i.e., both context activation/updating and context maintenance) or only in one of these components? Our initial study with older adults used a single cue–probe delay interval (5 s), and therefore it could not address questions about context maintenance. To examine these functions separately, we have found it necessary to vary the delay between the cue and the probe. Such delay manipulations have been successful at eliciting maintenance-related deficits in older adults in various cognitive domains, such as controlled semantic priming (Balota, Black, & Cheney, 1992), motor preparation (Amrhein, Goggin, & Stelmach, 1991), and prospective memory (McDaniel, Einstein, Stout, & Morgan, 2003). Within the *AX*-CPT, if older adults differ from younger adults only with a long cue–probe delay, then it would suggest that older adults have deficits in context maintenance but not in the initial activation/updating of context. In contrast, if older adults differ from younger adults equally at the short and long delay (i.e., there is no interaction of age and delay), then it would suggest that older adults have deficits in the initial activation/updating of context but not in context maintenance. Finally, older adults might show both context activation/updating and context-maintenance deficits.

A second question regarding context processing and aging is whether context processing is affected by the cognitive impairments associated with pathological aging, as well as by the normal cognitive decline associated with healthy aging. For example, are context-processing impairments more severe in individuals with dementia of the Alzheimer's type (DAT) than in healthy older adults? Moreover, if such deficits are present, then are they greater than what might be predicted from a generalized deterioration in cognitive function? Although DAT is classically associated with disturbances in episodic memory, emerging evidence has indicated that attentional control and executive functions are also selectively affected, particularly at the earliest stages of the disease process (Albert, 1996; Balota & Faust, 2001). Is DAT associated with qualitative changes in *AX*-CPT performance (i.e., a selective pattern of impairment), or do DAT individuals simply exhibit a quantitative impairment (i.e., same pattern as healthy older adults, but to a greater degree)? In particular, we focused on studying individuals with very mild DAT who represent the earliest reliably diagnosable stage of the illness, to determine whether changes in context-processing functions might serve as an important early cognitive manifestation of the disease process.

Last, we were also interested in generating additional data regarding the construct validity of the *AX*-CPT as a measure of cognitive control function. Given that our version of the *AX*-CPT was developed fairly recently, we were interested in whether performance on the *AX*-CPT was associated with performance on more traditional neuropsychological measures of cognitive control and executive functioning. If the *AX*-CPT also measures executive control and frontal lobe function, then we would predict that *AX*-CPT performance should be correlated with performance on other tasks that are assumed to measure these constructs.

To examine these questions, we conducted a study in which we administered our version of the *AX*-CPT to healthy young and older adults, as well as to adults with very mild DAT. We manipulated the delay between the cue and the probe in this *AX*-CPT task (1 s vs. 5 s) to enable examination of both the ability to represent/update context and the ability to maintain context information over time. In a subset of the participants, we examined the relationship between *AX*-CPT performance and performance on a range of neuropsychological tasks thought to measure executive control and frontal lobe function.

Method

Participants

A total of 166 participants were included in this study, comprising four groups: (a) healthy young adults (aged 18–24; $n = 51$); (b) healthy young-old adults (aged = 66–75; $n = 46$); (c) healthy old-old adults (aged = 76–92; $n = 43$); and (d) individuals with early stage DAT (aged = 66–98; $n = 26$). All of the young adults and a subset of the healthy young-old ($n = 33$) and old-old ($n = 23$) adults were recruited from subject pools maintained by the Department of Psychology at Washington University in St. Louis. The remaining healthy young-old ($n = 13$) and old-old adults ($n = 20$) and all of the DAT patients were recruited from the Alzheimer's Disease Research Center (ADRC) at Washington University. Additional demographic information for each of the four populations is summarized in Table 1. The groups differed significantly in education level, $F(3, 162) = 5.2$, $p < .01$. Post hoc contrasts, using Tukey's honestly significant difference (HSD), indicated that the young-old adults were more highly educated than the young adults and the old-old adults, but there were no other significant group differences in education. The groups did not differ on the percentage of individuals who were men, $\chi^2(3, N = 166) = 6.4$, $p = .09$.

Participants recruited from the ADRC were screened for depression, severe hypertension, and other medical and neurologic disorders (other than DAT) that could influence cognitive performance. Criteria for DAT diagnosis were based on standards set by the National Institute of Neurologic and Communication Disorders and Stroke and Alzheimer's Disease and Related Disorders Association (McKhann et al., 1984). Severity of dementia was rated by the Washington University Clinical Dementia Rating (CDR; Morris, 1993). Of participants recruited from the ADRC, only those with a CDR of 0 were included as healthy older adults, and those with a CDR of 0.5 (very mild dementia) were included in the DAT group. There has been debate as to whether the older adults diagnosed as CDR 0.5 truly represent Alzheimer's disease, or rather a transitional state known as *mild cognitive impairment* (MCI; Petersen et al., 1999). However, recent evidence has demonstrated that individuals with a CDR of 0.5 diagnosis progress to more severe stages of dementia (Storandt, Grant, Miller, & Morris, 2002) and that those who die while in the CDR 0.5 stage have neuropathological confirmation of Alzheimer's disease (Morris et al., 2001). Participants recruited from the ADRC were offered $25 remuneration for their participation.

Table 1
Demographic Information

	Group							
	Young		Young-old		Old-old		Very mild DAT	
Characteristic	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Age (in years)	19.8	1.9	71.7	2.3	81.0	4.7	80.1	7.1
Education (in years)	13.9	1.5	15.5	2.6	14.0	2.3	15.3	3.4
Gender (% male)	31		30		40		58	

Note. DAT = dementia of the Alzheimer's type.

Participants recruited from the subject pools in the Department of Psychology at Washington University were screened for any signs of medical disorders, neurologic disorders, psychiatric disorders, or medication histories that could influence cognitive performance. Because depression may affect psychomotor speed and general cognitive performance (White, Myerson, & Hale, 1997), all participants were administered the Beck Depression Inventory (BDI; Beck, Ward, Mendelson, Mock, & Erbaugh, 1961). Additionally, older adults were administered the Blessed Orientation–Memory–Concentration Test (BOMC; Katzman et al., 1983) over the telephone. Individuals obtaining five or more errors were not included. For the resulting older adult participants, the mean BOMC score was 1.14 ($SD = 1.33$). Both younger and older adults recruited through the subject pool were offered $15 remuneration for their participation.

Tasks and Apparatus

AX-*CPT.* Participants performed the *AX*-CPT under both long- and short-delay conditions. In both conditions, sequences of letters were presented visually one at a time in a continuous fashion on a computer display. Letter sequences were experimentally constructed as trials of repeating cue–probe pairs. *Target trials* were defined to be a cue–probe pair in which the letter *A* appeared as the cue followed by the letter *X* appearing as the probe. The remaining letters of the alphabet served as invalid cues and nontarget probes, with the exception of the letters *K* and *Y*, which were excluded because of their similarity in appearance to the letter *X*. Participants were not explicitly notified of the cue–probe structure of the task (nor was this structure obvious from viewing the presented sequence), but they were merely instructed to make a manual response to each presented letter (i.e., both cues and probes). The specific instruction was to press the target button if both the currently presented letter was an *X* and the immediately preceding letter had been an *A*. If these conditions were not met, then participants were to press the nontarget button. Cue–probe sequences were presented in pseudorandom order, such that target (*A-X*) trials occurred with 70% frequency, and nontarget trials occurred with 30% frequency. Nontargets were divided evenly (10% each) among three trial types: *BX* trials, in which an invalid cue (i.e., non-*A*) preceded the target; *AY* trials, in which a valid cue was followed by a nontarget probe (i.e., non-*X*); and *BY* trials, in which an invalid cue was followed by a nontarget probe.

Stimuli were presented centrally for 500 ms. The delay between cue offset and probe onset was 1,000 ms in the short-delay condition and 5,000 ms in the long-delay condition. The intertrial interval (ITI) varied inversely with delay and condition: 5,000 ms from probe offset in the short condition and 1,000 ms from probe offset for the long condition. Thus, total trial duration was equated across long- and short-delay conditions. Responses were recorded on a specially constructed button box connected to the computer that recorded response choice and RT with 1 ms accuracy. Right-handed individuals made responses with the middle (nontarget, middle button) and index (target, leftmost button) fingers of the right hand. Left-handed individuals made responses with the middle (nontarget, middle button) and index (target, rightmost button) fingers of the left hand. Participants were allowed 1,500 ms from stimulus onset in which to respond. Responses that were slower than this limit were not recorded and elicited feedback (a "bloop" sound) as a prompt to increase speed. The tasks were run on Apple Macintosh computers, using PsyScope software for stimulus presentation and data collection (Cohen, MacWhinney, Flatt, & Provost, 1993).

Neuropsychological tasks. Individuals recruited through the ADRC (both CDR 0 and CDR 0.5) were given a battery of neuropsychological tests that were designed to assess different aspects of cognitive function (for a full description, see Hill, Storandt, & LaBarge, 1992; Storandt & Hill, 1989). From this battery, we examined tasks believed to tap the controlled use of attention and memory, including category verbal fluency, backward digit span, logical memory, paired associates, and the trailmaking test. Correlational results are reported below only for the individuals with CDR ratings of 0 ($n = 33$). We excluded the CDR 0.5 from the correlational analyses to reduce the influence of Alzheimer's related pathology on the magnitude of the correlations.

Procedure

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. All participants were tested in a single testing session. Conditions were run in blocks of 50 trials, with a short rest break provided between each block. The two delay conditions (short, long) were performed in separate blocks, as pilot testing suggested that trial-by-trial mixing of the delay conditions produced an overall decrement in younger adult performance. Two blocks of each delay condition were performed, yielding 100 trials total per condition. Condition order (short first or long first) was counterbalanced such that there was an even distribution of participants to condition orders across all participant groups. Prior to beginning the session the experimenter provided detailed standardized instructions to participants and answered any questions. The task instructions emphasized that responses were to be made both as quickly and as accurately as possible. Participants were then given enough practice trials (a minimum of 10 in each delay condition) to ensure that the instructions were understood and the task was being performed appropriately.

Data Analysis

Data were analyzed in each condition, using arcsine corrected error rates (misses and false alarms), median RTs, and signal detection indices (d') as the dependent measures of interest. RTs were examined for correct responses only. Analyses of nontarget error rates and RTs were conducted in repeated measures analyses of variance (ANOVAs) that focused on different pairwise comparisons of participant groups: young versus young-old, young-old versus old-old, and old-old versus very mild DAT. Each ANOVA had group as a between-subjects factor and delay (short, long) and nontarget trial type (*AY*, *BX*, *BY*) as within-subjects factors. Analyses involving target (*AX*) trials were conducted separately. For RTs, these were conducted as two-factor ANOVAs with group as a between-subjects factor and delay (short, long) as a within-subject factor. For target errors, analyses focused on the signal detection measure d' (rather than simple error rate), because this measure can provide an estimate of sensitivity to the difference between targets and nontargets while controlling for any individual differences in response bias. Instead of the traditional computation of d' (i.e., using hits and all false alarms), d' was computed using just *BX* false alarms. This measure, hereafter referred to as d'-context, has been used in previous *AX*-CPT studies to provide a more specific index of sensitivity to context—that is, given an *X* probe, how sensitive is performance to the preceding context, *A* versus non-*A* (Cohen, Barch, Carter, & Servan-Schreiber, 1999; Servan-Schreiber et al., 1996)? A correction factor was applied in the d' computation in cases of a perfect hit rate (1.0) or false-alarm rate (0.0). This correction factor—hit rate $= 2^{-(1/N)}$; false alarm $= 1–2^{-(1/N)}$; N = number of target or nontarget trials—allows an unbiased estimation of d' in such cases (Nuechterlein, 1991).

A potential factor that could complicate the results is *posterror effects*—a change in processing that occurs on the trial following an error trial. Thus, we reanalyzed the data after excluding trials immediately following an error. None of the results reported below changed with the exclusion of posterror trials. Thus, only the original results are reported.

Results

Young Versus Young-Old Adults

We began by comparing the young adults with the young-old adults to examine the general effects of age on context representation and maintenance. For nontarget errors, a main effect of group, $F(1, 95) = 11.46, p < .001$, indicated that young-old adults made fewer overall nontarget errors than younger adults. This was modified by a Group × Trial Type interaction, $F(2, 190) = 7.38$, $p < .001$ (see Figure 1). Planned contrasts indicated that the young-old adults made significantly fewer nontarget errors than younger adults in the *AY* condition (young: 12.2%; young-old: 4.5%), $F(1, 95) = 17.72, p < .001$, but did not differ from young adults in the *BX* condition, $F(1, 95) = 1.08$, $p > .30$, and *BY* condition, $F(1, 95) = 1.43, p > .20$. The interaction between group and trial type was not further modified by delay, $F(1, 190) = 0.13$, $p > .8$.

For nontarget RTs, there was a main effect of group, $F(1, 95) = 57.48$, $p < .001$, with the older adults showing the typical pattern of age-related slowing. This main effect of group was modified by a Group × Trial Type interaction, $F(2, 190) = 23.2, p < .001$ (see Figure 2). Planned contrasts indicated that older adults showed a smaller difference between *AY* and *BY* condition RTs than did younger adults (young: 170 ms; young-old: 134 ms), $F(1, 95) = 6.5$, $p < .05$, suggesting that when holding the probe constant, older adults showed less interference from the *A* context. In contrast, older adults showed a larger difference between the *BX* and *BY* conditions than did younger adults (young: 6 ms; young-old: 102 ms), $F(1, 95) = 23.7$, $p < .001$, suggesting that when the context cue is held constant, older adults showed greater interference because of the *X* probe. In addition, there was a trend-level three-way interaction, Group × Trial Type × Delay, $F(2, 190) = 2.58$, $p = .08$. This trend-level interaction reflected that there was increased interference-related slowing on *AY* trials at the longer delay interval in younger adults but not in young-old adults (*AY* delay effect in young: 55 ms; *AY* delay effect in young-old: 6 ms). In other words, interference due to the presence of context increased from the short to long delay in young adults, but not in young-old adults. This led to a Group × Delay interaction for *AY* trials, $F(1, 95) = 12.90, p < .001$, but not for *BX*, $F(1, 95) = 0.80$, $p > .30$, or *BY* trials, $F(1, 95) = 0.4$, $p > .50$.

Last, we examined target trials using a two-way ANOVA with group as a between-subjects factor and delay as a within-subjects factor. For target RTs, there was again a main effect of group, $F(1, 95) = 36.5$, $p < .001$, indicating slowing in the young-old adults, but no further interaction with delay, $F(1, 95) = 0.3, p > .50$. For d'-context (see Figure 3), the ANOVA did not reveal either a main effect of group, $F(1, 95) = 0.90$, $p > .30$, or a Group × Delay interaction, $F(1, 95) = 0.80$, $p > .35$.

Young-Old Versus Old-Old Adults

We next compared the young-old and old-old adults to determine whether context-processing functions are sensitive to advancing age within an older adult population. The ANOVA for nontarget errors indicated a three-way interaction, Age × Delay × Trial Type, $F(2, 174) = 4.54, p < .05$. As shown in Figure 1, this interaction reflected that there were no age effects at the short delay (all *p*s $> .80$), but there was a significant Age × Trial Type

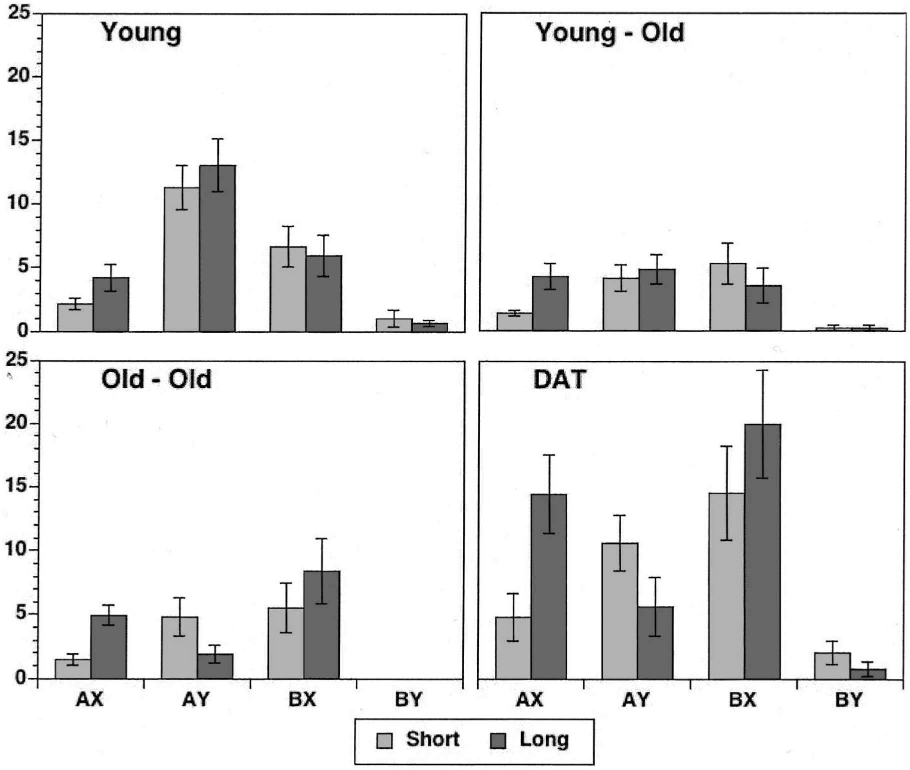

Figure 1. Graphs plotting error rates (percentages) for all task conditions (*AX*, *AY*, *BX*, and *BY*) in the *AX*-CPT for each of the four groups (young, young-old, old-old, dementia of the Alzheimer's type [DAT]). Error bars indicate standard error of the mean.

interaction at the long delay, $F(2, 174) = 4.8$, $p < .05$. At the long delay, the old-old adults made significantly fewer *AY* errors than did the young-old (young-old: 4.8%; old-old: 1.9%), $F(1, 87) = 4.9$, $p < .05$, but they also showed a trend toward more *BX* errors (young-old: 3.6%; old-old: 8.4%), $F(1, 87) = 2.9$, $p = .10$. The ANOVA for nontarget RTs did not show any significant main effects of age or interactions with age (all *p*s >.16).

For target trials, there was no main effect of age in either target RT, $F(1, 87) = 0$, $p > .9$, or d'-context, $F(1, 87) = 1.2$, $p > .2$. However, the Age × Delay interaction was significant for target RTs (*AX* delay effect in young-old: 33 ms; *AX* delay effect in old-old: 61 ms), $F(1, 87) = 4.6$, $p < .05$, and trend level for d'-context (delay effect in young: 0.22; delay effect in young-old: 0.42), $F(1, 87) = 3.3$, $p = .08$.

Age Effects After Controlling for Response Slowing

In our previous study of the *AX*-CPT with older adults, an important finding was that after controlling for general slowing, *BX* RTs were found to have a positive relationship with age, whereas *AY* RTs were found to have a negative relationship with age. In other words, older adults were relatively slower than younger adults on *BX* trials (the condition in which impaired context should make performance worse), but they were relatively faster than younger adults on *AY* trials (the condition in which impaired context should actually make performance better). We sought to determine whether this pattern replicated in the current study. However, we modified the approach used to control for general slowing. In Braver, Barch, Keys, et al. (2001), we used the approach of partialing out performance on long-delay *BY* trials, because these were postulated to be primarily context independent and thus a measure of general response speed. Although this approach is suitable, recent analyses suggest that a more powerful and less assumption-dependent method of correcting for response slowing is to use within-subject *z*-score transformations of RT (Faust, Balota, Spieler, & Ferraro, 1999).

Thus, we adopted the *z*-score approach for this study. Specifically, participants' data were rescaled by normalizing each trial's RT relative to the participants' grand mean RT and standard deviation of this mean across all task conditions. Following *z*-score transformation, we conducted regression analyses using the entire sample of healthy adults (i.e., excluding the DAT patients). The predictor variables were RTs in the long-delay condition, because this was the condition that matched the one in our previous study. To test the validity of this procedure, we first examined age relationships on *BY* trials. These trials would not be expected to show age effects beyond general slowing. As expected, once slowing effects were removed through normalization, this correlation was not significant, $r(138) = .14$, $p = .10$.

In contrast, the correlation between age and *BX* RTs was strongly positive and highly significant, $r(138) = .44$, $p < .001$. However, we predicted that for *AY* trials, after controlling for response slowing, increasing age would be associated with faster

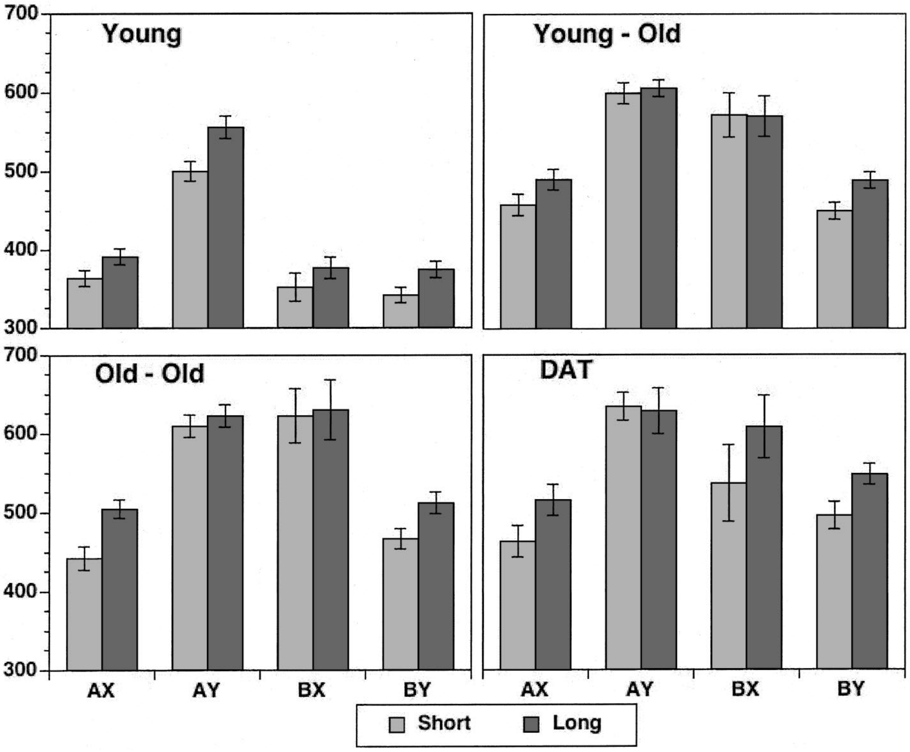

Figure 2. Graph plotting reaction times for all task conditions (*AX*, *AY*, *BX*, and *BY*) in the *AX*-CPT for each of the four groups (young, young-old, old-old, dementia of the Alzheimer's type [DAT]). Error bars indicate standard error of the mean.

AY RTs—that is, a negative correlation. This is what was observed: $r(138) = -.49, p < .001$. Because performance on *AY* and *BX* RTs showed correlations with age that were in opposite directions, we next tested whether these two performance measures (*AY* vs. *BX* RT) were also negatively correlated. This was the case: $r(138) = -.36, p < .001$. The negative correlation indicates that individuals showing slower *BX* RTs also exhibited faster *AY* RTs. This result supports the contention of the model that both patterns might have been due to a common underlying mechanism—context activation/updating. Finally, we tested a regression model in which age was correlated with the difference between *BX* and *AY* RTs (normalized). We found that almost 30% of the between-subjects variance in these performance measures was age-related, $r(138) = .54, p < .001$. It is important to note that this relationship appeared to hold even when restricting the sample to just the older adults. In just this subset of participants, the correlation was still significant at the trend level, $r(87) = .19, p = .07$. Taken together, the results suggest that increasing age, but not generalized response slowing, is a strong determinant of the relationship between *AY* and *BX* response latencies.

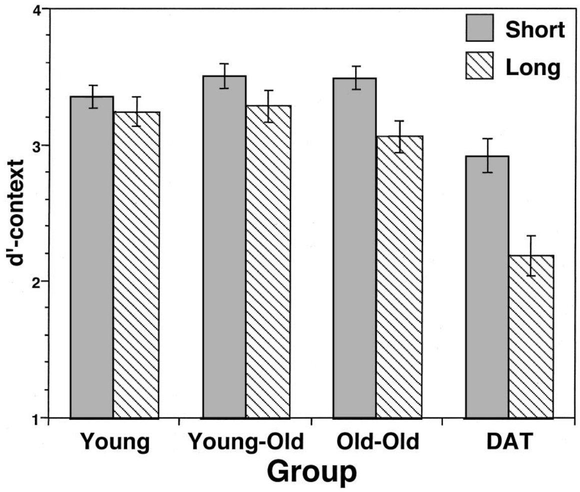

Figure 3. Graph plotting *d*′-context in the *AX*-CPT task for each of the four groups (young, young-old, old-old, and dementia of the Alzheimer's type [DAT]). Error bars indicate standard error of the mean.

Correlation With Other Neuropsychological Measures

We have argued that the *AX*-CPT provides a useful measure of a central component of cognitive control, namely context processing. This component of cognitive control is likely to be engaged during the performance of other standard neuropsychological measures of cognitive control function. Consequently, an important test of the construct validity of context-processing functions, and the *AX*-CPT as an index of such functions, is the extent to which it correlates with other well-known measures that may putatively involve the same construct. We tested this hypothesis by computing correlations in the subgroup of healthy older participants (the individuals with CDR ratings of 0 recruited from the ADRC; $n = 33$) who had completed a battery of standard neuropsychological tests that we thought might index cognitive (executive) control functions (including category verbal fluency, trailmaking test, backward digit span, logical memory and paired-associates). In particular, we were interested in whether the *AX*-CPT performance measure that most reliably discriminated among groups (*BX* errors–long delay) would be significantly correlated with other cognitive control tasks. The results of these correlations are presented in Table 2. As Table 2 indicates, increased *BX* errors were positively correlated with worse performance on all of the other tasks, except for backward digit span.

Next, we compared the level of correlations against a control measure of the *AX*-CPT that we predicted to have a different relationship to other measures of cognitive control. We selected *AY* false alarms for this control measure, because our theoretical model suggests that context-processing impairments have opposite effects on *AY* and *BX* performance—that is, leading to worse *BX* performance but better *AY* performance. We examined whether *BX* and *AY* errors were significantly different in their relationship to the other neuropsychological measures of cognitive control. To do so, we used the methods for comparing correlated correlation coefficients suggested by Meng, Rosenthal, and Rubin (1992). These analyses indicated that there was a significantly different relationship of *BX* and *AY* errors to trailmaking test, category verbal fluency, and logical memory (see Table 2). This result provides some level of discriminant validity for the context-processing construct by indicating that the correlations between *AX*-CPT performance and other standard neuropsychological measures are restricted to the task condition that most strongly indexes context-processing impairments (i.e., *BX* trials). In other words, the selective correlations of the other neuropsychological tasks with *BX* performance and not *AY* performance suggest that the results cannot be accounted for by a more general factor (i.e., nonspecific cognitive impairment).

Old-Old Adults Versus Early Stage DAT

Our old-old group was well matched in age with the DAT sample. Thus, for analyses that examined the effects of DAT on context processing, we compared the DAT individuals and the old-old healthy adults. This comparison enabled us to determine whether there were any selective effects of dementia on context-processing function, over and above the influence of age. The nontarget error ANOVA indicated a main effect of group, $F(1, 67) = 8.6$, $p < .005$, and a trend toward a Group × Trial Type interaction, $F(2, 134) = 2.8$, $p = .07$, but no three-way interaction with delay, $F(2, 134) = 1.2$, $p > .10$. As shown in Figure 1, the main effect of group reflected overall more nontarget errors among the individuals with DAT. Follow-up contrasts revealed that the DAT group made more errors in all three types, even *BY* control trials ($p < .05$). Given that *BY* trials provide an index of general cognitive function (rather than context processing, per se), the increased errors among DAT patients is indicative of a nonspecific decline in cognitive function. Nevertheless, the trend for a Group × Trial Type interaction was due to the smaller increase in *BY* errors among the DAT group compared with the increases in *BX* and *AY* errors (*BY* error increase: 1.4%; *BX* error increase: 10.3%; *AY* error increase: 4.8%).

Table 2
Correlations Between BX and Neuropsychological Tests

	AX-CPT measure		Diff. between
Neuropsychological test	*BX* errors Long Delay	*AY* errors Long Delay	*BX* and *AY* correlation
Trailmaking test-Part B (RT)	.41*	−.27	$Z = 2.50$*
Backward Digit Span	−.12	−.12	$Z = 0.01$
Category Verbal Fluency	−.44*	.15	$Z = 2.20$*
Paired Associates (Hard)	−.38*	−.06	$Z = 1.63$*
Logical Memory (Delayed)	−.63**	.01	$Z = 2.61$**

Note. Diff. = difference; RT = reaction time.
* $p \leq .05$. ** $p < .01$.

The ANOVA for nontarget RTs revealed no main effect of group, $F(1, 67) = 0.02$, $p > .80$, but a significant Group × Trial Type interaction, $F(2, 134) = 3.13$, $p < .05$, with no further three-way interaction with delay, $F(2, 134) = 0.9$, $p > .10$. As shown in Figure 2, the Group × Trial Type interaction reflected that DAT patients were slower than old-old healthy adults on *AY* and *BY* trials, but not on *BX* trials (*AY* slowing: 14 ms; *BY* slowing: 30 ms; *BX* slowing: 55 ms), although none of the simple effects tests were significant. That the individuals with DAT were not slower than healthy old-old adults on *BX* trials is somewhat surprising. A possible explanation for this pattern relates to the large number of errors the DAT group made on *BX* trials. Perhaps the *BX* trials that might have been among the slowest in the DAT group (if the participants had been able to get them correct) actually ended up as errors. In other words, it is possible that there was a speed–accuracy trade-off in the DAT group. Examination of the correlations between errors and RT across the different groups provides some support for this hypothesis. Specifically, we examined partial correlations between RTs and errors on *BX* trials, partialing out shared variance with *BY* RTs (to account for generalized slowing). At both the short and long delay, these correlations were not significant in the young, young-old, or old-old adults (*r*s ranged from −.22 to .19). The individuals with DAT, however, showed a strong negative partial correlation between errors and RT in the *BX* condition (short delay, $r = -.60$, $p < .01$; long delay, $r = -.35$, $p < .05$). Thus, DAT individuals showing faster *BX* RTs also made more *BX* errors, which may account for the overall group differences on *BX* trials.

Analyses of d'-context indicated a main effect of group, $F(1, 67) = 13.9$, $p < .001$, that was moderated by a Group × Delay interaction, $F(1, 67) = 4.3$, $p < .05$. As shown in Figure 3, simple effects tests indicated that individuals with DAT had lower d'-context than healthy old-old adults at both the short and long delays (*p*s < .01). The interaction reflected that the DAT group showed a much larger delay effect in d'-context than the healthy age-matched older adults (delay effect in old-old: 0.42; delay effect in DAT: 0.74). Thus, the d'-context measure at the long delay appeared to best discriminate the very mild DAT individuals from their age-matched controls. The discriminability of the two groups can be seen in terms of the magnitude of the effect size, Cohen's $d = 1.0$, which corresponds to a large behavioral effect. The ANOVA for target RTs did not reveal any significant group or Group × Delay interaction (*p*s > .6).

Discussion

The results of this study shed further light on the relationship between context-processing functions and advancing age. The results yielded four primary findings. First, compared with young adults, young-old adults demonstrated performance changes related to context processing. However, these effects were apparent at both the short- and long-delay conditions, indicating deficits in context activation/updating, but no additional impairment in context maintenance. Second, compared with young-old adults, old-old adults performed identically in the short-delay condition but had worse context processing the long-delay condition. This result suggests that advancing age within older adults produces a deficit in context maintenance but no further changes in context activation/updating. Third, compared with age-matched healthy older adults, individuals with very mild DAT demonstrated even greater context maintenance deficits, but they also showed evidence of a generalized decline in performance. Fourth, we found that other neuropsychological measures of executive function were related to the *AX*-CPT performance measure that best indexed context-processing deficits. Next, we discuss each of these points in greater detail.

Age-Related Changes in Context Processing

As noted, we found that young-old adults demonstrated deficits in context representation/updating compared with younger adults but no deficit in context maintenance. The lack of an age effect on context maintenance, as tested with varying delays between cue and probe, suggests that age-related difficulties in updating and representing context on a trial-by-trial basis are independent of context maintenance demands. Moreover, consistent with our previous results with the *AX*-CPT, age-related changes in context activation/updating produced both interfering and facilitating effects on behavioral performance (Braver, Barch, Keys, et al., 2001). Specifically, when compared to young adults, older adults displayed poorer *BX* performance but improved *AY* performance.

Although the reciprocal pattern of *AY* and *BX* performance changes in older adults was directly predicted by our theoretical model, as an indication of impairments in context activation/updating, it is noteworthy that the exact form of the data were not. Specifically, age-related *AY* improvements were primarily reflected in reduced error rates, whereas *BX* impairments were observed in terms of disproportionately slowed RTs but intact accuracy. Although this pattern replicates the findings observed in our previous study of aging effects in the *AX*-CPT, it was not directly predicted by our theoretical and computational model. Our model is somewhat agnostic as to which behavioral measure would be most impacted by context-processing disruption, but tends to predict equal changes in errors and RT. Thus, the specific pattern of the age-related performance changes might potentially necessitate a refinement of how context-processing impairments should be conceptualized. In particular, we tentatively suggest that the results might be best accommodated within an account that differentiates between proactive and reactive forms of cognitive control—a general framework that we have recently been developing on independent grounds (Braver, Gray, & Burgess, in press).

Under this account, older adults may be relying on a form of *reactive control* to successfully perform the *AX*-CPT. Reactive control refers to the transient reinstantiation of context information following onset of a probe stimulus, as a result of either strong bottom-up associations or through the detection of response conflict. Specifically, we postulate that the intact *BX* accuracy in older adults suggests that they do have preserved access to context information, potentially through some form of activated long-term memory (Cowan, 1999). Yet the increased slowing on *BX* trials indicates that this context information was not active prior to probe onset, but instead it was retrieved back into a contextual representation in response to the conflict generated by the *X* probe. The primary deficit observed in older adults may be in a failure to use *proactive control* mechanisms to support performance. Proactive control refers to the sustained maintenance of context information to prepare and configure attention systems to optimally process an upcoming probe. Specifically, we postulate that the counterintuitive age-related facilitation of *AY* performance was because of older adults' reduced tendency to use the *A* cue as predictive context for preparing a target response to the upcoming probe. This led to a paradoxical improvement of performance on *AY* trials, where such proactive biasing would be disruptive.

The hypothesis that the young-old adults show a reduced tendency to use proactive control, but an increased tendency to use reactive control, is also consistent with the lack of delay effects in this group. A reliance on reactive-control mechanisms should not be affected by delay manipulation, because the critical processing happens at the time of the probe. Furthermore, a reduced utilization of proactive control could come from an intermittent failure to activate or update context representations at the time of the cue, rather than a deficit in maintaining such representations once they become activated.

Thus, the proactive/reactive distinction might serve as a useful refinement to notions regarding the nature of context processing in cognitive control. For example, these same notions may apply well to studies of task switching, in which older adults show evidence of disproportionate slowing (but typically intact accuracy) on task-switch trials with high interference, even when a substantial precue (i.e., preparatory) interval is provided (Mayr, 2001). Thus, in task-switching studies, older adults may show less pretarget preparation than younger adults, but this effect tends to translate into increased slowing primarily under conditions where reactive (i.e., posttarget) control would be most vulnerable to target-driven interference. Nevertheless, it should be clear that the proactive/reactive control framework remains a post hoc interpretation of the current results rather than a specific a priori prediction of our preexisting theoretical model. Thus, future studies should be aimed toward directly investigating this hypothesis in older adults, to more systematically determine the extent of its explanatory and predictive power.

Context Processing and Advancing Age in Older Adults

The effect of advancing age in the older adult sample revealed a strikingly selective pattern of effects. In particular, no differences were observed between the young-old and old-old groups in RT or in errors at the short delay. Yet at the long delay, the old-old group made both more *BX* errors and fewer *AY* errors than did the young-old group. Further, they showed a greater effect of delay on d'-context and target RT. Thus, we interpret the results as suggesting that advancing age within older adults primarily affects context maintenance functions rather than context activation and updating. When the demands of context maintenance were high, as in the long-delay condition, the old-old adults showed reduced sensitivity to context information in biasing performance compared with young-old adults. This reduced context sensitivity both increased the tendency of the old-old adults to fail to suppress a dominant but contextually inappropriate response tendency (on *BX* trials) and reduced the tendency to use context in a proactive fashion to prepare an upcoming target response (on *AY* trials). Thus, the data support a functional dissociation in which impairments in context updating appear to be an early consequence of increasing age, but then plateau and do not show additional decline with further advances in age. In contrast, context maintenance may be preserved across a wider age span, with impairments in context maintenance occurring much later in old age. Thus, it would be informative to directly examine the effect of age within older adult populations in other types of experimental paradigms that have used delay manipulations to reveal age effects (Amrhein et al., 1991; Balota et al., 1992; McDaniel et al., 2003).

It is worth noting that an alternative explanation of the delay effects is possible.[1] Our task manipulated the cue–probe delay while holding total trial duration constant. This meant that in the long-delay conditions there was a short interval between the probe and the next cue (i.e., the ITI). It is plausible that it was the manipulation of ITI rather than cue–probe delay that may have caused the observed performance differences among young-old and old-old adults (as well as between old-old and individuals with DAT). In particular, the reduced ITI duration in the long-delay condition may have reduced the ability to encode and retrieve cue-related information, because the ITI reduction also decreased the temporal distinctiveness of the cue relative to the preceding probe. One obvious solution to this issue would be to manipulate delay by increasing both delay and ITI durations equivalently. In the current study, we chose not to do this because of concerns about differences in time on task that may have led to changes in fatigue or overall task pacing across delay conditions. Nevertheless, this issue could be addressed in future studies.

Another direction for future studies would be to examine age-related effects on context maintenance under conditions involving distractor-filled delay periods, instead of the empty intervals used in the current study. In previous work, we demonstrated more pronounced age-related changes in *AX*-CPT performance under such conditions, but only tested a single delay interval (Braver, Barch, Keys, et al., 2001). It is possible that under distractor-filled delay conditions, changes in context maintenance abilities might appear as an earlier consequence of increasing age.

Context Processing in DAT

Our study also compared healthy older adults with those suffering from age-related pathology in the form of early stage DAT. In this comparison, we observed that the DAT group showed a further reduction in the ability to maintain context over a delay period. The DAT individuals showed a significantly reduced sensitivity to context information (as indexed by the d'-context measure) when compared with age-matched healthy older adults, and this effect was most prominent in the long-delay condition. Another notable aspect of the results was that the DAT group showed an increased tendency to make *BX* errors when compared with age-matched controls but no slowing of response latency, even though slowing was observed in other conditions. A follow-up analysis suggested that the DAT individuals, but none of the other sampled groups, were making a trade-off of speed for errors in the *BX* condition. In other words, rather than taking the extra processing time needed on *BX* trials to inhibit inappropriate response tendencies associated with the *X* probe, individuals with DAT were more likely to succumb to the probe-related interference and generate an error response. This effect is very reminiscent of earlier work in the Stroop task, in which individuals with DAT were not found to have increased interference in response latency but did manifest a much greater tendency to make Stroop intrusion errors (Spieler et al., 1996). One general interpretation of both findings is that the DAT group had such a weak representation of task-relevant context on some proportion of trials that this context was unable to compete successfully and eventually overcome the inappropriate response tendencies associated with the interfering information.

A final aspect of the data from the DAT group is worth commenting on. The performance impairments we observed in the DAT group were not restricted to context-processing functions. In particular, we observed a slightly increased tendency for DAT individuals to make errors on *BY* trials, which provided an index of context-independent responding. This increased *BY* error rate suggests that patients with early stage DAT were more globally impaired in their ability to perform the *AX*-CPT task than healthy older adults and that any context-processing effects should be considered to be superimposed on this general background of cognitive impairment. Nevertheless, the specific measure of context maintenance function, indexed by the d'-context measure at the long delay, was found to have a large effect size in discriminating the individuals with DAT from age-matched controls. Thus, context-maintenance impairments observed in individuals with early stage DAT appear to be a highly reliable component of the disease, rather than just a proxy for general cognitive decline.

Context Processing as a Cognitive Construct

A secondary component of this study was to examine the association between *AX*-CPT performance in older adults and performance on other neuropsychological tests that might measure similar cognitive constructs. Specifically, our hypothesis suggests the centrality of the context-processing construct to cognitive control. Thus, other neuropsychological tests that are thought to putatively index cognitive or executive control, more broadly construed, might also tap into context-processing abilities. We examined correlations between *AX*-CPT performance and the trail-making test, backward digit span, category verbal fluency, logical memory (delayed), and paired associates. The trailmaking test is a widely used measure of attention control and attention switching, category verbal fluency is thought to index the controlled retrieval of semantic knowledge, and the backward digit span is a measure of short-term storage capacity and the ability to manipulate the contents of the short-term store. Logical memory and paired-associates learning measure retrieval of information from episodic memory. Although these last two memory tests are primarily thought to be probes of memory retrieval, they may also be

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[1] We thank a reviewer for making this point.

influenced by specific encoding and retrieval strategies. Thus, performance on all five tests might plausibly require the appropriate processing and use of task-relevant contextual information. We found that performance on the *AX*-CPT was significantly correlated with performance by older adults on the other neuropsychological tests, with the exception of backward digit span. The failure to find a significant correlation with short-term memory span might at first seem surprising, because the *AX*-CPT task can be thought to index the short-term storage of information—context—over delay periods. This result, however, may actually be consistent with more recent work, suggesting that backward digit span may not place as great demands on control processes as other complex span tasks used in the individual differences literature (e.g., reading span, operation span; Engle, Tuholski, Laughlin, & Conway, 1999). Instead, backward digit span may more strongly measure short-term storage of verbally coded information (i.e., involving the phonological loop), which we have argued is significantly different than context maintenance; the latter is more related to storage of goal-relevant information (Braver et al., 2002; Cohen et al., 1999; Engle et al., 1999). Another aspect of the correlational analyses was that the relationships between the *AX*-CPT and the neuropsychological tasks were found exclusively for the measure of *BX* performance, which we have argued most strongly indexes context-processing impairments. The selectivity in the correlations provides a first step in establishing some discriminant validity for the context-processing construct by indicating that the associations between the *AX*-CPT and other neuropsychological tasks of cognitive control are not likely to reflect some more nonspecific component of performance (e.g., generalized cognitive impairment). A next important step toward examining the context-processing construct will be to explicitly manipulate context-processing demands across different cognitive tasks to determine how this affects cross-task correlations. Our hypothesis is that correlations of the *AX*-CPT with other cognitive tasks will be highest when the tasks place maximal demands on context processing.

Neural Mechanisms of Context Updating Versus Maintenance

The functional dissociability between context updating and context maintenance that we observed in the current study is intriguing, because it brings up the question of what underlying mechanisms might produce such a dissociation. Our own approach to the investigation of cognitive aging has been to link age-related cognitive differences to declines in neurobiological function, using computational models as a tool for understanding the mechanisms of brain-behavior linkage. Our computational model of cognitive control postulates that a primary neural mechanism that modulates context-processing functions is the projection of midbrain dopamine (DA) system into the lateral prefrontal cortex (PFC). This DA projection is hypothesized to modulate the representation and maintenance of context information that occurs within lateral PFC. We suggest that age-related breakdown within these DA projections, which have been strongly suggested by the existing literature (e.g., Arnsten, Cai, Murphy, & Goldman-Rakic, 1994; Arnsten, Cai, Steere, & Goldman-Rakic, 1995; de Keyser, De Backer, Vauquelin, & Ebinger, 1990; Goldman-Rakic & Brown, 1981; Suhara et al., 1991; Volkow et al., 1998), produce a disruption in the ability to represent, update, and maintain context information.

It is worth noting that over the last few years there has been an evolution in both the general neurophysiological literature and in our own computational analyses regarding the precise mechanisms by which DA might modulate PFC function. It is important to note that this shift in theorizing might provide an account as to how context maintenance and context-updating functions could be dissociable. Early empirical and computational studies of DA modulatory effects, including our own (Braver, Cohen, & Servan-Schreiber, 1995), focused on the tonic or sustained actions of DA release (Chiodo & Berger, 1986; Servan-Schreiber, Printz, & Cohen, 1990). However, current evidence suggests that the midbrain DA system signals information in terms of phasic as well as tonic activity changes (Schultz, 1998) and that these two types of activity dynamics are functionally dissociable (Grace, 1991). Our recent computational analyses suggest that tonic and phasic DA activity might also have different computational effects on cognitive control function. Specifically, we have postulated that phasic bursts of DA activity may trigger the updating of context information in PFC, by signaling the presence of salient (i.e., reward predictive) information in the environment that should be represented as context (Braver & Cohen, 2000). In contrast, the tonic level of DA activity may serve an important role in the active maintenance of context information by altering the responsivity (or gain) of PFC neurons to local recirculating inputs (which provide the mechanism of maintenance). Such DA-mediated gain modulation would serve to reduce the tendency of context information to decay over time (Durstewitz, Kelc, & Gunturkun, 1999). Consequently, DA may support both the updating and maintenance of context information, but through different neural and computational mechanisms (Cohen, Braver, & Brown, 2002).

This account of the dissociable roles of DA in context representation versus maintenance might provide an explanation of the findings in this study. Perhaps phasic DA responses are the first to be disrupted by increasing age, whereas tonic DA responses become disrupted only with more advanced age. Thus, young-old adults may show impairment in context representation related to altered phasic DA activity but not yet show impairments in context maintenance if the tonic DA system is still relatively intact. With advancing age, the old-old adults may show both context representation and maintenance difficulties because both tonic and phasic DA activity are impaired. Of course, this hypothesis will require testing and validation through additional simulation and empirical studies, which are currently ongoing in our laboratory.

Conceptualizing the Nature of Cognitive Impairment in DAT

An important goal of the current study was to investigate whether impairments in context-processing functions might be a component of pathological aging, such as in DAT, over and above the deficits in context processing that occur with healthy aging. It is noteworthy that the strongest evidence for impairments in context-processing functions associated with DAT were observed in the measures related to context maintenance. At the same time, increasing age within healthy older adults was also clearly associated with impairments in context maintenance. This raises the question of whether the effects found in DAT individuals can be conceptualized as being an exaggeration of effects that occur as part of the “normal” cognitive decline with further advancing age among older adults (e.g., DAT as accelerated aging). Thus, one possibility is that there is not a clear discontinuation between the cognitive deficits found in DAT and healthy aging. In other words, it could be argued that the only difference between the DAT patients and healthy older adults is that the DAT patients look “cognitively older” than they should given their chronological age. In contrast, others have argued that there are unique cognitive deficits associated with DAT that are not found in healthy aging (Morris & Price, 2001). Our data could be construed as consistent with the DAT as accelerating aging viewpoint. However, because our study was cross-sectional rather than longitudinal, we cannot rule out the possibility that the cognitive declines found in the old-old adults compared with the young-old adults reflect either cohort effects or undetected preclinical DAT. Longitudinal data can address these potential confounds by, for example, retrospectively removing individuals from the sample who are later diagnosed with DAT (Sliwinski, Lipton, Buschke, & Stuart, 1996).

Nonetheless, the results of the current study do suggest that deficits in context maintenance may be an important correlate of early DAT. The effect size for discriminating DAT individuals with age-matched healthy older adults was large (1.0). Further, this large effect size was found even though the DAT individuals were in the earliest phases of the disease. These results are noteworthy, given the primary emphasis in the DAT literature on episodic-memory impairments as the core cognitive component of the illness. Our study thus adds to the growing literature that suggests that cognitive functions related to attentional or executive control may also be important in the understanding the nature of impairment in DAT. Moreover, dysfunctions in cognitive control may serve as a contributing mechanism of memory decline in this illness (Balota et al., 2000; Balota & Faust, 2001). In particular, in the last decade a number of studies have pointed to the importance of control processes within episodic memory (Buckner, Kelley, & Peterson, 1999; Cowan, 1995; Jacoby, Kelley, & McElree, 1999; Moscovitch, 1994). We have suggested that context processing is a fundamental aspect of cognitive control (Braver et al., 2002) and may be important in a variety of cognitive domains, including episodic memory (Braver, Barch, Kelley, et al., 2001). The *AX*-CPT task was developed to be a sensitive and selective probe of context-processing function, and its utility in this respect has been validated in a number of prior studies, including those involving other clinical populations, such as schizophrenia (Barch et al., 1997, 2001; Braver & Cohen, 2001). The results of this study further suggest that the *AX*-CPT may also be useful in understanding the nature of cognitive deficits that occur in the earliest stages of DAT.

Conclusion

In summary, we believe that the results of the current study contribute both to the basic theoretical understanding of context processing and to the understanding of age-related cognitive changes. The examination of different age groups revealed that context activation/updating might be potentially independent of context-maintenance functions. As such, these functions could be subserved by separable mechanisms, a hypothesis that warrants further investigation. From the perspective of healthy and pathological aging, the study is informative in that it provides further support for the utility of the context-processing construct as an indicator of cognitive changes occurring as a normal consequence of aging, and those that may be further exacerbated with disease.

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Received November 6, 2003
Revision received July 1, 2004
Accepted July 14, 2004 ■