Journal of Memory and Language 67 (2012) 285–294

Contents lists available at SciVerse ScienceDirect

Journal of Memory and Language

journal homepage: www.elsevier.com/locate/jml

Impact of aging on the dynamics of memory retrieval: A time-course analysis

Ilke Öztekin [a,*], Nur Zeynep Güngör [b], David Badre [c,d]

[a] Department of Psychology, Koç University, Turkey
[b] Center for Molecular and Behavioral Neuroscience, Rutgers University, United States
[c] Department of Cognitive, Linguistic, and Psychological Sciences, Brown University, United States
[d] Brown Institute for Brain Sciences, Brown University, United States

ARTICLE INFO

Article history:
Received 8 December 2011
revision received 30 April 2012
Available online 5 June 2012

Keywords:
Aging
Memory retrieval
Item-recognition
Interference
Recent negative
Response-deadline speed–accuracy trade-off procedure

ABSTRACT

The response-signal speed–accuracy trade-off (SAT) procedure was used to provide an in-depth investigation of the impact of aging on the dynamics of short-term memory retrieval. Young and older adults studied sequentially presented 3-item lists, immediately followed by a recognition probe. Analyses of composite list and serial position SAT functions found no differences in overall accuracy, but indicated slower retrieval speed for older adults. Analysis of false alarms to recent negatives (lures from the previous study list) revealed no differences in the timing or magnitude of early false alarms that are thought to reflect familiarity-based judgments. However, onset and accrual of recollective processing required for resolving interference was slower for older adults. These findings suggest that older adults have a selective impairment on controlled and recollective retrieval operations, and further specify this impairment to arise primarily from delayed onset of cognitive control potentially coupled with reduced availability of recollective information.

Introduction

It is widely recognized that aging results in deficits in memory functioning in a variety of cognitive tasks (reviewed in Salthouse, 2011). However, the nature of the mechanisms that lead to these age-related deficits remains controversial.

A large body of work indicates that aging might differentially affect controlled processing (Hay & Jacoby, 1999; Jacoby, Debner, & Hay, 2001), such as elaborative encoding and strategic retrieval during memory processing (e.g., Benjamin & Ross, 2008; Kester, Benjamin, Castel, & Craik, 2003). Alternatively, it is possible that aging results in a global cognitive decline (e.g. Benjamin, 2008; Craik & Byrd, 1982; Hasher & Zacks, 1979), such as a decline in processing speed (Salthouse, 1996). Accordingly, empirical dissociations may reflect factors other than a selective sparing or impairment of individual processes.

The two alternative explanations differ in terms of their predictions regarding contributions of automatic and controlled processes to memory performance in young and older adults. Most empirical tasks use overall accuracy or reaction time as dependent measures, and hence cannot separately estimate the contributions of automatic and controlled processes to memory judgments. Thus, it is not clear whether the reported deficits are selective to controlled processing in the elderly or reflect a general deficit affecting both automatic and controlled processing, as would be predicted by a global deficit model. The present study attempts to adjudicate between automatic and controlled memory processing by employing the response-deadline speed–accuracy trade-off (SAT) procedure.

Response-deadline speed–accuracy trade-off (SAT) procedure

The SAT procedure has been used to independently measure the accuracy and speed of processing in a wide

* Corresponding author. Address: Department of Psychology, Koç University, Rumeli Feneri Yolu, Sariyer 34450, Istanbul, Turkey.
E-mail address: ioztekin@ku.edu.tr (I. Öztekin).

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http://dx.doi.org/10.1016/j.jml.2012.05.003

range of cognitive processes, including automatic and controlled memory processing (e.g., Benjamin & Bjork, 2001; Hintzman & Curran, 1994; McElree & Dosher, 1989; Wickelgren, Corbett, & Dosher, 1980; Öztekin & McElree, 2007, 2010). An important advantage of SAT over traditional paradigms is that it provides conjoint measures of the accuracy and the speed of processing, independent of each other. This is in contrast to response time (RT) measures derived from traditional tasks, which cannot provide pure measures of processing speed because they are subject to speed–accuracy trade-offs (McElree, 2006).

Previous research has provided insight into the speed accuracy trade off problem with respect to aging (e.g., see Laver, 2000; Ratcliff, 2008; Smith & Brewer, 1995; Starns & Ratcliff, 2010). Specifically, older adults are more reluctant to make errors compared to young adults, leading them to adapt different response thresholds, and as a consequence slower response times compared to young adults. Recent work has further identified neural pathways indicative of this bias (e.g., Fortsmann et al., 2011). The response-deadline SAT procedure is one way researchers can overcome the speed accuracy tradeoff confound, and obtain separate estimates of the speed and level of retrieval across consecutive moments during retrieval. A further advantage of the SAT procedure is that sampling the full time-course of retrieval allows independently probing automatic versus controlled operations, as the output of automatic operations have typically been observed to be available before the output of controlled operations across a wide range of tasks (e.g., Hintzman & Curran, 1994; McElree, Dolan, & Jacoby, 1999; McElree & Dosher, 1989; Öztekin & McElree, 2007, 2010; Yonelinas, 2002). Accordingly, the SAT procedure enables independent estimation of both the timing and magnitude of the output of these processes via quantitative modeling routines.

In SAT, participants are cued to respond to a response signal (a tone) presented at one of several (typically 6–7) times ranging from about 60 to 3000 ms after the onset of the probe. The time of the response signal is random on any trial, and participants are trained to respond within 100–300 ms of the tone. Varying the response signal across this range of times allows one to measure the full time-course of retrieval. Accordingly, one is able to construct a retrieval function that plots accuracy as a function of processing time, for each condition of interest across each individual participant (see Fig. 1).

As retrieval time progresses, SAT retrieval functions typically show an early period of chance performance, followed by a period of rapid increase in accuracy, and finally an asymptote, where additional retrieval time does not improve accuracy (shown in Fig. 1A). The shape of the functions is usually well fit by an exponential approach to a limit. Three parameters describe these functions: (a) an asymptote, reflecting overall limitations of memory, (b) an intercept, indicating the point in time at which performance departs from chance, and (c) a rate of rise from chance, reflecting retrieval speed. The asymptote parameter indicates the probability of successful retrieval, while the intercept and the rate parameters jointly constitute retrieval speed measures.

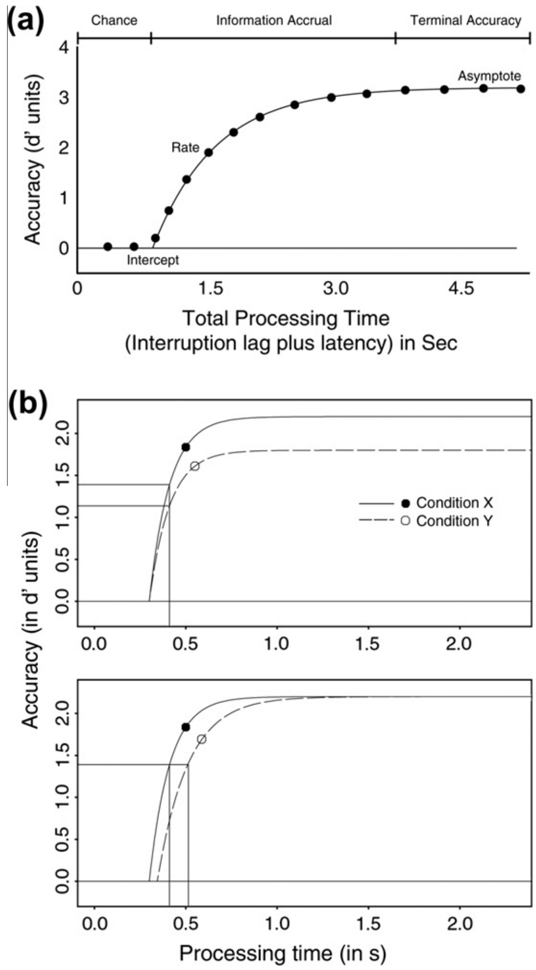

Fig. 1. Illustration of hypothetical SAT functions. (a) An example SAT function that shows how accuracy (in d' units) grows over processing time (in seconds). The SAT curve reflects three phases: A period where performance is at chance (the departing point in time from chance is marked by the intercept parameter), followed by a period of information accrual (the rise of this information accumulation is reflected by the rate parameter of the SAT function), and following this period, the maximum level of accuracy is reached, where performance does not improve any more (the asymptote parameter of the SAT function) and (b) examples of two SAT functions that illustrate differences in retrieval success versus retrieval speed. Both panels indicate accuracy measured (in d' units) plotted against total processing time (in seconds). The top panel shows a case where two experimental conditions differ in probability of retrieval alone (e.g. a manipulation that affects memory strength alone). This difference is reflected in the asymptote parameter of the SAT function (i.e. condition X has a higher asymptote than condition Y), but both conditions have same retrieval speed measures (i.e. same intercept—the point in time where performance departs from chance, and same rate—that reflects the rate of information accrual). The bottom panel on the other hand illustrates a hypothetical case, where two experimental conditions differ in retrieval speed measures, displaying disproportional dynamics.

Current study

In this study, we employed the response-deadline SAT procedure in order to measure the impact of aging on automatic and controlled processes during memory retrieval. We sought to achieve two goals. First, as SAT allows the independent assessment of retrieval success and retrieval speed, we assessed differences between young adults (YAs) and older adults (OAs) in these components of performance during a short-term recognition task. Second, we investigated how the contributions of automatic and controlled processes to memory performance differ across YA and OA by manipulating interference during memory retrieval in a widely-used recent negative probe task (Monsell, 1978). Previous studies investigating the time-course of responses in this task (e.g., Hintzman & Curran, 1994; McElree & Dosher, 1989; Öztekin & McElree, 2007, 2010) have indicated higher false alarm rates for a recent negative (RN) compared to a nonrecent, distant negative (DN) probe. However, this high false alarm rate gradually diminishes later in retrieval, as participants are able to recover diagnostic details from memory. This nonmonotonic function is thought to reflect that the automatic assessments of familiarity engender high levels of false alarms early in retrieval, which are then attenuated later in retrieval with the engagement of controlled, strategic retrieval operations that access detailed episodic information from memory (e.g., Hintzman & Curran, 1994; McElree & Dosher, 1989; Öztekin & McElree, 2007, 2010). If aging selectively impacts controlled processing, we should see differences only in later phases of retrieval. On the other hand, if aging results in a global deficit affecting both automatic and controlled operations, we should see differences in early phases as well.

Methods

Participants

Eleven YA (age range 18–26, mean age 20.64, average education 14 years), and 11 OA (age range 60–74, mean age 67.72, average education 15 years) participated in the study. Participants were screened for use of CNS affecting drugs, for psychiatric and neurological conditions, and for their general health.

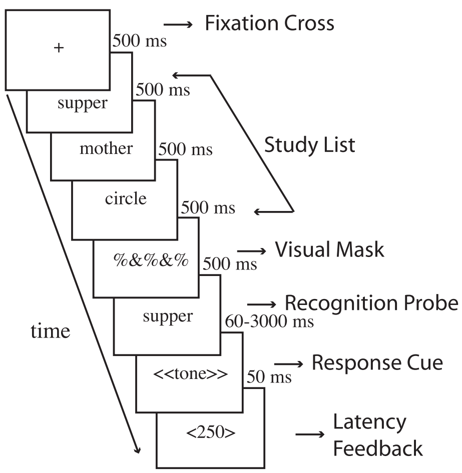

Fig. 2. A sample trial sequence from the experimental procedure.

Design and stimuli

The experiment consisted of three sessions, containing eight blocks of 84 trials each, in which participants studied a 3-item list and were cued to respond to a recognition probe following a brief visual mask (Fig. 2). The first session served as practice and was excluded from analysis.

Stimuli consisted of a thousand high frequency words from the Toronto Noun Pool (Friendly, Franklin, Hoffman, & Rubin, 1982). A study list was constructed by randomly selecting (without replacement within a trial) three words from the word pool. A study word was repeated for a maximum of three times across the entire experiment. Half the probes consisted of targets, drawn from one of the three serial positions (SPs). Half the probes consisted of lures, consisting of recent negatives (RNs), lures drawn from the studied words of the preceding trial, and distant negatives (DNs); lures that had not been presented for at least 250 trials.

Procedure

Fig. 2 illustrates the sequence of events in a single trial: Three study words were presented for 500 ms each. Then, a visual mask consisting of non-letter symbols was presented for 500 ms. Next, the recognition probe was presented for the duration of the response-deadline. At 60, 200, 300, 500, 800, 1500, 3000 ms after the onset of the recognition probe, a 50-ms tone sounded to cue the participants to respond. Participants were trained to respond within 300 ms of the tone, and informed that responses longer than 300 ms were too slow. Responses faster than 100 ms, and responses longer than 600 ms were excluded from analyses.

Model fitting routine

Each participant's hit rates were scaled against the false alarm (FA) rates to DNs to obtain (equal-variance Gaussian) d' measures. We estimated the full-time course of retrieval by fitting each individual participants' data as well as the average group data for OA and YA with an exponential approach to a limit (Dosher, 1981; McElree & Dosher, 1989, 1993; Wickelgren et al., 1980; Öztekin & McElree, 2007, 2010):

$$d'(t) = l(1 - e^{-b(t-d)}), t > d, \quad \text{else } 0. \tag{1}$$

In Eq. (1), $d'(t)$ is the predicted d' at time t; l is the asymptotic accuracy level reflecting the overall probability of recognition; d is the intercept reflecting the discrete point in time when accuracy departs from chance; b is the rate parameter, which indexes the speed at which accuracy grows from chance to asymptote.

The quality of the model fits were assessed by: (a) The value of an adjusted R^2 statistic (Reed, 1973); (b) the consistency of parameter estimates across participants; (c) evaluation of whether the fit yielded systematic deviations that could be accounted for by additional parameters. These latter two metrics were assessed by statistical tests conducted on the parameter estimates derived from the model fits across participants.

Results

Retrieval dynamics within lists

SAT functions in both groups exhibited similar dynamics of retrieval as a function of SP. SAT functions for the 3 SPs were fit with sets of nested models that systematically varied the three parameters in Eq. (1). These models ranged from a null model in which all functions were fit with a single asymptote (l), rate (b), and intercept (d) across SPs, to a fully saturated model in which each SP function was fit with a unique asymptote (l), rate (b), and intercept (d). The best-fitting model (termed the 3l–2b–1d model) allocated a separate asymptote (l) to each SP, one rate (b) for SPs 1–2, another rate (b) for SP 3 (the most recently studied item), and a common intercept (d) for all the three SPs. Including a separate rate for the last SP significantly increased adjusted-R^2 value compared to a model with only one rate across SPs [$t(21) = 2.94$, $p < .008$]. The rate for the last SP was faster than the previous two SPs in both OA [$t(10) = 2.63$, $p < .025$ Hedges's $g = .89$, Bayes factor (Rouder, Speckman, Sun, Morey, & Iverson, 2009) = .26] and YA [$t(10) = 2.83$, $p < .018$, $g = .87$, Bayes factor = .19]. A distinct and faster rate parameter for the last item suggests that the most recent item benefits from a privileged state in the focus of attention, replicating prior work (McElree & Dosher, 1989, 1993; Öztekin & McElree, 2007, 2010; Wickelgren et al., 1980) and extending this phenomenon to OA.

Age related differences in retrieval dynamics, in the absence of interference

We next tested overall group differences collapsed across SPs in terminal accuracy and retrieval speed for the targets (Fig. 3 and Tables 1A and 1B).[1] The two groups were comparable in their maximum level of accuracy achieved. The average asymptote (l) parameters derived from the average model fits were 3.65 and 3.63 respectively for YA and OA and did not differ between groups ($t = .05$). Likewise, the intercept (d) parameter did not differ across the two groups [$t = .07$]. However, the two groups did differ in retrieval speed (Fig. 3). Specifically, OA had a slower rate (b) than YA [$t(20) = 2.75$, $p < .012$, $g = 1.13$, Bayes factor = .16].

Importantly, age difference in rate of information accrual was selective to the first two SPs (Fig. 4 and Tables 2A and 2B). SP was modeled using the 3l–2b–1d model described above. Between-group comparison of the asymptote (l) parameter did not reveal a reliable difference for any of the three SPs [SP 1, $t = -.007$; SP2, $t = -.53$; SP3, $t = .84$]. However, OA had a slower rate (b) parameter compared to YA for SPs 1–2 [$t(20) = 2.27$; $p < .035$, $g = .93$, Bayes factor = .35]. By contrast, the rate (b) parameter for SP 3, the most recently studied item did not differ between the two groups [$t = 1.45$]. Hence, impact of aging on retrieval speed was evident for items that need to be accessed from memory, but not to the contents of focal attention. However, this result should be interpreted with caution. Specifically, it is possible that a difference might emerge with larger samples (see Salthouse (2000) for a discussion).

Age related differences in interference resolution

In order to investigate the impact of aging on interference resolution, we analyzed FA rates to RN and DNs. In general, FA rates declined with longer response deadlines for both RN [$F(6120) = 19.87$, $p < .001$] and DN [$F(6120) = 22.41$, $p < .001$]. For RNs, OA exhibited marginally higher FA rates than YA across response deadlines [$F(1,20) = 3.97$, $p < .060$]. A comparable group effect was not evident for DNs. In addition, collapsing over groups, there was a significant probe (RN versus DN) × response-deadline interaction [$F(6126) = 5.12$, $p < .01$]. That is, participants had a higher tendency to false alarm more to RNs early in retrieval, but this difference diminished later in retrieval. We further investigate this interaction below.

In order to assess group differences in susceptibility to item familiarity during interference conditions, we computed the difference in FA scores between RN and DN probes at each of the response-deadlines. This measure allowed an unbiased measure of performance by factoring out participants' bias to judge an item as a member of the study list (e.g., tendency to respond yes more often than no, regardless of the type of test probe).

Fig. 5 plots the FA difference scores for the average OA and YA data. Due to the FA difference scaling, higher scores indicate a higher tendency to false alarm to RNs. For both groups, the FA difference scores increase early in retrieval and then diminish later in retrieval. This nonmonotonic pattern indicates that the information basis for the recognition memory judgments has shifted across retrieval and is consistent with predictions of dual-process theories of recognition memory: The early high FA rates indicate the contribution of familiarity (because the RN has been studied on the previous trial, it has high residual familiarity compared to the DN) or stimulus identification. The observed reduction in FA rates later in retrieval suggests the accrual of new information that contributes to the recognition judgments, presumably reflecting source or list-specific information recovered by a recollective process (e.g., the fact that the RN probe was studied on previous trial, or that it was not a member of the current study list). Below, we statistically assess these differences with a quantitative two-process model.

We fit the FA difference scores with a two-process retrieval model that explicitly assumes that retrieval shifts from one source of information to another source across processing time (McElree & Dosher, 1989; Ratcliff, 1980):

$$FA_{diff}(t) = \begin{cases} l_1(1 - e^{-b(t-d1)}), & \text{for } d_1 < t < d_2 \\ l_2 + (l_1 - l_2)(d_2 - d_1)/(t - d_1) * (1 - e^{-b(t-d1)}), & \text{for } t \geqslant d_2 \end{cases} \quad (2)$$

[1] Note that the first observation collected for older adults comes later in time compared to the young adult group. That is, although the deadlines are given at the same offsets for each participant, older adults are slower. The fitting routine estimates the full time-course of the retrieval function assuming an exponential approach to a limit as noted on Eq. (1). To the degree that information accrual for older adults follows a pattern consistent with this exponential approach, the model can accurately estimate the retrieval dynamics. However, violations of this assumption could potentially affect the estimation of the intercept and perhaps the rate parameters for older adults.

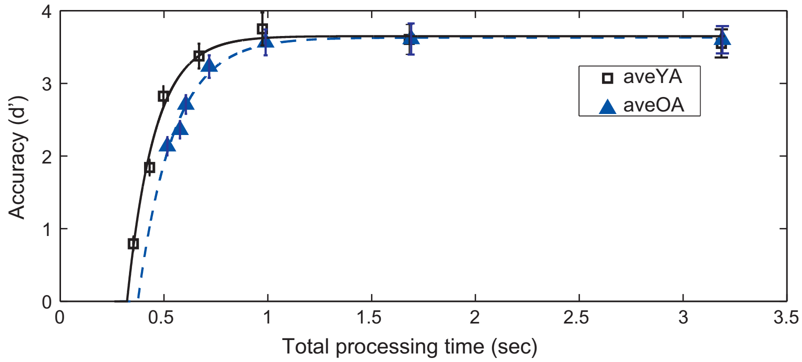

Fig. 3. Illustration of composite list SAT functions and model fits. Accuracy (in d' units) for composite list (averaged over serial position of the test probe) SAT functions plotted against total processing time (duration of the response deadline plus latency in seconds) for the average OA and YA groups. The symbols indicate empirical data points, and the smooth lines indicate the model fits derived from Eq. (1). Error bars indicate 95% confidence intervals. *Note*: aveOA = average older adult group; aveYA = average young adult group.

Table 1A
Parameter estimates from the composite list fit for young adults.

P	Ave	Participant										
		1	2	3	4	5	6	7	8	9	10	11
l	3.65	2.82	3.86	4.14	3.98	3.35	3.69	2.91	3.74	3.79	4.11	3.99
b	7.52	4.12	9.59	12.18	14.73	16.93	10.89	7.55	4.43	26.32	20.25	14.50
d	.322	.338	.397	.340	.346	.388	.405	.373	.244	.408	.317	.410
R^2	.981	.826	.938	.926	.996	.805	.981	.977	.840	.982	.991	.970

Note: *P* = Parameter. Ave = Average. Average parameters are based on data averaged over participants.

Table 1B
Parameter estimates from the composite list fit for older adults.

P	Ave	Participant										
		1	2	3	4	5	6	7	8	9	10	11
l	3.63	2.87	3.68	4.12	4.05	3.92	3.73	3.86	3.62	3.27	3.61	3.56
b	5.86	4.10	7.38	7.01	6.94	6.01	4.14	5.04	9.11	4.45	4.52	15.0
d	.374	.404	.433	.277	.290	.428	.374	.406	.418	.398	.233	.325
R^2	.972	.872	.805	.967	.628	.761	.951	.908	.874	.960	.624	.471

Note: *P* = Parameter. Ave = Average. Average parameters are based on data averaged over participants.

Eq. (2) states that during the initial retrieval period ($d_1 < t < d_2$), accuracy depends on accrual of one type of information, such as familiarity information, or stimulus/item identity. During this initial period, accuracy is modeled by the top portion of Eq. (2), a simple exponential approach to an asymptote (l_1). At time d_2, a second source of information starts to contribute to the recognition memory judgments, arising from the output from a second process, such as a controlled retrieval operation that accesses detailed episodic information (e.g. source memory). The accrual of this second type of information leads to the change in retrieval, shifting the asymptote from l_1 to l_2. The bottom portion of Eq. (2) states that response accuracy gradually shifts to the new asymptote (l_2) starting at time d_2.

We should note that the two processes noted in the model presented in Eq. (2) are intended to independently assess the recovery of information through an automatic versus a controlled retrieval operation, and need not be equivalent to familiarity versus recollection. Although the notion of a fast/automatic familiarity assessment (or a component of stimulus/item identification that could lead to an increase in false alarm rates) is consistent with dual-process theories of recognition (e.g., see Yonelinas (2002) for review), the slower controlled component might not necessarily equal general recollection, but could also reflect the independent accrual of diagnostic episodic information (e.g. source information) that can aid the successful resolution of interference. The slower accrual of this diagnostic episodic information can overrule the contribution of the fast/automatic assessments (independent of whether the automatic process has reached completion), leading to the nonmonotonic pattern observed in the data.

An independent-samples t-test comparison across OA and YA indicated that neither the familiarity asymptote

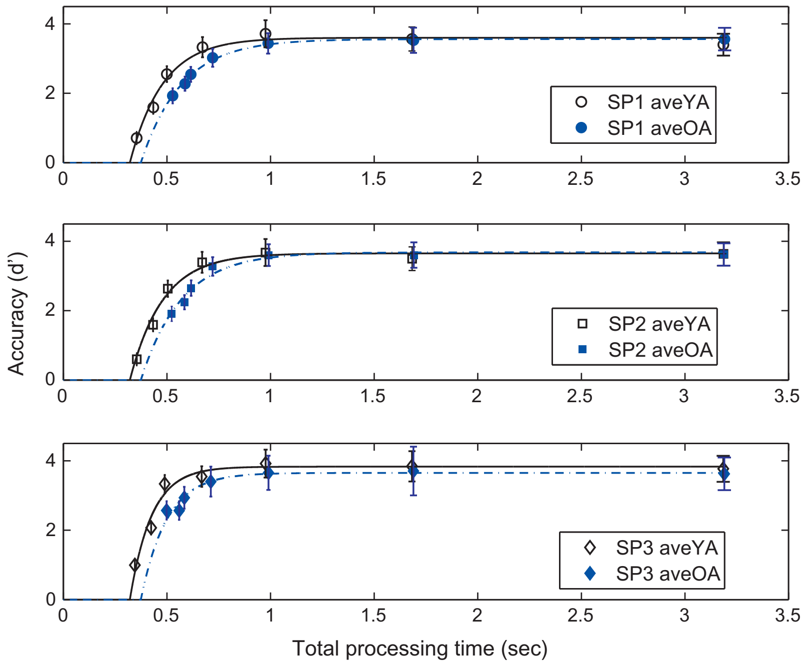

Fig. 4. Illustration of serial position SAT functions and model fits. Accuracy (in d' units) for each serial position plotted against total processing time (duration of the response deadline plus latency in seconds) for the average OA and YA groups. The symbols indicate empirical data points, and the smooth lines indicate the model fits derived from Eq. (1). Error bars indicate 95% confidence intervals. *Note*: SP = serial position; aveOA = older adult group; aveYA = young adult group.

Table 2A
Parameter estimates from the serial position fits for young adults.

P	Ave	Participant										
		1	2	3	4	5	6	7	8	9	10	11
l_1	3.60	2.22	3.67	4.27	4.10	3.36	3.41	2.58	3.69	3.90	4.10	4.16
l_2	3.65	2.72	4.03	4.09	3.80	3.26	3.67	3.02	3.85	3.45	4.09	4.02
l_3	3.83	3.48	3.78	4.10	4.07	3.51	4.05	3.14	3.72	4.08	4.14	4.19
b_1	6.29	6.55	8.76	9.80	11.60	9.30	8.12	6.44	3.89	18.87	22.56	4.54
b_2	9.50	3.76	22.03	15.86	28.23	31.57	20.80	10.35	5.76	47.74	16.61	7.85
d	.321	.376	.405	.335	.349	.374	.407	.371	.244	.405	.317	.327
R^2	.970	.811	.925	.900	.964	.744	.890	.969	.790	.932	.968	.872

Note: *P* = Parameter. Ave = Average. SP = Serial position. Average parameters are based on data averaged over participants.

Table 2B
Parameter estimates from the serial position fits for older adults.

P	Ave	Participant										
		1	2	3	4	5	6	7	8	9	10	11
l_1	3.56	3.00	3.65	4.05	4.06	3.75	3.36	3.66	3.58	3.51	3.39	3.45
l_2	3.68	2.80	3.77	4.20	4.14	3.90	3.84	3.81	3.78	3.69	3.51	3.60
l_3	3.65	2.85	3.64	4.09	3.97	4.12	4.04	4.12	3.45	2.72	3.95	3.61
b_1	5.10	3.59	5.38	7.95	5.07	5.39	3.48	4.35	7.70	3.64	3.65	12.23
b_2	8.01	4.71	9.54	35.0	17.22	7.24	4.72	5.93	21.0	6.81	5.78	15.00
d	.374	.397	.414	.366	.243	.426	.363	.394	.472	.399	.200	.272
R^2	.955	.765	.736	.872	.485	.703	.915	.832	.832	.915	.297	.261

Note: *P* = Parameter. Ave = Average. SP = Serial position. Average parameters are based on data averaged over participants.

(l_1) nor the familiarity intercept (d_1) estimates differed across the two groups (l_1, $t = .99$; d_1, $t = 1.55$), suggesting that OA and YA groups did not differ in either the point in time when they began to false alarm more to RNs than

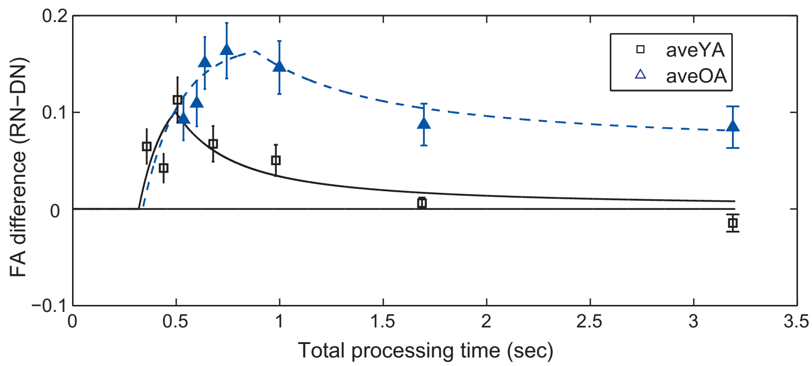

Fig. 5. Difference in false alarm rates across the recent and distant negative probes plotted against total processing time (duration of the response deadline plus latency in seconds) for the average OA and YA groups. The symbols indicate empirical data points, and the smooth lines indicate the model fit derived from Eq. (2). Error bars indicate 95% confidence intervals. *Note*: RN = recent negative; DN = distant negative; aveOA = average older adult group; aveYA = average young adult group.

DNs or the degree to which they false alarmed to the two probe types early in retrieval (see Tables 3A and 3B for parameter estimates).

By contrast, there was a reliable age difference in the timing of when detailed episodic information began to accrue (d_2). The d_2 intercept parameter was significantly slower for OA compared to YA [$t(20) = 2.24$, $p < .036$, $g = .92$, Bayes factor = .36], with a reliable parameter (d_1 versus d_2) by group interaction [$F(1,20) = 5.38$, $p < .03$]. In the average data, d_2 estimates were 884 ms for OA and 496 ms for YA, suggesting that the accumulation of detailed episodic information, presumably recovered by controlled retrieval operations, might onset and/or begin to influence performance later in time compared to YA. In addition, the l_2 asymptote parameter, reflecting the maximum level of accuracy reached after the accumulation of specific episodic information, was lower for OA (.06 on the average OA data) compared to YA (.01 on the average YA data) [$t(20) = 2.58$, $p < .018$, $g = 1.06$, Bayes factor = .21]. This difference in terminal accuracy suggests that the availability of task-relevant recollective information in memory might be less for OA compared to YA, or that the controlled retrieval operation that accesses recollective information from memory had not been completed for OA even by the longest interruption lag (approximately 3.2 s). However, a comparison between the last two interruption lags indicates no measurable difference [$t = .30$], and thus does not support this second account.

Despite the late engagement of the controlled recollective operations in OA, the overall decrease in FA rates between the groups was comparable. Specifically, the change in FA difference was computed from the onset of

Table 3A
Parameter estimates from the two-process model fits for young adults.

P	Ave	Participant										
		1	2	3	4	5	6	7	8	9	10	11
l_1	.13	.22	.17	.14	.35	.15	.19	.25	.09	.10	.01	.35
l_2	.01	.01	.01	.01	.01	.01	.01	.01	.01	.03	.01	.01
b	8.37	5.28	5.35	13.34	9.58	19.99	16.61	8.35	5.14	18.58	20.0	6.29
d_1	.319	.348	.306	.329	.297	.384	.407	.364	.265	.375	.305	.320
d_2	.496	.518	.498	.430	.305	.528	.617	.527	.428	.999	.300	.347
R^2	.995	.903	.953	.994	.996	.978	.974	.984	.977	.994	.996	.964

Note: *P* = Parameter. Ave = Average. SP = Serial position. Average parameters are based on data averaged over participants.

Table 3B
Parameter estimates from the two-process model fits for older adults.

P	Ave	Participant										
		1	2	3	4	5	6	7	8	9	10	11
l_1	.17	.11	.35	.28	.19	.17	.15	.35	.03	.32	.22	.35
l_2	.06	.07	.03	.01	.010	.01	.06	.05	.12	.01	.10	.30
b	5.81	4.07	12.45	6.45	19.99	3.11	4.96	8.94	6.07	6.45	6.35	19.99
d_1	.338	.307	.443	.189	.100	.113	.333	.424	.299	.398	.297	.100
d_2	.884	.805	.526	.300	1.34	.998	.659	.557	.537	1.00	.617	2.00
R^2	.996	.965	.937	.994	.978	.925	.965	.942	.975	.965	.970	.841

Note: *P* = Parameter. Ave = Average. SP = Serial position. Average parameters are based on data averaged over participants.

interference resolution in each group, defined as the deadline closest to d_2, to the longest interruption lag. This change in FA rates did not differ between the two groups ($t = .16$), even when controlling for amount of time spent resolving interference (i.e., adjusting for the earlier onset of YA; $t = 1.13$). However, this null result could be due to a floor effect in the YA (who fully resolve interference by the longest lag), and should be interpreted with caution.

Discussion

Here, we evaluated age related changes in the dynamics of memory retrieval. Employing the SAT procedure enabled us to derive unbiased and independent estimates of age-related differences in overall accuracy and the speed with which information is accessed from memory. In addition, through an interference manipulation, we were able to distinguish age-related changes in automatic versus controlled processing during memory retrieval. Results suggest that older adults are comparable to young adults when retrieval is automatic and cue driven, and further, can overcome limitations in retrieval by maintaining an item in focal attention. However, in contexts where information must be brought back to mind in a more controlled/strategic way, such as when it has dropped from the focus of attention or must be retrieved/selected in the presence of familiarity-induced interference, older adults have difficulty, being slower to engage necessary control mechanisms to aid memory performance.

Age related differences in short-term item recognition

In the absence of interference, SAT functions did not differ between the two age groups in terms of overall accuracy for studied items. Nevertheless, older adults exhibited slower access speed. Because both familiarity and recollective information could contribute to the responses for studied items, this rate difference could stem from differences in automatic information recovery, strategic access and evaluation of remembered information, or both. However, based on the selective impact of aging on recollective controlled processes during interference resolution (discussed below), the decline in retrieval speed for studied items might primarily reflect a difference in the application of controlled processing at retrieval. Nonetheless, we should stress that the contribution of automatic and controlled processing cannot be independently assessed and estimated in the absence of interference, and thus the false alarm analyses during interference resolution (discussed below) provides a more diagnostic interpretation of the data as it allows independent assessments regarding the contribution of automatic and controlled processing.

A potential concern with respect to the observed difference across the two groups could be that the response signal itself may be contributing to a difference in addition to the actual experimental manipulations employed. That is, older adults might simply be performing worse because of the additional demand of having to respond to a cue that comes at an unpredictable point in time. However, we believe this concern is eliminated by the nonmonotonic pattern observed in the false alarm data (discussed further below). Specifically, the evident interaction between performance and the duration of the response deadline rules out a potential explanation of the data to solely arise from employing a cue to signal participants to respond.

Effects of aging on interference resolution

Previous work has indicated that older adults are particularly impaired when conscious or controlled processing is required (e.g., Benjamin & Ross, 2008; Hay & Jacoby, 1999; Jacoby et al., 2001), including in the presence of interference (e.g., Bowles & Salthouse, 2003; Emery, Hale, & Myerson, 2008; Ikier, Yang, & Hasher, 2008; Jonides et al., 2000) and switching attention, such as during the n-back task (Schmiedek & Lindenberger, 2009; Verhaeghen & Basak, 2005; Verhaeghen & Cerella, 2002; Verhaeghen, Cerella, & Basak, 2006). However, there remains some debate as to whether this represents a deficit of degree, whereby older adults have general cognitive or memory impairments, which are also present during automatic retrieval but are compounded when retrieval becomes effortful (e.g., Benjamin, 2008), or alternatively, that deficits in memory arise from a selective impairment when cognitive control is required (e.g., Jacoby et al., 2001).

Our data indicate that older and young adults do not differ in the magnitude or timing of early, familiarity-based responses, and so find no measurable impact of aging on this type of automatic, obligatory retrieval. In contrast, FA rates differ substantially later in retrieval, when participants must engage in controlled, recollective operations in order to resolve interference. Thus, the current data provide evidence for a selective aging deficit on controlled memory processes, specifically. However, we should stress the fact that this was the case during resolution of interference in the current paradigm. The notion that automatic processes are typically available and contribute to memory performance earlier than controlled, recollective processes may not generalize to all contexts. However, the nonmonotonic pattern observed in our current data set allowed us to independently estimate the contributions of the two processes in the current study.

Notably, the point at which participants began to correct their FA rates to RNs came considerably later in time for older compared to young adults. There are at least two accounts of this delay. First, older adults might be slower in engaging in controlled retrieval or selection of relevant episodic information to counteract the misleading effects of high familiarity associated with RNs. From this perspective, discriminating which list a familiar item came from requires recollecting diagnostic details from the encoding event. Older adults may be slower to engage this controlled retrieval and/or selection process. As a consequence, they allow irrelevant information more time to build up than young adults resulting in relatively more interference to resolve. Alternatively, older adults may take longer to shift their memory criteria away from familiarity-based information to more diagnostic, recollective information. In other words, the delayed onset of interference resolution could reflect perseveration on the wrong criterion. In this case, participants primarily rely on familiarity to drive responding, but in cases where familiarity is misleading, such as for RNs, it is necessary to shift criteria to more diagnostic, recollective information, and older adults take longer to make this shift.

In general, previous work investigating proactive interference during short-term item recognition have highlighted both of these potential mechanisms (Badre & Wagner, 2005; Jonides & Nee, 2006). Neuroimaging studies have repeatedly observed activation in left ventrolateral prefrontal cortex (lVLPFC) under conditions of proactive interference (Badre & Wagner, 2005; Bunge, Ochsner, Desmond, Glover, & Gabrielli, 2001; Jonides, Smith, Marshuetz, & Koeppe, 1998; Öztekin & Badre, 2011; Öztekin, Curtis, & McElree, 2009). And, lVLPFC appears to be crucial for resolution of the interference, as disruption of lVLPFC, either due to stroke (Thompson-Schill et al., 2002) or transcranial magnetic stimulation (Feredoes & Postle, 2010; Feredoes, Tononi, & Postle, 2006), results in greater vulnerability to interference. These effects have been related to both episodic recollection and shifts in memory criteria (Badre & Wagner, 2005; Jonides & Nee, 2006) and are consistent with a broader role of lVLPFC in the cognitive control of memory (Badre & Wagner, 2007).

PFC in general, including lVLPFC, is known to undergo changes during aging (Cabeza, Nyberg, & Park, 2004), and functional neuroimaging has repeatedly observed differences in PFC function (e.g., Ryma & D'Esposito, 2000). Furthermore, deficits in proactive interference resolution in older adults have been associated with decreased activation in lVLPFC specifically (Cabeza, Anderson, Houle, Mangels, & Nyberg, 2000; Jonides et al., 2000). Thus, the present results build on these findings to suggest that this functional deficit may express itself, at least partly, in a slowed onset of control relative to younger adults.

Regardless of the source of the delayed onset of interference resolution, the consequence of this delay is that substantially more irrelevant information has the opportunity to build up in older adults before they begin resolving it, setting them a more difficult task of interference resolution. Thus, a key question is whether widely observed age differences in memory generally and in interference resolution specifically, are primarily accounted for by this slowed onset of control. In other words, the application of cognitive control itself is comparable across the two groups, but older adults start from a worse baseline because of their delayed onset, and so perform worse. Or, alternatively, older adults not only face higher baseline interference but also lack resources to resolve it. The present data set is not conclusive on this point, but does provide some intriguing clues from both perspectives.

There was a reliable age difference in the RN–DN difference in FA rates at the longest deadline (l_2 from Eq. (2)), and these terminal rates were asymptotic. One interpretation of these observations is that this terminal FA effect stems entirely from the initial difference in the baseline level of interference. In concrete terms, due to their delay, older adults have greater interference to resolve than young adults, and so completely resolving this interference, as the young adults do, is not possible. Perhaps consistent with this hypothesis, the change in FA rate difference over time did not differ across the two groups. However, this null difference in rate may simply be a function of a floor effect for young adults, who have had sufficient opportunity to fully resolve interference by the longest deadline. Thus, another possibility is that older adults differ in the availability of recollective information needed to resolve interference and/or are limited in the degree to which they can effectively apply control to resolve interference. Along with the already noted age differences in PFC structure and function, a selective reduction in the availability of recollective information with aging is consistent with observed changes in hippocampal functioning during encoding and retrieval, and the coupling of reduced activation in this region with reduced recollection accuracy (e.g., Daselaar, Veltman, Rombouts, Raaijmakers, & Jonker, 2003; Gutchess et al., 2005; Mitchell, Johnson, Raye, & D'Esposito, 2000).

In conclusion, the present study demonstrates that older adults are impaired when controlled, recollective processes are required for memory performance, but show little difference in automatic, familiarity-driven retrieval. Moreover, at least one component of this deficit arises from a delayed onset of control and so a greater baseline level of interference relative to young adults.

Acknowledgments

This research was supported by an FP7 Marie Curie IRG (PIRG08-GA-2010-277016) to I. Öztekin, and grants from the National Institute of Neurological Disease and Stroke (R01 NS065046) and Alfred P. Sloan Foundation to D. Badre.

References

Badre, D., & Wagner, A. D. (2005). Frontal lobe mechanisms that resolve proactive interference. *Cerebral Cortex, 15*(12), 2003–2012.

Badre, D., & Wagner, A. D. (2007). Left ventrolateral prefrontal cortex contributions to the control of memory. *Neuropsychologia, 45*, 2883–2901.

Benjamin, A. S., & Bjork, R. A. (2001). On the relationship between recognition speed and accuracy of words rehearsed via rote versus elaborative rehearsal. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 26*, 638–648.

Benjamin, A. S. (2008). Behavioral approaches to the study of learning and memory. In M. Guadagnoli, A. S. Benjamin, S. de Belle, B. Etnyre, T. Polk, & G. Stelmach (Eds.), *Human learning: Biology, brain, and neuroscience*. Holland: Elsevier.

Benjamin, A. S., & Ross, B. H. (2008). Introduction and overview. In A. S. Benjamin & B. H. Ross (Eds.). *The psychology of learning and motivation: Skill and strategy in memory use* (Vol. 48, pp. xi–xiv). London: Academic Press.

Bowles, R. P., & Salthouse, T. A. (2003). Assessing the age-related effects of proactive interference on working memory tasks using the Rasch model. *Psychology and Aging, 18*, 608–615.

Bunge, S. A., Ochsner, K. N., Desmond, J. E., Glover, G. H., & Gabrielli, J. D. (2001). Prefrontal regions involved in keeping information in and out of mind. *Brain, 124*, 2074–2086.

Cabeza, R., Anderson, N. D., Houle, S., Mangels, J. A., & Nyberg, L. (2000). Age-related differences in neural activity during item and temporal-order memory retrieval: A positron emission tomography study. *Journal of Cognitive Neuroscience, 12*, 197–206.

Cabeza, R., Nyberg, L., & Park, D. C. (2004). Cognitive neuroscience of aging: Emergence of a new discipline. In R. Cabeza, L. Nyberg, & D. C. Park (Eds.), *Cognitive neuroscience of aging: Linking cognitive and cerebral aging*. New York: Oxford University Press.

Craik, F. I. M., & Byrd, M. (1982). Aging and cognitive deficits: The role of attentional resources. In F. I. M. Craik & S. E. Trehub (Eds.), *Aging and cognitive processes* (pp. 191–211). New York: Plenum.

Daselaar, S. M., Veltman, D. J., Rombouts, S. A. R. B., Raaijmakers, J. G. W., & Jonker, C. (2003). *Neurobiology of Aging, 24*, 1005–1011.

Dosher, B. A. (1981). The effect of delay and interference: A speed-accuracy study. *Cognitive Psychology, 13*, 551–582.

Emery, L., Hale, S., & Myerson, J. (2008). Age differences in proactive interference, working memory, and abstract reasoning. *Psychology and Aging, 23*, 634–645.

Feredoes, E., & Postle, B. R. (2010). Prefrontal control of familiarity and recollection in working memory. *Journal of Cognitive Neuroscience, 22*, 323–330.

Feredoes, E., Tononi, G., & Postle, B. R. (2006). Direct evidence for a prefrontal contribution to the control of proactive interference in verbal working memory. *Proceedings of the National Academy of Sciences of the United States of America, 103*, 19530–19534.

Fortsmann, B. U., Tittgemeyer, M., Wagenmakers, E. J., Derrfus, J., Imperati, D., & Brown, S. (2011). The speed–accuracy tradeoff in the elderly brain: A structural model-based approach. *Journal of Neuroscience, 47*, 17242–17249.

Friendly, M., Franklin, P. E., Hoffman, D., & Rubin, D. C. (1982). The Toronto Word Pool: Norms of imagery, concreteness, orthographic variables, and grammatical usage for 1080 words. *Behavior Research Methods & Instrumentation, 14*, 375–399.

Gutchess, A. H., Welsh, R. C., Hedden, T., Bangert, A., Minear, M., Liu, L. L., et al. (2005). Aging and the neural correlates of successful picture encoding: Frontal compensate for decreased medial–temporal lobe activity. *Journal of Cognitive Neuroscience, 17*, 84–96.

Hasher, L., & Zacks, R. T. (1979). Automatic and effortful processes in memory. *Journal of Experimental Psychology: General, 108*, 356–388.

Hay, J. F., & Jacoby, L. L. (1999). Separating habit and recollection in young and older adults: Effects of elaborative processing and distinctiveness. *Psychology of Aging, 14*, 122–134.

Hintzman, D. L., & Curran, T. (1994). Retrieval dynamics of recognition and frequency judgments: Evidence for separate processes of familiarity and recall. *Journal of Memory & Language, 33*, 1–18.

Ikier, S., Yang, L., & Hasher, L. (2008). Implicit proactive interference, age, and automatic versus controlled retrieval strategies. *Psychological Science, 19*, 456–461.

Jacoby, L. L., Debner, J. A., & Hay, J. F. (2001). Proactive interference, accessibility bias, and process dissociations: Valid subjective reports of memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 27*, 686–700.

Jonides, J., & Nee, D. E. (2006). Brain mechanisms of proactive interference in working memory. *Neuroscience*, 181–193.

Jonides, J., Marshuetz, C., Smith, E. E., Reuter-Lorenz, P. A., Koeppe, R. A., & Hartley, A. (2000). Age differences in behavior and PET activation reveal differences in interference resolution in verbal working memory. *Journal of Cognitive Neuroscience, 12*, 188–196.

Jonides, J., Smith, E. E., Marshuetz, C., & Koeppe, R. A. (1998). Inhibition in verbal working memory revealed by brain activation. *Proceedings of the National Academy of Sciences of the United States of America, 95*, 8410–8413.

Kester, J. D., Benjamin, A. S., Castel, A. D., & Craik, F. I. M. (2003). Memory in the elderly. In A. Baddeley, M. D. Kopelman, & B. A. Wilson (Eds.), *Handbook of memory disorders* (2nd ed., pp. 543–567). New York: Wiley.

Laver, G. D. (2000). A speed–accuracy analysis of word recognition in young and older adults. *Psychology and Aging, 15*, 705–709.

McElree, B. (2006). Accessing recent events. In B. H. Ross (Ed.). *The psychology of learning and motivation* (Vol. 46). San Diego: Academic Press.

McElree, B., Dolan, P. O., & Jacoby, L. L. (1999). Isolating the contributions of familiarity and source information in item recognition: A time-course analysis. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 25*, 563–582.

McElree, B., & Dosher, B. A. (1989). Serial position and set size in short-term memory: Time course of recognition. *Journal of Experimental Psychology: General, 18*, 346–373.

McElree, B., & Dosher, B. A. (1993). Serial retrieval processes in the recovery of order information. *Journal of Experimental Psychology: General, 122*, 291–315.

Mitchell, K. J., Johnson, M. K., Raye, C. L., & D'Esposito, M. (2000). fMRI evidence of age-related hippocampal dysfunction in feature binding in working memory. *Cognitive Brain Research, 10*, 197–206.

Monsell, S. (1978). Recency, immediate recognition memory, and reaction time. *Cognitive Psychology, 10*, 465–501.

Öztekin, I., & Badre, D. (2011). Distributed patterns of brain activity that lead to forgetting. *Frontiers in Human Neuroscience, 5*. http://dx.doi.org/10.3389/fnhum.2011.00086.

Öztekin, I., Curtis, C. E., & McElree, B. (2009). The medial temporal lobe and the left inferior prefrontal cortex jointly support interference resolution in verbal working memory. *Journal of Cognitive Neuroscience, 21*, 1967–1979.

Öztekin, I., & McElree, B. (2007). Proactive interference slows recognition by eliminating fast assessments of familiarity. *Journal of Memory and Language, 57*, 126–149.

Öztekin, I., & McElree, B. (2010). Relationship between measures of working memory capacity and the time-course of short term memory retrieval and interference resolution. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 36*, 383–397.

Ratcliff, R. (1980). A note on modeling accumulation of information when the rate of accumulation changes over time. *Journal of Mathematical Psychology, 21*, 178–184.

Ratcliff, R. (2008). Modeling aging effects on two-choice tasks: Response signal and response time data. *Psychology and Aging, 23*, 900–916.

Reed, A. (1973). Speed–accuracy trade-off in recognition memory. *Science, 181*, 574–576.

Rouder, J. N., Speckman, P. L., Sun, D., Morey, R. D., & Iverson, J. (2009). Bayesian *t* tests for accepting and rejecting the null hypothesis. *Psychonomic Bulletin & Review, 16*, 225–237.

Ryma, B., & D'Esposito, M. (2000). Isolating the neural mechanisms of age-related changes in human working memory. *Nature Neuroscience, 3*, 509–515.

Salthouse, T. (1996). Processing speed theory of adult age differences in cognition. *Psychological Review, 103*, 403–428.

Salthouse, T. (2011). Consequences of age-related cognitive declines. *Annual Review of Psychology, 63*, 5.1–5.26.

Salthouse, T. (2000). Methodological assumptions in cognitive aging research. In F. I. M. Craik & T. Salthouse (Eds.), *Handbook of aging and cognition*. Hillsdale, NJ: Lawrence Erlbaum Associates.

Schmiedek, F., & Lindenberger, U. (2009). Interference and facilitation in spatial working memory: Age-associated differences in lure effects in the n-back paradigm. *Psychology and Aging, 24*, 203–210.

Smith, G. A., & Brewer, N. (1995). Slowness and age: Speed–accuracy mechanisms. *Psychology and Aging, 10*, 238–247.

Starns, J. J., & Ratcliff, R. (2010). The effects of aging on the speed–accuracy compromise: Boundary optimality in the diffusion model. *Psychology and Aging, 25*, 377–390.

Thompson-Schill, S. L., Jonides, J., Marshuetz, C., Smith, E. E., D'esposito, M., Kan, I. P., et al. (2002). Effects of frontal lobe damage on interference effects in working memory. *Cognitive, Affective, & Behavioral Neuroscience, 2*, 109–120.

Verhaeghen, P., & Basak, C. (2005). Aging and switching of the focus of attention in working memory: Results from a modified N-Back task. *Quarterly Journal of Experimental Psychology A, 58*, 134–154.

Verhaeghen, P., & Cerella, J. (2002). Aging, executive control, and attention. A review of meta-analyses. *Neuroscience and Biobehavioral Reviews, 26*, 849–857.

Verhaeghen, P., Cerella, J., & Basak, C. (2006). Aging, task complexity, and efficiency modes: The influence of working memory involvement on age differences in response times for verbal and visospatial tasks. *Aging, Neuropsychology, and Cognition, 13*, 254–280.

Wickelgren, W. A., Corbett, A. T., & Dosher, B. A. (1980). Priming and retrieval from short-term memory. *Journal of Verbal Learning and Verbal Behavior, 19*, 387–404.

Yonelinas, A. P. (2002). The nature of recollection and familiarity: A review of 30 years of research. *Journal of Memory and Language, 46*, 441–517.