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Original Research Report

Aging Slows Access to Temporal Information From Working Memory

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Abstract

Objectives: To evaluate the impact of aging on controlled memory search operations, we investigated the retrieval of temporal order information from working memory (WM).
Method: Young and older adults completed a relative judgments-of-recency (JOR) task. In each trial, participants studied 5-item lists and were presented with two probes from the study list. Participants indicated the probe that had appeared more recently in the study list.
Results: Analyses of accuracy data showed that young adults were more successful in correctly detecting the more recent probe compared with older adults. To evaluate the retrieval dynamics, we applied Hacker's (1980) serial scanning model on reaction time data. Results from the model fits revealed that older adults were slower in engaging in the serial memory search operations required to access temporal order information from WM.
Discussion: These findings suggest that this age-related impairment in a JOR task might arise from a slower deployment of controlled memory operations, such as serial search.

Keywords: Judgments of recency—Serial memory search—Temporal order memory—Working memory

It has been well established that aging causes a decline in performance across various memory tasks (for reviews see Craik & Jennings, 1992; Salthouse, 2011; Zacks, Hasher, & Li, 2000). Specifically, retrieval from working memory (WM) weakens with advancing age (see Hasher & Zacks, 1988 for a review). Earlier studies showed susceptibility of older adults to interference, such that memories compete with each other less effectively (e.g., Bowles & Salthouse, 2003; Healy, Hasher, & Campbell, 2013, Ikier & Hasher, 2006; Ikier, Yang, & Hasher, 2008; Öztekin, Güngör, & Badre, 2012). One debate regarding this decline in memory has been whether aging mainly affects controlled or automatic processes.

Although age-related decline in memory has been suggested to be global across processes (e.g., Benjamin, 2010; Hasher & Zacks, 1979; Salthouse, 1996), others argued that only the controlled processes are impaired in older adults (e.g., Hay & Jacoby, 1999; Jacoby, Debner, & Hay, 2001; Jennings & Jacoby, 1993). Earlier studies showed that aging is related with decreased ability to resolve interference caused by earlier occurrences of test items (e.g., Öztekin et al., 2012) or resembling items (e.g., Ikier et al., 2008). Interference builds up as the number or resemblance of the potential responses increase during retrieval (e.g., Watkins & Watkins, 1975). Resolving interference requires a more elaborate search through memory representations such as retrieval of contextual information. Thus, when older adults are impaired in such controlled processes, an automatic activation of the test probe can cause more incorrect responses compared with young adults.

Öztekin and colleagues (2012) showed that retrieval of contextual information was slowed by aging while the dynamics of the retrieval of item information was comparable across age groups in a recent negative (RN) probe paradigm (Monsell, 1978). In the RN probe task, participants are presented with a 5-item list and later tested on negative probes either drawn from the recent (RN) trials (e.g., last three trials) or from the distant trials (DNs). Previous studies investigating the time course of recognition judgments showed that participants produced higher false alarms for RN probes compared with DN probes. However, the decrease of false alarms in RN probes later at retrieval (e.g., Hintzman & Curran, 1994; McElree & Dosher, 1989, Öztekin & McElree, 2007, 2010) suggests that once participants accessed contextual information, they could accurately discriminate between negative and positive probes. That is, interference resulting from familiarity of an RN probe resolved as the diagnostic information was retrieved from memory. Öztekin and colleagues (2012) showed that the increase in the false alarm rates in RN trials against DN trials early at retrieval was comparable across age groups. This suggested that the activation of item information that relies on early/automatic familiarity based judgments was intact, whereas the time point when diagnostic information recovered was delayed for older adults. These findings demonstrated an age-related impairment in controlled processes that enabled retrieval of diagnostic episodic information.

Critically, these investigations point to a selective impact of aging on controlled operations in the presence of interference in the retrieval context. However, whether this impact can be generalized to other conditions that require cognitive control remains yet to be addressed. To further investigate and test the generalizability of the impact of aging on controlled processes, we assessed age-related changes in controlled memory operations in the absence of interference. To do so, we evaluated access to relational memory, which requires controlled memory search operations without manipulating interference in memory.

Investigations of memory retrieval have demonstrated that the nature of the to be retrieved information determines the type of retrieval operation engaged in memory. In particular, access to item representations in WM tends to be direct, without the need to search through irrelevant memories (Clark & Grounlund, 1996; McElree, 1998; 2006; McElree & Dosher, 1989; Öztekin & McElree, 2007). On the other hand, access to relational information (such as temporal or spatial order) requires a slower serial search through active memory representations (Chan, Ross, Earle, & Caplan, 2009; Hacker, 1980; Hockley, 1984; Liu, Chan, & Caplan, 2014; McElree & Dosher, 1993; Muter, 1979). More recent neuroimaging work (e.g., see Öztekin, McElree, Staresina, & Davachi, 2009) has complemented the earlier behavioral investigations in showing that the magnitude of neural activity in regions that support controlled memory retrieval (e.g., the ventrolateral prefrontal cortex) parametrically varies with the number of serial search operations carried out in order to access temporal order information from WM. As such, temporal order memory retrieval enables assessing age-related effects on controlled memory operations in a unique fashion in the absence of directly manipulating interference in memory, and hence can serve as a rigorous test for the generalizability of age-related effects on controlled processing beyond the widely established literature on interference resolution.

To this end, we employed a relative judgments-of-recency (JOR) task, where participants are presented with two studied items and asked to indicate the more recent probe. Thus, the familiarity of the probes would not be sufficient to correctly choose the more recent probe. Rather, behavioral (e.g., Hacker, 1980; McElree & Dosher, 1993; Muter, 1979) and neural (Öztekin et al., 2009) investigations of the JOR task have implicated that a controlled serial memory search strategy was deployed to recover the temporal order information.

Earlier models of JOR suggested that the recency of the probes was judged based on the strength of the memory traces of the test pairs. As the distance between the study positions (SPs) of the probes in a test pair increased, participants were more likely to indicate the more recent probe correctly (e.g., Yantema & Trask, 1963). Tzeng and Cotton (1980) explained this distance effect by retrieval of a third item, which is used as a cue to estimate the relative order within the test pair. For example, if the retrieved third item has been studied in a position between the items of the test pair, one could infer the position of the probes relative to the third item. Because the probability to retrieve an item between the probes increases as a function of the distance between the probes, participants would be more likely to respond correctly. McCormack (1982) showed that older adults benefited from the distance between probes as much as young adults did, despite an overall age-related decrease in performance. According to McCormack, this was observed due to the parallel comparison of the two probes and thus, the distance was not expected to produce an additional effect on the age-related decline in recency judgments. However, the distance explanation has been challenged by the studies that reported the reaction time (RT) of responses in addition to accuracy across the serial positions of the test pairs (Hacker, 1980; Hockley, 1984; McElree & Dosher, 1993; Muter, 1979, Öztekin et al., 2009).

If the recency judgments were based on the comparison between the two probes, the RT of correct responses should have decreased as the two probes were drawn from distant serial positions. However, earlier studies showed that distance did not have an effect on the RT of correct responses and that RT decreased only as a function of the recency of later probe (e.g., Hacker, 1980; Hockley, 1984; McElree & Dosher, 1993, Muter, 1979). McElree and Dosher (1993) further employed a response-deadline speed-accuracy tradeoff procedure in a JOR task, which provides unbiased measures of speed and accuracy by cueing participants to respond at given time points ranging from 60 ms to 3 s. This procedure reveals the retrieval functions that could be estimated from accuracy defined as a function of time allowed for retrieval. The results obtained from the retrieval functions of probe combinations showed that the time point at which retrieval exceeds chance delayed only as a function of the serial position of the later test probe. Specifically, recency judgments exceeded chance earlier for more recent later probes, whereas the recency of the earlier probe increased only the rate of retrieval. Together, these results indicated that participants were serially scanning the items in memory backwards, and the search terminates once the later test probe is reached. Accordingly, the recovery of temporal information in the JOR paradigm constitutes a controlled process that requires serial scanning and as a result, familiarity for the probes would not be adequate to correctly indicate the temporal order of the probes.

If aging selectively impairs controlled processes in general, regardless of whether interference is present, we should observe age-related slowing in serial search operations that are deployed to access temporal order information in the JOR task. To be able to provide a quantitatively rigorous comparison of these controlled serial memory search operations, across young and older adults, we employed Hacker's serial scan model (1980) as it allows to pinpoint the specific components (such as availability of a memory representation and the scanning rate for successive retrieval operations) that might differentiate the two groups' performance (but also see Brown, Preece, & Hulme, 2000; Howard, Shankar, Aue, & Criss, 2015 for more recent implementations of serial scanning mechanism). The reason we preferred this model over more recent models was that Hacker's model provided descriptive results with simple assumptions of backward serial scanning and allowed us to quantitatively assess the success and efficiency of the serial memory search operations across the two groups.

Method

Participants

Eighteen young adults from Koç University and sixteen older adults (60–75 years, M_{age} = 69, SD_{age} = 5.11, 14 women, 14 years of education on average) from the community participated in the study in exchange for monetary compensation. Older adults were screened for psychiatric and neurological conditions and the Mini-Mental State Examination (MMSE) was applied for cognitive assessment (M_{MMSE} = 27.33, SD_{MMSE} = 1.75). In Turkish population, the cutoff score 23/24 was found to have highest sensitivity and predictive values for the diagnosis of mild dementia (Gürgen, Ertan, Eker, Yaşar, & Engin, 2002). All of the older participants reported good health and were free of memory impairments.

Materials and Design

The stimulus set consisted of 18 consonants (b, c, d, f, g, h, j, k, l, m, n, p, r, s, t, v, y, z), which were presented in lower case during study and upper case as probe. In each trial, five consonants were randomly sampled and were presented as a study list, which was followed by a relative JOR task. The probes consisted of two items from the current study list, and the participants were required to indicate the probe that was presented most recently. Accordingly, there were 10 serial position combinations, which were tested randomly and with equal frequency.

Procedure

Figure 1 presents the sequence for an experimental trial. Each trial started with a centered fixation cross presented for 500 ms. Afterwards, each letter from the study list was displayed on the center of the screen one at a time for 500 ms immediately following the previous letter. At the end of the study list, a visual mask (&#&#&#&) was presented for 500 ms, displaying that the test would follow immediately. Participants used right and left keys to indicate their choice. Probes remained on the screen until the participants responded. The order of the probes was counterbalanced such that in half of the trials more recent probe was presented on the right. Each participant completed two sessions on two separate days, and each session consisted of four blocks of 140 trials, which total to 1,120 trials for each participant.

Results

Responses earlier than 300 ms and longer than 6 s were removed from the subsequent analysis. That corresponds to 7.5% and 3% of total responses for older and young

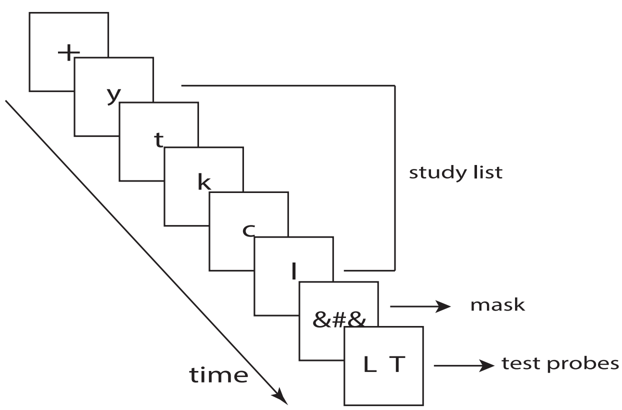

Figure 1. Illustration of a sample trial in a judgments-of-recency task. Following a fixation point, participants were presented with a study list of five letters. After the visual mask, two letters from the study list were displayed and participants indicated the more recent letter.

adults, respectively. For the remaining responses, accuracy and RT were analyzed, later were fit with Hacker's (1980) serial scanning model.

Accuracy

Figure 2A presents the average percent correct (PC) as a function of the SP of the later probe. Accuracy was greater for more recent probes, when SP of earlier probe was collapsed across conditions. A 2 (age: young, older) × 4 (SP of later probe: 2, 3, 4, and 5) mixed analysis of variance (ANOVA) on PC revealed a main effect of the SP of later probe, $F(3,96) = 25.39$, $p < .001$, $\eta_p^2 = .45$, with a significant linear trend, $F(1,32) = 37.86$, $p < .001$, $\eta_p^2 = .55$. Average PC of older adults ($M = .84$, $SD = .03$) was significantly lower than the average PC of young adults ($M = .91$, $SD = .07$), $F(1,32) = 5.49$, $p = .025$, $\eta_p^2 = .15$, showing an overall age-related decline in temporal order retrieval. Decrease in accuracy for probes that were studied in earlier positions was significantly greater for older adults compared with young adults, $F(3,96) = 6.73$, $p < .001$, $\eta_p^2 = .17$, suggesting that retrieval of temporal information weakens by age as the probes are drawn from earlier SPs.

Further analysis on PC as a function of SP of the earlier probes (SP-E) also revealed a decline in accuracy as the difference between the SPs of the test pairs decreased. Figure 3 presents the average PC as a function of the SP of all test probe combinations. Holding the later probe (SP-R) constant, a 2 (age: young, older) × 4 (SP-E: 1, 2, 3, 4) mixed ANOVA on PC of SP-R 5 revealed a main effect of SP-E, $F(3,96) = 13.75$, $p < .001$, $\eta_p^2 = .30$. Neither the age main effect nor the interaction of age by SP-E reached significance, suggesting that correctly choosing the later probe is comparable across age groups, just as the rate of decline in accuracy as a function of the SP-E. This finding shows that when recovery of temporal information is not effortful but automatic, presumably due to availability of the most recent item in focal attention (McElree, 2001, 2006; McElree & Dosher, 1989; Öztekin & McElree, 2007; 2010; Öztekin et al., 2012), older adults do not show a decline in their performance. However, when the later probe was drawn from SP-R 4, accuracy decreased significantly as a function of age. A 2 (age) × 3 (SP-E: 1, 2, 3) mixed ANOVA on PC revealed a main age effect, $F(1,32) = 5.59$, $p = .02$, $\eta_p^2 = .15$, where younger adults ($M = .92$, $SD = .06$) performed better than older adults ($M = .85$, $SD = .11$). Similar to the findings from SP-R 5, accuracy decreased significantly as the SP-E increased, $F(2,64) = 27.43$, $p < .001$, $\eta_p^2 = .46$, and this decrease was more prominent for older adults, $F(2,64) = 5.65$, $p < .01$, $\eta_p^2 = .15$. Finally, a 2 (age) × 2 (SP: 1, 2) mixed ANOVA on PC of SP-R 3 revealed a main age effect, $F(1,32) = 11.11$, $p < .01$, $\eta_p^2 = .26$, showing that overall PC of SP-R 3 was significantly lower for older adults ($M = .78$, $SD = .13$) compared with younger adults ($M = .90$, $SD = .08$). PC of the SP13 condition was significantly greater than the PC of the SP23 condition, $F(1,32) = 22.22$, $p < .001$, $\eta_p^2 = .41$, which reveals a SP-E effect similar to that observed in test pairs sampled from later SPs. This effect was also more pronounced for older adults, $F(1,32) = 5.11$, $p = .03$, $\eta_p^2 = .14$.

Overall, these results suggest that older adults are impaired in recovery of temporal order memory when retrieval is effortful and controlled. In contrast, the two groups did not differ in their memory performance when the test probe matched the contents of focal attention, a case where the memory judgment can be executed without the need to engage in controlled retrieval operations. To

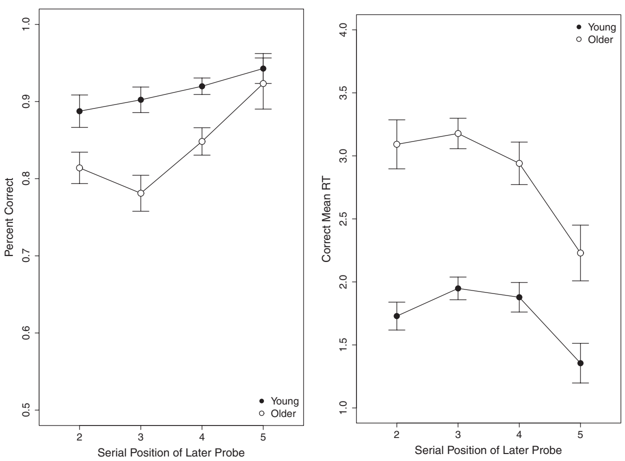

Figure 2. (**A**) Percent correct and (**B**) mean reaction time (in seconds) for correct responses plotted as a function of serial position of the later probe. Error bars are the 95% within-subjects confidence intervals. For a given later probe, earlier serial positions are averaged. Average percent correct is lower for older adults compared with younger adults, and older adults responded slower on average compared with younger adults.

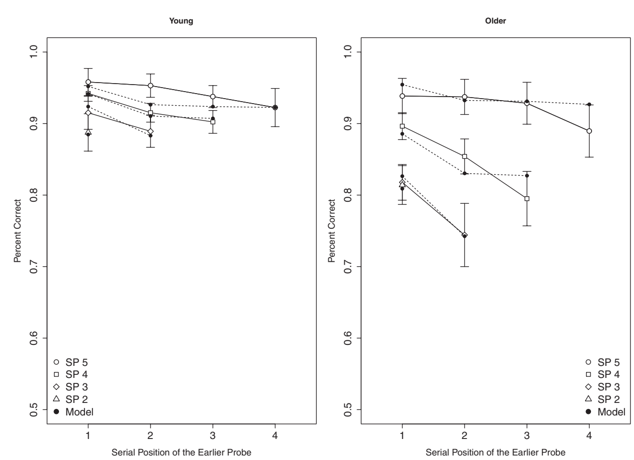

Figure 3. Percent correct plotted as a function of serial position of the earlier probe. Separate lines represent conditions for the more recent probe. Error bars are the 95% within-subjects confidence intervals. Accuracy decreased as a function of serial position of the later probe and also as a function of the earlier probe. The rate of the decrease was more prominent for older adults. (**A**) Younger adults, $r2 = .91$, $\chi 2(9) = 0.0005$, $p > .99$. (**B**) Older adults, $r^2 = .93$, $\chi 2 = 0.003$, $p > .99$.

further assess group-related differences in controlled serial memory search, we next present the mean RT of correct responses, which directly measures the time required for the retrieval of temporal information in a JOR task. To quantitatively model the age-related changes in the search rate, we applied Hacker's model and evaluated the best fitting parameters.

Reaction Time

Figure 2B depicts the mean RT of correct responses as a function of the SP of the later test probe. A 2 (age: young, older) × 4 (SP-R: 2, 3, 4, and 5) mixed ANOVA showed that the mean RT lengthened as the SP-R decreased, $F(3,96) = 34.89$, $p < .001$, $\eta_p^2 = .52$. The significant quadratic component, $F(1,32) = 56.96$, $p < .001$, $\eta_p^2 = .64$, also suggests that the slowing of responses that were drawn from earlier SPs was nonlinear as was observed in prior studies (McElree & Dosher, 1993; Liu et al., 2014) and was also predicted by Hacker's model due to differences in item availability in memory. Older adults (M = 2.86 s, SEM = 0.12) responded slower than young adults (M = 1.73 s, SEM = 0.11), $F(1,32) = 48.90$, $p < .001$, $\eta_p^2 = .60$. A significant age by SP interaction revealed that older adults required more time to correctly indicate the more recent probe as the SP of the probe decreased, $F(3,96) = 3.33$, $p < .03$, $\eta_p^2 = .09$. Further contrasts showed that the time to retrieve the temporal information of the more recent probes extended, $F(1,32) = 5.67$, $p < .03$, $\eta_p^2 = .15$, indicating longer search time for pairs sampled from earlier SPs for older adults compared with younger adults.

The effect of the SP of the earlier probe (SP-E) was investigated by holding the SP of the later probe (SP-R) constant across conditions. In contrast to the results from the accuracy data, the SP-E did not reveal a meaningful effect on the RT data (Figure 4), suggesting that search time is not a direct function of the earlier probe in a JOR task. Although, a 2 (age: young, older) × 4 (SP-E: 1, 2, 3, 4) mixed ANOVA on mean RT of SP-R 5 revealed a main effect of SP-E, $F(3,96) = 3,46$, $p = .02$, $\eta_p^2 = .09$, the linear trend was not significant. That is, the main effect was not due to a systematic slowing of responses as a function of the distance between the probes. It is important to mention that this is not consistent with the strength-based models, which predict distance effects in the RT, but more in line with the serial scan models that predict RT to vary as a function of the SP-R only. Further contrasts showed that only the mean RT of SP15 was significantly faster than the rest of the probes when the later probe is hold constant at SP 5, $F(1,32) = 6.58$, $p = .015$, $\eta_p^2 = .1$. Consistent with the findings reported earlier, the mean RT of older adults (M = 2.23 s, SEM = 0.13) was significantly longer than that of younger adults (M = 1.35 s, SEM = 0.13), $F(1,32) = 21.94$, $p < .001$, $\eta_p^2 = .41$.

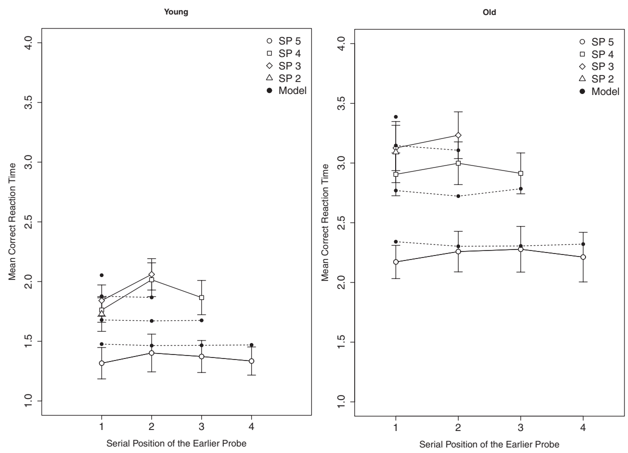

Figure 4. Mean reaction time of correct responses (in seconds) plotted as a function of serial position of the earlier probe. Separate lines represent conditions for the more recent probe. Retrieval of temporal information slows as a function of serial position of the later probe. Older adults were slower in recency judgments compared with younger adults. Error bars are the 95% within-subjects confidence intervals. (**A**) Younger adults, $r2$ = .52, $\chi 2(9) = 0.21$, $p > .99$. (**B**) Older adults, $r2$ = .85, $\chi 2(9) = 0.09$, $p > .99$.

Similar findings were observed when the later probe was held constant at SP-R 4. A 2 (age) × 3 (SP-E: 1, 2, 3) mixed ANOVA on mean RT of correctly selecting SP-R 4 as the most recent probe revealed a significant main effect of age, $F(1,32) = 30.94$, $p < .002$, $\eta_p^2 = .49$, where younger adults (M = 1.88 s, SEM = 0.13) responded faster than older adults (M = 2.94 s, SD = .14). The main effect of SP-E was significant, $F(2,64) = 8.26$, $p < .01$, $\eta_p^2 = .20$, whereas the linear effect failed to reach a significant level. Specifically, only the responses to pairs with SP24 were meaningfully slower than those of SP14, $F(1,32) = 28.12$, $p < .001$, $\eta_p^2 = .48$, and SP13, $F(1,32) = 7.06$, $p < .02$, $\eta_p^2 = .18$. Similar to the earlier findings, these data are consistent with the serial scanning model.

A 2 (age) × 2 (SP: 1, 2) mixed ANOVA on the mean correct RT to test pairs drawn from SP-R 3 revealed a main effect of age, $F(1,32) = 42.56$, $p < .001$, $\eta_p^2 = .57$, showing that older adults (M = 3.18 s, SEM = 0.14) were significantly slower than young adults (M = 1.95 s, SEM = 0.14), and a main effect of SP-E, $F(1,32) = 13.90$, $p < .01$, $\eta_p^2 = .30$, showing that the RT of SP31 was shorter than that of SP32. However, this distance effect on RT was not observed in other conditions, suggesting that the distance effect in the current JOR task is not consistent.

To summarize, these results indicate that older adults required longer scanning time to retrieve the temporal order in the relative JOR task. To further describe the impact of aging on serial memory scanning, we further fit Hacker's serial scanning model with the accuracy and the mean RT data.

Hacker's (1980) Model

The model assumes that participants examine the items in memory through serial backward scanning, and scanning terminates once the most recent probe is reached. In the model, the probability that an item is available in memory (represented with the parameter *a*) decreases when new items enter into memory. Hacker (1980) defined the RT for choosing the correct probe based on the time required for backward scanning and guessing and the base time. When the more recent probe is available, each item that is presented later than the more recent probe is scanned serially for the duration identified by the *s* parameter, which is the scanning time. If neither probe is available, scanning does not yield a match. In that case, the model assumes an exhaustive search that ends with a random selection of the correct probe. Consequently, the items in memory other than the current probes are scanned and search finally ends with a guess. In order to account for the time required for guessing, the parameter *g* is added to the mean RT of the correct responses when the correct probe is identified randomly. Finally, the base time (*b*) is added as the time required for processes such as motor responses (see Supplementary Material for the details of the model).

Table 1 presents the best fitting parameter estimates of averaged data and average parameter estimates from the fits of individual participants. Comparisons between age groups showed that the availability of items studied in SP 5 were statistically comparable across age groups. However, as the SP decreases, the age-related differences in availability parameters becomes significant, (SP 4: $t(18.27) = -2.60$, $p < .02$; SP 3: $t(19.64) = -3.54$, $p < .01$; SP 2: $t(18.82) = -2.71$, $p < .02$), showing that the items studied earlier than SP 5 were less available for older adults. Additionally, the model fitting criteria (Akaike information criterion [AIC] and Bayesian information criterion [BIC]) preferred the model that forces a constant value for the availability of the most recent item in the study list as the best fitting model for the average data (see Supplementary Material for the details of the model fitting routine). These results are not surprising, as the analyses on accuracy showed that the PC was comparable across age groups when the later probe was drawn from SP 5 while accuracy decreased faster for older adults for the later probe drawn from earlier serial positions. More importantly, RT fits allow evaluating the efficiency of the controlled memory search operations.

The best fitting values further revealed a general age-related slowing, as the base time for older adults was extended compared with that of young adults, $t(27.36) = -2.74$, $p < .02$, $d = 0.96$. More importantly, the mean scan time was longer for older adults compared with young adults, $t(21.04) = -3.79$, $p < .01$, $d = 1.35$. That is, when general slowing of older adults was taken into account as the base time, older adults took longer to scan serially backwards. Finally, guess time was comparable across age groups, $t(31.41) = 0.62$, suggesting that when serial search did not end with a match, aging did not have an impact on guessing time. To further evaluate the implications of the individual model fits, we fit four models to the mean correct RT data that are averaged across participants. These four models were (i) the full model, in which all the parameters were allowed to vary across age groups; (ii) a base rate and scanning model, in which only the *g* parameter was constant across age groups; (iii) a guessing model, in which both the *b* and the *s* parameters were constant across age groups; (iv) and finally, a baseline model, in which both the *g* and the *s* parameters were constant across age groups. The model fit criteria (AIC and BIC) values preferred the second model as the best fitting model (see Supplementary Material for the model fitting procedure and model fit criteria values for each model). These results further strengthen the contention that older adults slowed both in their motor responses and in their scanning time during temporal order memory retrieval.

When the availability parameter values from individual fits are examined, especially for older adults, one can observe that some of the participants show a dramatic decrease in the availability of items that were presented in less recent positions. That dramatic decrease in some older participants might suggest variability in the WM capacity (WMC) related to aging (e.g., Verhaeghen, 2014). In order to address this potential impact of WMC on scanning time, we divided older participants into two groups based on the availability parameter values from the model fits to their individual mean PC data (see Table 1 for the group

Table 1. Parameter Estimates From the Fits of Hacker's (1980) Model

Age group	a_1	a_2	a_3	a_4	a_5	b	s	g
Young (fit to average data)	.17	.80	.87	.90	.91	1.24	0.22	0.10
Young (average parameters)	.33	.83	.87	.90	.93	1.17	0.25	0.52
Young (*SE* of parameters)	.09	.03	.02	.02	.01	0.12	0.03	0.19
Older (fit to average data)	.12	.66	.69	.79	.91	1.81	0.49	0.10
Older (average parameters)	.14	.64	.65	.77	.88	1.73	0.54	0.69
Old (*SE* of parameters)	.07	.07	.06	.05	.04	0.17	0.07	0.21
Old (high WMC)	.26	.87	.84	.91	.96	1.98	0.43	1.05
Old (low WMC)	.02	.40	.46	.62	.81	1.49	0.65	0.34

Notes: a_i is the availability parameter for the item with the serial position *i*. Greater values indicate greater availability of the item *i*. *b* is the base time in seconds, *s* is the scanning time in seconds, and *g* is the guessing time in seconds.
WMC = working memory capacity.

parameter values). Later, the RT parameters were compared across the WMC groups, and the results did not reveal a significant effect (b, $t(12.04) = 1.51$; s, $t(13.97) = -1.78$; g, $t(8.92) = 1.84$), suggesting that the differences in the availability parameters do not predict a difference across RT parameters. This finding shows that the variability in WMC observed in older adults did not contribute to the age-related differences in the ability of accessing temporal order information.

In summary, a self-terminating serial scanning model effectively described the decrease in accuracy along with an increase in RT when the more recent probe is drawn from earlier serial positions (e.g., Chan et al., 2009; Hacker, 1980; Liu et al., 2014; McElree & Dosher, 1993; Öztekin et al., 2009). Results further showed that the age-related decrement in correctly indicating the more recent probe was associated with the slowing of correct responses. This slowing can be explained due to impaired controlled memory search processes that are required to access temporal order information from memory.

Discussion

In a relative JOR task, participants were required to retrieve the temporal relational information of the two test probes and use that information to select the probe that was studied more recently. As was reported in previous studies (Hacker, 1980; McElree & Dosher, 1993; Öztekin et al., 2009), correctly choosing the more recent probe decreased as a function of the recency of the more recent probe. That is, as the probes were drawn from earlier serial positions, frequency of correct responses declined. Results from a comparison between the age groups showed that, this recency effect was more prominent for older adults, suggesting that the relative recency judgments were impaired with advancing age. In other words, older adults showed a decline in the controlled serial search operations that are required to access temporal order information from WM.

Analysis of the RT data showed that both young and older adults employed a serial scan retrieval operation through the study list in backwards in order to assess the recency of the probes. This has been observed as faster responses when the later probe was drawn from more recent serial positions. Importantly, recency of the earlier serial position did not have an effect on the RT data. This pattern of results has been explained by serial search models (Hacker, 1980), in which the search terminates when either probe matches with an available item in memory. Further comparisons showed that the slowing of RT as a function of later probe was more prominent for older adults, indicating that aging slows the controlled serial search operations, which could not be explained by a general slowing. In contrast to the group differences observed when controlled serial memory search was required, the two groups did not differ when memory judgments could be executed without the need to engage in controlled retrieval, namely for when the test probe contained the most recently studied item, a case where the probe can be automatically matched to the contents of focal attention (e.g., McElree & Dosher, 1989; Öztekin et al., 2009; Öztekin, Davachi, & McElree, 2010).

Quantitative modeling comparison of the two groups' accuracy and RT data further implicated two important conclusions. First, the availability parameter of the items in memory estimated from the PC data decreased as the lag between study and test increased, and the items that were studied earlier in the list were less available for older adults. These findings are consistent with earlier studies showing that memory performance decreased more dramatically for older adults when the lag between study and test increased in a continuous recognition memory task (e.g., Kılıç, Hoyer, & Howard, 2013). Balota, Duchek, and Paullin (1989) also showed that older adults were impaired in contextual binding and that slower drift in context resulted in a less effective retrieval of context (see also Howard, Kahana, & Wingfield, 2006). Second, the scanning rate estimated from the RT data was slower for older adults (see also, Ferraro & Balota, 1999) even when guessing time and slowing due to motor responses were controlled. Taken together, these results suggest that with advancing age, in addition to items becoming less available in memory, critically, controlled serial memory search operations are executed slower, leading to a decline in the ability to retrieve temporal information.

The application of Hacker's model showed that the guessing time parameter did not reliably differ across age groups, restricting the age-related slowing to sensory-motor processes and scanning time. However, some studies have also suggested that cognitive slowing in aging is more general and is not task specific (Cerella, 1985). For instance, Lange and Verhaeghen (2009) recently argued that the slowing in memory search might not be particular to memory but is a result of slowing in sensory-motor and decision processes. In Lange and Verhaeghen's study, digits were displayed on the screen one at a time from left to right and from top to bottom in reading order. Later, participants were presented with a display cueing a backward, forward, or random search. Two tasks followed the cue display: recognition memory task and a magnitude judgment task. For the recognition memory task, participants were required to decide whether the test probe was presented in the identical location as was in study list, and for the magnitude judgment task, they were asked to decide whether the probe digit was smaller or greater than digit 5. By employing hierarchical statistical analyses, they showed that the scanning rate across the two tasks did not differ while there was a significant slowing for older adults in both tasks. They concluded that slowing of scanning rate was not specific to memory scanning but rather due to a global slowing caused by sensory-motor processes. However, different from the current study, the recognition task in Lange and Verhaeghen's study required recovery of item information that is cued with a spatial location. Thus, the memory judgments required in Lange and Verhaeghen's study might not have assessed the same controlled demands as the retrieval of temporal relational information in the JOR task. This is also consistent with previous research that has dissociated access to item versus temporal order memory representations both behaviorally (e.g., McElree & Dosher, 1989) and neurally (Öztekin et al., 2009) in showing that the former can be accessed directly, whereas the latter requires slower, controlled retrieval operations.

Another important finding of the current study indicated that aging impaired retrieval of items that were outside of focal attention (McElree, 1998, 2001, 2006, Öztekin et al., 2009). Accuracy did not decrease by aging for the test probes that consisted of the most recent item. That is because the most recent item was still in focal attention, and thus the recency judgment was made by automatic processes rather than a serial search that required the retrieval of temporal information. The availability parameter value for the most recent item also did not differ across age groups, suggesting that age-related decline was not observed for the contents of focal attention and thus, aging did not impact the automatic activation of the most recent probe. Age-related effects were rather selectively observed for controlled memory operations.

The current findings showed that older adults were impaired in controlled memory search operations even in the absence of interference induced by the task (e.g., Öztekin et al., 2012). However, one potential concern could be that the current set of results does not completely rule out the possibility of interference-related slowing in aging in the present investigation. More specifically, the test probes in the JOR task were sampled from a list of 18 letters. That resulted in presentation of the same letters across multiple trials. Thus, one could be concerned that interference from earlier trials could have slowed participants in general and because older adults are more susceptible to interference, their slowing was inflated by interference. In order to address this potential concern, we conducted a set of additional analyses that targeted interference-related changes in performance. More specifically, when the trials that consisted of probe letters that were presented in the immediately preceding two trials were eliminated from the data set, neither mean accuracy nor mean correct RT differed qualitatively from the dependent variables of the original data set. Similarly, another subsequent analysis showed that the number of preceding trials did not decrease accuracy and did not increase RT over the course of experiment sessions. For instance, when trials were binned into blocks of four trials, and plotted as a function of the test blocks, the slope of the linear trend did not differ reliably from 0. Although these additional analyses strengthen our conclusion that slowing in the ability to access temporal information could be generalized to controlled processes, future research further investigating experimental settings in which interference is fully controlled (e.g., using study material that does not repeat across the entire experiment) could provide additional insight.

In conclusion, the age-related impairment in controlled memory search operations observed in the current task further suggests that the impairment observed in previous research investigating age-related effects on interference resolution (e.g., Bowles & Salthouse, 2003; Healy et al., 2013, Ikier & Hasher, 2006; Ikier et al., 2008; Öztekin et al., 2012) could be generalized to controlled processes deployed in the absence of interference. The current investigation provided a demonstration to this fact during relational memory retrieval, namely temporal order information. The comparable memory performance for the most recently studied item that resides in the current focal of attention further showed that automatic processes are not impaired. Aging selectively impacted controlled, serial memory search.

Supplementary Material

Supplementary data is available at *The Journals of Gerontology, Series B: Psychological Sciences and Social Sciences* online.

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