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Working memory capacity and controlled serial memory search

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ABSTRACT

The speed–accuracy trade-off (SAT) procedure was used to investigate the relationship between working memory capacity (WMC) and the dynamics of temporal order memory retrieval. High- and low-span participants (HSs, LSs) studied sequentially presented five-item lists, followed by two probes from the study list. Participants indicated the more recent probe. Overall, accuracy was higher for HSs compared to LSs. Crucially, in contrast to previous investigations that observed no impact of WMC on speed of access to item information in memory (e.g., Öztekin & McElree, 2010), recovery of temporal order memory was slower for LSs. While accessing an item's representation in memory can be direct, recovery of relational information such as temporal order information requires a more controlled serial memory search. Collectively, these data indicate that WMC effects are particularly prominent during high demands of cognitive control, such as serial search operations necessary to access temporal order information from memory.

1. Introduction

Individual variations in working memory capacity (WMC) correlate with performance in a broad range of complex cognitive activities such as reading comprehension (e.g., Daneman & Carpenter, 1980; Kane & McVay, 2012), logical reasoning (Kyllonen & Christal, 1990), drawing inferences (Linderholm, 2002) and retrieving relevant information from memory (Öztekin & McElree, 2010). WMC is also found to be a good predictor of general fluid intelligence (Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Conway, Kane, & Engle, 2003) and Scholastic Aptitude Test scores (Engle, Tuholski, Laughlin, & Conway, 1999). In addition to WMC differences predicting performance on cognitive function, WM deficits have been found to be related to psychological disorders such as schizophrenia, attention deficit disorder, and Alzheimer's disease as well (Ilkowska & Engle, 2010).

WMC can be measured by complex span (CS) tasks, and individual differences can then be examined by comparing performance of individual scoring in the upper and lower ends: high span individuals (HSs), who perform well in CS tasks and score in the upper quartile, and low span individuals (LSs), whose scores fall within the lower quartile (e.g., Kane & Engle, 2003; also see Redick et al., 2012 on the use of CS tasks to measure WMC). Numerous studies have compared the performance of HSs and LSs across multiple various tasks. Differences in performance have been noted even on tasks without an explicit memory component such as the dichotic listening task (Conway, Cowan, & Bunting, 2001), Stroop (Kane & Engle, 2003), the antisaccade (Kane, Bleckley, Conway, & Engle, 2001), flanker (Redick & Engle, 2006), and go/no-go tasks (Redick, Calvo, Gay, & Engle, 2011). CS tasks operationally measure the number of items that can be recalled, however, it is thought to tap a domain-general construct that constitutes the strong correlation between CS performance and cognition (Broadway, Redick, & Engle, 2010).

It is crucial to note that these differences emerge under certain conditions when controlled attention is required to actively maintain task relevant information, especially in situations where there is substantial external and internal distraction. Theories that base attentional control as the underlying factor for WMC differences posit that the ability to maintain goal-relevant representations in the face of distraction requires successful and controlled allocation of attention (Engle, 2002, 2010; Engle & Kane, 2004). Accordingly, the controlled attention framework suggests that HSs are better at allocating their attention on goal-relevant information than LSs. Critically, this theory predicts that LSs perform worse in the presence of interference and distraction, but perform comparable in its absence, indicating that WMC does not reflect a general deficit in cognitive processing. In this respect, attentional control determines the predictive power of WMC on cognitive tasks.

More recently, studies considered WMC related effects using memory tasks that specifically measured retrieval differences

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across the high and low span groups. Unsworth and Engle (2007) proposed a ‘‘dual-component framework” for explaining individual differences in WMC, and suggested that differences between HSs and LSs arise from the maintenance of items in an accessible state and retrieval of items that are not in accessible state via controlled/strategic retrieval. Within this framework, while attentional control is still an important component, controlled retrieval is also an essential determinant of WMC (Unsworth & Spillers, 2010). Attentional control is required to maintain representations in an active state and successful allocation of attention to goal-relevant information protects the memory contents from interfering material. If external or internal distractors capture attention, the maintenance/availability of the representations would be affected. In this case, a controlled search through memory representations would be required to recover the items that were not maintained in an accessible state. Successful retrieval of items may then rely on the encoding quality, the ability to reinstate the context at retrieval, and delimit the search set to target items via excluding the interfering items (Unsworth & Engle, 2007). Accordingly, in this framework individual differences in controlled attention and controlled retrieval jointly explain the individual variations in WMC. While a majority of studies investigating individual differences in WMC focused on maintenance operations, the impact of WMC on controlled retrieval of task-relevant information is a relatively newly attended area of research that promises to improve our understanding regarding the relationship between WMC and cognition.

How does WMC affect the dynamics of memory retrieval? Öztekin and McElree (2010) tested HSs and LSs with a modified version of Sternberg probe recognition task. Because the traditional probe recognition task requires access to only item representations, this can be achieved via direct access to the relevant representation, without the necessity to engage in a search through memory representations (e.g., see McElree, 2006 for an overview). However, in the modified version (Monsell, 1978) on particular trials proactive interference was induced by selecting a lure from previous study list. Due to the high residual familiarity of this lure, successful resolution of PI necessitates controlled processing, such as controlled episodic memory retrieval (e.g., Badre & Wagner, 2005; Öztekin & McElree, 2007; Oztekin, Curtis, & McElree, 2009; see Jonides & Nee, 2006 for review). Their findings showed although HSs exhibited higher accuracy than LSs, retrieval speed differences depended on whether the trials required controlled processing or not. Namely, LSs' speed of directly accessing the items from their memory was at similar levels with HSs in the absence of interference. However, when there was interference in the retrieval context, LSs were delayed in initiating the controlled retrieval operations that resolve interference in memory. Accordingly the results suggested that, with respect to access to item information in memory, WMC affected speed of processing only when the task demanded controlled retrieval operations due to the presence of interference in the retrieval context.

Manipulating interference in memory is one way to manipulate demands on controlled retrieval, and a well-established determinant of WMC related changes in cognitive performance (e.g., Kane & Engle, 2000; Öztekin & McElree, 2010). Another variable that determines the nature of retrieval operations is the type of information that needs to be accessed from memory. Specifically, access to item representations in memory can be achieved via a direct access mechanism, without the need to search through irrelevant memory representations (see McElree, 2006 for a review). Access to relational information (e.g., temporal or spatial order) on the other hand requires a slower, more controlled serial memory search, namely, controlled retrieval (Hacker, 1980; McElree & Dosher, 1993; Öztekin, McElree, Staresina, & Davachi, 2008). The present study aimed to assess the impact of WMC on the dynamics of retrieval during access to relational- namely temporal order-information from working memory. Critically, this approach enabled assessing WMC related changes in controlled memory retrieval without directly manipulating the presence of distractors or interference in the retrieval context.

A widely used task to measure temporal order memory is the judgments of recency (JOR) paradigm (Hacker, 1980; Liu, Chan, & Caplan, 2014; McElree & Dosher, 1993; Muter, 1979; Öztekin et al., 2008) in which participants are presented with a study list and asked to judge the relative recency of two test probes (e.g., which item appeared later in the study list). This task requires serial memory search operations, the efficiency of which would depend on both the maintenance of the items in an active state and executing the successive retrieval of items in order. Consequently, studying access to temporal order information from working memory can provide further insight with respect to how WMC modulates controlled retrieval.

Earlier work investigating the factors that modulate performance in the JOR task suggested that participants make strength-based judgments (Yntema & Trask, 1963). According to this hypothesis, the more recent probes evoke more strength than the less recent probes. Therefore, by making a strength comparison, it is possible to decide which item was presented more recently in the study list. In this case, the distance between the study positions of the test probes would determine the memory performance. The more distant the tested items were to each other, the better the memory performance would be (i.e., faster response times or higher accuracy). For instance, judging the recency of the 5th and 4th item in the study list would be easier than judging the recency of the 5th and 1st item as the strength level of the two items would be more similar in the former than the latter. As a consequence, strength based models predict performance to be modulated by the distance between the earlier and later probes. This pattern, however, was not observed with further investigations of the recovery of temporal order information (Hacker, 1980; Hockley, 1984; McElree & Dosher, 1993; Muter, 1979; Öztekin et al., 2008). What affected the memory performance was not the distance between the tested items but the recency of the later probe- the test probe which was presented later in the study list. Memory performance significantly increased (decreased RTs and increased accuracy) when the later probe was drawn from more recent positions in the study list, while earlier probe did not have an effect on the performance. These findings implicated that participants retrieved temporal order information via a serial search/scan through study list items.

A serial search through memory representations would operate as follows; participants start searching the studied items from the first (forward scan) or last (backwards scan) item in serial order, and the search is terminated upon reaching the later probe. For instance, in a backwards scan, the search will start with the last studied item, and the duration of the scan would depend on the study position of the later probe. The more recent the later probe, the shorter the scan would last. McElree and Dosher (1993) tested the serial memory search/scan hypothesis by employing the speed-accuracy trade-off (SAT) procedure to the JOR task with a 6-item study list (SAT procedure is explained in detail in the section below). When all combinations of all-pairwise study positions (e.g., 2-1, 3-1, 4-1, 4-2, 4-3, 5-1, 5-2, etc.) were fitted with SAT retrieval functions, the observed pattern was in support for a serial scan process. Asymptotic accuracy, and retrieval speed (with more drastic differences in the intercept parameter) increased as the later probe was from the more recent positions. Accordingly, it has been suggested that the cognitive strategy that is used to recover temporal order information was a self-terminating backwards serial scan.

1.1. Present study

In the current investigation, we tested HSs and LSs with a JOR task, using the SAT procedure. The aim of the study was to reveal whether HSs and LSs differ at recovering temporal order information, which typically requires an effortful controlled search through memory representations. To begin with, HSs and LSs might select different strategies while recovering temporal order information, which would be reflected in the retrieval dynamics measurements. Strategy selection has been suggested as a partial explanation to performance differences between HS and LS individuals (Cokely, Kelley, & Gilchrist, 2006; McNamara & Scott, 2001; Schelble, Therriault, & Miller, 2011). If HSs and LSs use different retrieval strategies we might observe differences in the retrieval dynamics across test probes as a function of study position; i.e., LSs using the distance between the items as a base for their judgments (the accuracy and retrieval speed will change as a function of the distance between the probes) and HSs using self-terminating serial scan (the performance will depend on the recency of the later probe). Alternatively, HSs and LSs might adapt the same strategy but LSs might not implement it as efficiently as HSs. If LSs were less efficient than HSs during the implementation of the strategy, the accessibility of temporal order information would be slower, which can be tracked by the retrieval speed estimates in the SAT functions, namely the rate of information accrual or the intercept, the time when information first becomes available. This might be due to the inability to generate and effectively use cues to delimit the search to relevant items. In particular, temporal order memory retrieval requires a serial search that demands more controlled processing than recognition memory judgments. As such, the time-course analysis of recovery of recency judgments can provide us more detailed information for the generalizability of variations in controlled processing as a function of WMC.

1.2. SAT procedure

SAT is a variation of a deadline method in which subjects are signaled to respond at variable intervals following the onset of each test item, allowing a time course function that measures the growth of retrieval as a function of processing time. An important advantage of SAT over traditional paradigms is that it provides conjoint measures of the accuracy and speed of processing, independent of each other. This is in contrast to response time measures derived from traditional tasks, which cannot provide pure measures of processing speed because they are subject to speed–accuracy trade-offs (McElree, 2006). The SAT procedure can be used to measure the accuracy and speed of processing in a wide range of cognitive processes, including sentence comprehension (Foraker & McElree, 2007; Martin & McElree, 2009; McElree, Foraker, & Dyer, 2003), visual attention (e.g., Carrasco, McElree, Denisova, & Giordano, 2003; McElree & Carrasco, 1999), and memory (reviewed in McElree, 2006). Application of SAT in the memory domain has largely focused on investigations of item recognition (e.g., Benjamin & Bjork, 2000; Hintzman & Curran, 1994; McElree & Dosher, 1989; Öztekin & McElree, 2007; Wickelgren, Corbett, & Dosher, 1980), although it has been implemented to characterize relational memory processes as well (e.g., spatial order; Gronlund, Edwards, & Ohrt, 1997; n-back discriminations; McElree, 2001; and temporal order; McElree & Dosher, 1993).

Sampling the full time-course of retrieval also 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 (Hintzman & Curran, 1994; McElree, Dolan, & Jacoby, 1999; Öztekin & McElree, 2007, 2010). Accordingly, the SAT procedure enables independent estimation of both the timing and magnitude of the output of these processes via quantitative modeling routines (see Fig. 1 for illustration and description of a hypothetical SAT function).

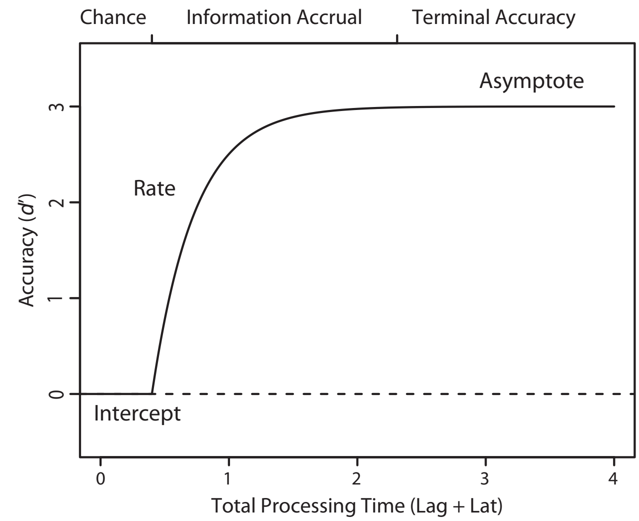

Fig. 1. Illustration of a hypothetical SAT function that shows how accuracy (in d' units) grows over processing time (in seconds). The SAT curve reflects three phases: A period where performance is at chance (the departing point in time from chance is marked by the intercept parameter), followed by a 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).

2. Method

2.1. Participants

Five-hundred and ninety adults were screened using the automated operation span task (Unsworth, Heitz, Schrock, & Engle, 2005) to attain WMC measures. 12 High Span (HS) individuals (upper quartile of the sample) and 12 Low Span individuals (lower quartile of the sample) participated in the experiment. Data from one participant of Low Span group, who failed to comply with the SAT procedure, was excluded from analyses, leaving 11 participants for the Low Span (LS) group. For the screening session, all participants received credit for Introduction to Psychology class via the Koç University subject pool system. For the experimental sessions, participants were compensated for their time.

2.2. Design and stimuli

2.2.1. Operation span task

Participants were asked to solve math operations while trying to maintain a set of letters (F, H, J, K, L, N, P, R, S, T, Y) in their working memory. After each math operation, a letter was presented on the screen for 1000 ms. The list-length was varied from 3 to 7. At the test phase, participants recalled the order of the presented letters by marking the letters with numbers. Before the actual testing, participants were trained with three practice sets of list-length two. WMC scores were achieved by calculating the proportion of correct items marked at the correct position (Unsworth et al., 2005).

2.2.2. Judgment of recency task

The experiment was an adapted version of the Judgment of Recency task with the response deadline method. It consisted of six 50-min sessions, completed over a period of several weeks. In

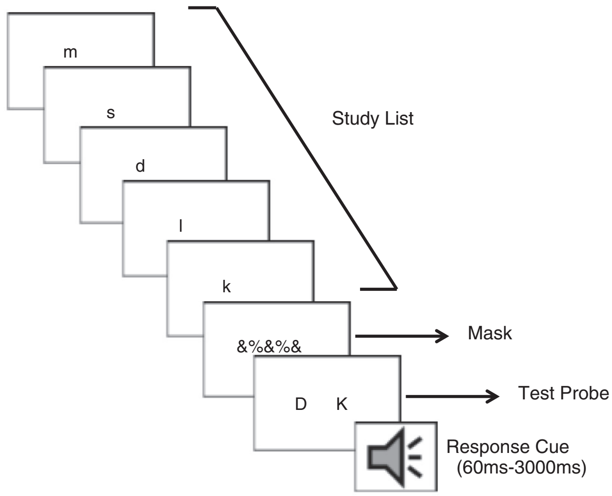

Fig. 2. A sample trial sequence from the experimental procedure. Test probe consists of two items from the study list. K is the later probe, D is the earlier probe.

each session, there were 4 blocks of 140 experimental trials. Stimuli consisted of 18 consonants (b, c, d, f, g, h, j, k, l, m, n, p, r, s, t, v, y, z) displayed in lower case. Each study list comprised 5 consonants drawn randomly without replacement from the stimulus pool that had not appeared in the two preceding lists. Following a brief mask, participants were cued to respond to the test probe presented in upper case that consisted of two letters from the study list. Participants were asked to choose the most recently studied item. The position of the correct answer (left or right) was counterbalanced for each experimental session and participant.

2.3. Procedure

Fig. 2 illustrates the sequence of a trial. Each trial began with a fixation point presented for 500 ms. Each study item (a lowercase consonant) was presented one at a time for 500 ms. Following the 5-item study list, a visual mask was presented for 500 ms. Then, the test probes (two items from the study list presented as uppercase) appeared on the screen for the duration of the response deadline. At 60, 200, 300, 500, 800, 1500, or 3000 ms after the onset of the recognition probe, a 50 ms tone sounded to cue the participants to respond. Participants chose one of the presented items that corresponded to the "later item", the item that appeared most recently in the study list. Participants indicated their response as quickly as possible after the onset of the tone by pressing a key. After indicating their response, participants were given feedback on their latency to respond. Participants were trained to respond within 300 ms of the tone. They were informed that responses longer than 300 ms were too slow and responses under 100 ms were anticipations, and that both should be avoided.

There were ten conditions which utilized all possible study position pairings as the probe combinations: 2-1, 3-1, 3-2, 4-1, 4-2, 4-3, 5-1, 5-2, 5-3, and 5-4.

3. Results

3.1. Overview of results

We first analyzed the data to reveal which strategy HSs and LSs applied to recover temporal order information (see Sections 3.2.1, and SM-text 1.1 and 1.2). To do so, we assessed whether the study position of the earlier probe (SP-E), the probe that was presented earlier in the study list, or the study position of the later probe (SP-L), the probe that was presented later in the study list impacted the retrieval success and retrieval speed.

Next, in Section 3.3 we compared the efficiency of the groups while applying the chosen strategy (also see SM-text for group differences in asymptotic accuracy measurements). We conducted between group comparisons on the performance measurements reflecting the availability (asymptotic accuracy, asymptote parameter estimates) and accessibility (rate and intercept estimates) of access to temporal order information. We also showed how WMC affects the retrieval dynamics when retrieval requires an effortful/controlled memory search.

3.2. Retrieval dynamics

In order to obtain (equal-variance Gaussian) d' measures, an asymmetric d' scaling was calculated as such; $d' = [z\ (1|1) - z\ (1|2)]/2^{1/2}$. z here corresponds to the standard normal deviate of the probability of responding that the most recent item was the first alternative, given that the test probe was either the first (1|1) or the second (1|2) alternative. We estimated the retrieval dynamics by fitting the individual participants' data and the average data (derived by averaging d' values for each condition across participants) with an exponential approach to a limit:

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

In Eq. (1), $d'(t)$ is the predicted d' at time t; λ is the asymptotic accuracy level reflecting the overall probability of recognition; δ is the intercept reflecting the discrete point in time when accuracy departs from chance ($d' = 0$); β is the rate parameter, which indexes the speed at which accuracy grows from chance to asymptote. Previous studies have indicated that this equation provides a good quantitative summary of the shape of the SAT functions (Dosher, 1981; McElree, 2001; McElree & Dosher, 1989; Wickelgren & Corbett, 1977; Wickelgren et al., 1980).

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; and (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.

Initially, we fit the full model (10λ-10β-10δ) to individual participants' data for both groups to examine the impact of WMC on each test probe combination and to evaluate the patterns in support for the serial search mechanism.[1] Parameter estimates derived from the full model were used for the statistical analysis of WMC and serial scan effects (see Tables SM-1, SM-2, SM-3 and SM-4 in Supplemental Material for a complete list of the parameter estimates from the full model and adjusted-R^2 values). We additionally tested models by varying the number of parameters allocated to different conditions in order to attain the best fitting model.

3.2.1. Strategy choice effects on retrieval dynamics

As overviewed in the Introduction, there are two possible strategies participants could employ in the JOR task. If participants judge the recency of the items by making a strength comparison, we expect performance to improve as a function of the distance between SP-E and SP-L. If, on the other hand, participants apply a self-terminating serial scan, performance would be determined by the changes in the SP-L alone.

[1] The full model estimated one asymptote (λ), one rate (β) and one intercept (δ) parameter for each condition.

3.2.1.1. Probe distance effects. It is possible to assess distance effects by comparing conditions in which SP-L is held constant and only SP-E is varied. We started with holding SP-L 5 constant and varying SP-E; a 2 (Group [HS vs. LS]) × 4 (SP-E: 1, 2, 3, 4 compared with SP-L 5) ANOVA indicated that SP-E did not have a measurable effect on the asymptote ($p = 0.54$], the rate ($p = 0.40$), or the intercept ($p = 0.69$). We did not observe interactions between the WMC and the SP-E on asymptote ($p = 0.56$), rate ($p = 0.30$), and intercept parameters ($p = 0.50$).

We next analyzed variations in SP-E for SP-L 4. A 2 (Group [HS vs. LS]) × 3 (SP-E: 1, 2, 3 compared with SP-L 4) mixed ANOVA analysis showed no main effect of SP-E on asymptote ($p = 0.31$), rate ($p = 0.24$), and intercept ($p = 0.28$) parameters. There was also no Group × SP-E interaction for asymptote: ($p = 0.86$), rate ($p = 0.75$), and intercept: ($p = 0.21$) measurements.

Finally, a 2 (Group [HS vs. LS]) × 2 (SP-E: 1, 2 compared with SP-L 3) revealed that while SP-E had no main effect on asymptote ($p = 0.11$) and rate measures ($p = 0.21$), it significantly affected the intercept parameter [$F(1,21) = 10.66$, $p < 0.005$, $\eta_p^2 = 0.19$]. Similar to the findings above, there was no interaction of SP-E with WMC for all parameter estimates (asymptote: $p = 0.49$, rate: $p = 0.66$, intercept: $p = 0.21$). Further post hoc tests on the intercept measures showed that the SP-E effect was only apparent for LSs with 3-1 test probe combination having significantly lower intercept ($t(21) = -3.462$, $p < 0.003$) measures than 3-2 combination. We speculate that LSs might have applied a different strategy on certain trials while recovering the 3-1 combination.

According to temporal context model (Howard & Kahana, 2002), nearby positions are coded in a similar fashion so that judging the nearby positions would be more difficult than judging the positions that are not nearby. We did not observe such differences for SP-L 4 or SP-L 5. This might be because these items are still available in memory and the backward self-terminating serial scan can be applied when the item is still available (McElree, 2006). However, on trials when the item availability was poor, they might have switched their strategy to a strength-based comparison. A similar pattern was observed in a previously tested JOR paradigm (see Klein, Shiffrin, & Criss, 2007), participants substituted their strategy by a strength comparison when contextual based judgments did not work. This would explain the performance differences between probe combinations 3-1 and 3-2 and also the lack of WMC impact on the intercept parameter for probe 3-1. We did further analysis to investigate whether this might be due to a primacy effect (see SM-Text), however, we did not observe any primacy effects. Specifically, when SP-E was the 1st study list position, memory performance was not better compared to other positions of SP-E. This is also consistent with previous studies that also showed no evidence for primacy effects in JOR paradigm (e.g., Klein, Criss, & Shiffrin, 2004).

3.2.1.2. Self-terminating serial scan. After establishing that the SP-E did not modulate the retrieval dynamics, we assessed the impact of the SP-L. With a similar approach, this time we held the SP-E constant across conditions and investigated how SP-L modulated memory performance.

A 2 (Group [HS vs. LS]) × 4 (SP-E: 1, SP-L: 2, 3, 4, 5) mixed ANOVA analysis on the asymptote [$F(2.14,44.92) = 26.37$, $p < 0.001$; $\eta_p^2 = 0.33$],[2] rate [$F(2.59,54.33) = 8.17$, $p < 0.001$; $\eta_p^2 = 0.19$], and intercept [$F(1.55,32.47) = 24.62$, $p < 0.001$; $\eta_p^2 = 0.47$] parameters showed that SP-L had a significant impact on the retrieval accuracy and retrieval speed. The more recent the SP-L, the better the performance was for both groups. Group by condition interactions on asymptote [$F(2.14,44.92) = 4.58$, $p < 0.02$; $\eta_p^2 = 0.08$] and intercept parameters [$F(1.55,32.47) = 3.19$, $p < 0.07$; $\eta_p^2 = 0.10$] showed that LSs' performance were affected more with the changes in SP-L compared to HSs. Namely, LSs performed worse than HSs when SP-L was drawn from less recent study positions.

A 2 (Group [HS vs. LS]) × 3 (SP-E: 2 compared with SP-L: 3, 4, 5) mixed ANOVA analysis conducted on asymptote [$F(1.90,39.83) = 36.56$, $p = 0.001$, $\eta_p^2 = 0.35$], rate [$F(1.76,36.88) = 6.83$, $p < 0.005$, $\eta_p^2 = 0.18$], and intercept [$F(1.41,29.67) = 27.51$, $p < 0.001$, $\eta_p^2 = 0.39$] parameters also indicated a significant main effect of SP-L. We also observed significant Group × SP-L interactions on both asymptote [$F(1.90,39.83) = 12.05$, $p < 0.001$, $\eta_p^2 = 0.15$] and intercept parameters [$F(1.41,29.67) = 5.18$, $p < 0.02$, $\eta_p^2 = 0.11$] indicating a similar pattern explained above.

Finally, a 2 (Group [HS vs. LS]) × 2 (SP-E: 3 compared with SP-L: 4, 5) revealed that SP-L determined the changes in asymptote [$F(1,21) = 27.66$, $p < 0.001$, $\eta_p^2 = 0.24$], rate [$F(1,21) = 39.76$, $p < 0.005$, $\eta_p^2 = 0.20$], and intercept parameters [$F(1,21) = 6.72$, $p < 0.03$, $\eta_p^2 = 0.13$]. We observed Group × SP-L interaction only for asymptote measurements for this analysis [$F(1,21) = 13.18$, $p < 0.003$, $\eta_p^2 = 0.13$].

After establishing that SP-L modulated the memory performance, we collapsed SP-E across SP-L and conducted a 2 (Group [HS vs. LS]) × 4 (SP-L: 2, 3, 4, 5) mixed ANOVA analysis on the asymptote [$F(1.82,38.31) = 31.22$, $p < 0.0002$; $\eta_p^2 = 0.36$], rate [$F(2.51,52.70) = 25.06$, $p < 0.001$; $\eta_p^2 = 0.2$], and intercept [$F(1.38,29) = 23$, $p < 0.0001$; $\eta_p^2 = 0.45$] parameters, which showed that SP-L had a significant impact on the retrieval accuracy and retrieval speed. Specifically, HSs and LSs were more accurate and faster when SP-L were from more recent study positions. WMC also had a significant main effect on both retrieval accuracy and speed measurements: asymptote [$F(1,21) = 10.8$, $p < 0.005$; $\eta_p^2 = 0.24$], rate [$F(1,21) = 4.64$, $p < 0.05$; $\eta_p^2 = 0.06$], intercept [$F(1,21) = 17.54$, $p < 0.0005$; $\eta_p^2 = 0.17$]. There was also interactions between group and SP-L on asymptote [$F(1.82,38.31) = 6.29$, $p < 0.006$; $\eta_p^2 = 0.10$] and intercept $F(1.38,29) = 3.33$, $p < 0.07$; $\eta_p^2 = 0.11$] measurements showing a more profound impact of SP-L on LSs' memory performance. These effects are further investigated in the following sections (see Section 3.3).

There were significant linear trends for both groups showing that asymptote estimates increased as a function of SP-L [HS: estimated slope = 2.79, $t(63) = 4.956$, $p < 0.001$, LS: estimated slope = 4.99, $t(63) = 8.48$, $p < 0.001$]. For the rate parameter, the pattern was similar [HS: estimated slope = 13.39, $t(63) = 2.26$, $p < 0.03$, LS: estimated slope = 12.39, $t(63) = 2.008$, $p < 0.05$]. There was also an operative linear trend for the intercept parameter [HS: estimated slope = −1.58, $t(63) = -3.589$, $p < 0.001$, LS: estimated slope = −3.58, $t(63) = -7.77$, $p < 0.0001$]. Specifically, the intercept parameter was faster as a function of SP-L. Accordingly, our analyses indicated that performance varied as a monotonic function of SP-L, indicating a backwards serial search strategy.

The most important indicator of a serial scan mechanism is the delays in the initial availability of the temporal order information (e.g., see McElree & Dosher, 1993). Depending on the chosen strategy, forward or backwards, the intercept parameter will vary as a function of the recency of the later probe. In our case, retrieving temporal order information for SP-L 2 comparisons took longer than all the other combinations (slowest intercept parameter for each group), while significantly improving as a function of SP-L, which is suggestive for backwards scanning strategy. The intercept measurements allocated for SP-L 5 was significantly faster than all other conditions, suggesting that participants were much faster

[2] Throughout the manuscript degrees of freedom (df) are Greenhouse-Geisser corrected in ANOVAs for repeated-measures factors with more than two levels.

while accessing the temporal order information when the test probe contained the most recently studied item.

To further investigate the serial scan effects on the data, we sought to identify models that most adequately describes the data taking both model fit and flexibility account (see SM-Text for the detailed model selection procedure). We started fitting the data with a null model, which allocated a common asymptote [λ], a common rate [β], and a common intercept [δ] parameter to each probe combination. We then tested models, which varied the parameters as a function of the later probe.

Allocating different parameter values to different later probe conditions for both retrieval accuracy (asymptote), and retrieval speed (intercept and rate) parameters as a function of the later probe significantly increased the adjusted-R^2 statistics for both groups (see SM-text). Varying the parameters as a function of the SP-L helped us to explain the systematic deviations, and revealed the linear trends that were also prominent in the parameter estimates derived from the full models.[3] The observed linear trends, the significant impact of SP-L on the parameter estimates, and the properties of best fitting models evidently show us both HSs and LSs applied the self-terminating serial strategy. We next investigated whether there were any differences between the two groups while applying the strategy.

3.3. WMC impact on temporal order memory retrieval

After establishing the data can be explained by a backwards serial scan, we evaluated WMC related effects on the asymptote and retrieval dynamics parameters.

3.3.1. Retrieval accuracy

Results from independent samples *t*-tests and the average of the parameter estimates with the standard deviations from both groups are shown in Table 1.

Between-group comparisons conducted on the asymptote parameter estimates derived from the SAT functions indicated a lower asymptote for LS compared with HS group for all conditions, except for those containing SP-L 5. This pattern also holds for the empirical measurements of asymptotic accuracy (see SM-Text 1.1 and 1.2). Thus, WMC impacted the probability of successful retrieval of temporal order information unless the later probe is the latest presented item, which is presumably still in the FoA.

3.3.2. Retrieval speed

As shown in Table 2, the groups did not differ in the rate parameter estimates in any of the test probe combinations. However, the groups had significant differences in the intercept parameter estimates. Table 3 shows the between group comparisons on the intercept estimates for each test probe combination. Overall, the intercept parameter, which marks the point in time when information first becomes available in memory, was slower for LSs compared to HSs. The observed differences between the groups were apparent in all test probes, except for SP-L 5 (i.e., SP-L 4, SP-L 3, and SP-L 2). In contrast to rate estimates, WMC had an obvious impact on the intercept measurement except for SP-L 5 (see the depiction of the SAT functions from the full fit in Fig. 3). This finding is consistent with previous research indicating the most recently studied item is maintained in the current focus of attention (FoA) hence does not require an effortful search through memory representations (McElree, 2006; Mızrak & Öztekin, 2016; Öztekin, Gungor, & Badre, 2012; Öztekin & McElree, 2007, 2010). Accordingly, that WMC effects on retrieval speed and accuracy were prominent when controlled processing is required, and not present when the memory judgment entailed matching the probe to the contents of focal attention is in line with the contention that WMC selective impacts controlled processing.

As described in the previous sections, there were significant linear trends in estimated parameters for both groups, which is consistent with the application of a backwards serial scan. Both groups had slower intercept parameters when SP-L was drawn from earlier study list positions. What is striking here is that the group differences were not limited to the intercept estimates across SP-L conditions: the data also showed a WMC effect on the slope of the linear increase in the intercept parameters across SP-L conditions. In other words, LS individuals further slowed down with SP-L being drawn from earlier study positions [$t(63) = 3.132$,

Table 1
Between group comparisons of asymptote estimates derived from the full model and the means for HS and LS groups.

Test Probe Combination	SP-L	HS- Mean (SD)	LS- Mean (SD)	*t*	df	*p*
2-1	2	1.64 (0.90)	0.93 (0.70)	2.12	20.58	0.047
3-1	3	2.14 (0.65)	1.21 (0.62)	3.49	20.948	0.002
3-2	3	2.01 (0.65)	0.91 (0.63)	3.78	20.346	0.001
4-1	4	2.50 (0.51)	1.55 (0.81)	3.28	16.774	0.004
4-2	4	2.37 (0.56)	1.38 (0.64)	3.94	19.997	0.001
4-3	4	2.29 (0.64)	1.42 (0.69)	3.13	20.387	0.005
5-1	5	2.51 (0.47)	2.47 (0.42)	0.19	20.976	0.849
5-2	5	2.50 (0.49)	2.46 (0.47)	0.19	20.921	0.846
5-3	5	2.49 (0.54)	2.49 (0.44)	−0.03	20.178	0.978
5-4	5	2.41 (0.52)	2.43 (0.40)	−0.08	20.399	0.935

Table 2
Between group comparisons of rate estimates derived from the full model and the means for HS and LS groups.

Test Probe Combination	SP-L	HS- Mean (SD)	LS- Mean (SD)	*t*	df	*p*
2-1	2	5.24 (3.68)	7.76 (5.18)	−1.34	17.90	0.199
3-1	3	5.19 (6.06)	5.96 (6.16)	−0.31	20.76	0.770
3-2	3	6.59 (6.59)	8.86 (5.72)	−0.88	20.95	0.388
4-1	4	5.76 (6.31)	7.94 (7.20)	−0.77	19.99	0.452
4-2	4	2.90 (3.98)	6.92 (6.32)	−1.81	16.62	0.089
4-3	4	3.11 (2.80)	5.77 (5.80)	−1.37	14.04	0.193
5-1	5	11.48 (6.70)	13.79 (6.70)	−0.82	20.82	0.419
5-2	5	12.37 (7.43)	11.17 (6.78)	0.40	21.00	0.689
5-3	5	10.11 (7.94)	10.71 (7.07)	−0.19	20.99	0.850
5-4	5	7.50 (7.76)	12.62 (8.88)	−1.50	20.00	0.158

[3] We did not use the parameter values estimated by the most adequate model to statistically compare the two groups performance. HS and LS groups' empirical data were best explained by models with different numbers of parameters, hence it would not be appropriate to perform a between group comparison on the estimated parameters from these models. However, we used the parameter estimates from the most adequate models for each group to depict the SAT functions in Fig. S3. A more detailed description is provided in SM-text.

Table 3
Between group comparisons of intercept estimates derived from the full model and the means for HS and LS groups.

Test Probe Combination	SP-L	HS- Mean (SD)	LS- Mean (SD)	*t*	df	*p*
2-1	2	0.759 (0.430)	1.386 (0.730)	−2.47	15.97	0.024
3-1	3	0.418 (0.170)	0.593 (0.299)	−1.69	15.78	0.109
3-2	3	0.570 (0.290)	1.090 (0.561)	−2.75	14.71	0.015
4-1	4	0.292 (0.080)	0.470 (0.291)	−1.94	11.53	0.077
4-2	4	0.293 (0.240)	0.603 (0.215)	−3.25	20.99	0.003
4-3	4	0.410 (0.280)	0.520 (0.296)	−0.88	20.60	0.380
5-1	5	0.255 (0.100)	0.298 (0.090)	−1.06	20.99	0.299
5-2	5	0.266 (0.162)	0.301 (0.124)	−0.58	20.37	0.570
5-3	5	0.313 (0.122)	0.295 (0.068)	0.44	17.46	0.660
5-4	5	0.305 (0.129)	0.289 (0.110)	0.31	20.99	0.762

$p < 0.003$]. This finding implicates that LS group initiated the serial scan strategy later than HS group, and they were also less efficient in completing the search after the search started.

As mentioned above, the variation in the intercept parameter of the SAT function is seen as a major index of the application of the serial scan mechanism (McElree & Dosher, 1993). In our case, both HSs and LSs employed a backwards serial scan strategy to recover temporal order information. However, LSs intercept measurements were significantly slower than HSs, showing that LSs started serial memory search operations later than HSs. The data further suggested that LSs were less efficient in applying the backwards scanning strategy. That WMC effects were prominent on the intercept parameters of the SAT function strongly indicates the groups differences to arise from efficacy of the serial memory search.

3.4. Summary of results

In summary, WMC had a significant impact on both retrieval accuracy, measured by empirical asymptotic accuracy measurements and asymptote parameters from the SAT functions, and retrieval speed, namely on the intercept parameter. Specifically, high-span group outperformed low-span group by having higher availability of the temporal order information and by accessing the required information faster. The data further implicated the WMC related differences in retrieval dynamics to specifically reflect less efficient serial memory search. However, this pattern was absent when the more recent probe of the test probes were the last item in the study list, which can be maintained in the current focus of attention. That no group differences are observed for the contents of FoA supports previous research suggesting that WMC differences emerge only under certain conditions (Barrett, Tugade, & Engle, 2004; see Engle, 2002 for a review; Öztekin & McElree, 2010), namely, in situations when the information can only be accessed via strategic, controlled operations.

4. Discussion

In this study, we investigated the role of WMC on the dynamics of temporal order memory retrieval. Specifically, we tested HS and LS individuals with a relative JOR paradigm, in which they were asked to retrieve the temporal information of the items presented and judge the recency of the test probes. To independently assess

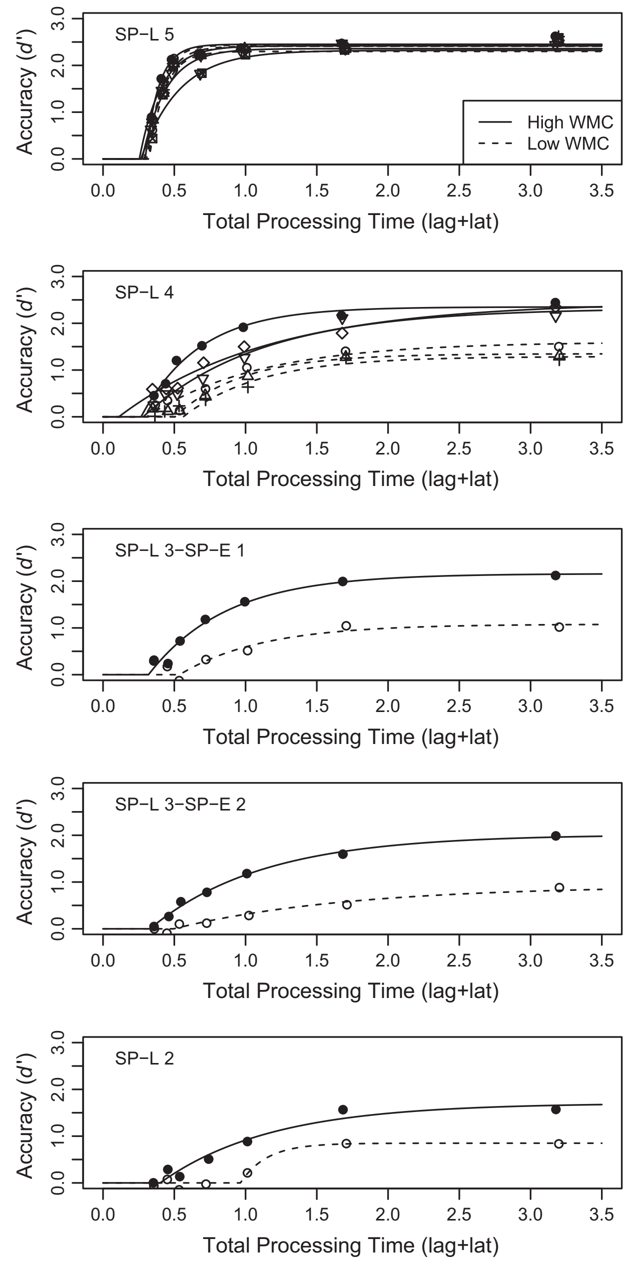

Fig. 3. Accuracy (in d' units) plotted for test probe combinations as a function of total processing time (in seconds) for the average high-span (HS) and low-span (LS) groups. For each test probe combination, except from the SP-L 5 combinations, LSs had later intercepts and lower asymptote levels derived from the SAT function parameters. The symbols indicate empirical data points, and the smooth curves indicate the model predictions derived from Eq. (1). SP-L 5 = all test probes in which the later probe was the 5th item in the study list. SP-L 4 = all test probes in which the later probe was the 4th item in the study list. 3-1 = test probe which had the 3rd item as the later probe and 1st item as the earlier probe from the study list. 3-2 = test probe which had the 3rd as the later probe and 2nd item as the earlier probe from the study list. SP-L 2 = test probe which has the 2nd item from the study list as the later probe.

retrieval accuracy and retrieval speed, we employed the response-deadline SAT procedure and obtained full time-course retrieval functions. The overall accuracy of temporal order information retrieval, measured by asymptotic accuracy (average of the two last response deadlines), was lower for LSs than HSs except for the test probes containing the most recently studied item. This lower performance was also evident in the asymptote estimates derived from quantitative modeling of the SAT functions.

Consistent with the previous research showing that LSs perform worse than HSs across a variety of cognitive tasks (reviewed in Engle, 2002, 2010), WMC measures correlating with the probability of retrieval is not surprising. The more novel contribution of the current investigation concerns the dramatic retrieval speed differences across the two groups during access to temporal order information in working memory: LSs were slower in engaging in the controlled serial memory search operations that access temporal order information from working memory. In particular, our data pinpointed the WMC group differences to predominantly affect the intercept parameters of the SAT function across successive retrieval operations. Below, we provide possible explanations to the observed findings.

4.1. WMC selectively impacts controlled retrieval

It is noteworthy to first emphasize that WMC did not have an impact on the success or speed of access to temporal order information that was still in the focus of attention, a case when no memory operation is required, and hence retrieval can be regarded as largely automatic. Theories explaining the underlying mechanisms that lead to individual differences in WMC capitalize on controlled attention with LSs performing worse in situations that necessitate controlled processes (Engle & Kane, 2004), with no measurable differences in automatic processing. While shunting information outside of the focal attention requires controlled retrieval, the contents of focal attention exhibit privileged access (McElree, 2001, 2006; McElree & Dosher, 1989; Mızrak & Öztekin, 2016; Öztekin & McElree, 2007, 2010; Öztekin et al., 2012). The lack of group differences in either the success or speed of retrieval in the current study supports the contention that WMC selectively affects controlled processing, rather than a leading to a more global deficit (Redick et al., 2012). In contrast, for material outside of current focus of attention, WMC impacted on both the success and efficiency of the serial search operations deployed to access temporal order memory.

4.2. Serial memory search: WMC does not affect the strategy to recover temporal order memory retrieval

Earlier theories (Yntema & Trask, 1963) of judgments of recency suggested that the distance between the test probes should have an effect on the temporal order retrieval performance; however, we did not observe this distance effect in our study. Alternatively, the recency of the more recent probe in the test probes (the later probe) mediated the retrieval success and retrieval speed for both HSs and LSs. The performance decreased linearly as the more recent probe was drawn from earlier study positions and this decrease was more prominent for LSs compared to HSs. In this regard, our findings were consistent with previous literature in showing that access to temporal order information in the JOR task requires a serial search through memory representations (Hacker, 1980; McElree, 2006; McElree & Dosher, 1993; Öztekin et al., 2008). Notably, the dynamics of memory retrieval obtained from quantitative modeling applied to each individual participant's, as well as the group data implicated a serial search strategy for both HS and LS groups. This pattern was extracted from faster retrieval dynamics (earlier intercepts) and higher retrieval success when the more recent test probe was from later study positions. McElree and Dosher (1993) showed that the recency of the later probe had drastic impact on the intercept parameter of the SAT function, with more recent probes having earlier intercepts. They interpreted this pattern as indicative of a backward serial search (see also Hacker, 1980), that starts from the last item in the study list and if the tested probe is the last item, this search will be less effortful and take less time. Our findings indicated a similar pattern for both groups: When the later probe matched the last item in the study list; both groups exhibited the fastest intercept and highest accuracy rate amongst all the test probes. Moreover, changes in the intercept parameter as a function of the position of the later probe further confirmed that participants were engaging in a serial search, namely the intercept was earlier as the position of the later probe was more recent. We next discuss WMC's impact on the efficiency of this serial memory search.

4.3. WMC and efficiency of serial memory search

Although HSs and LSs implemented the same retrieval strategy, namely a serial memory search, LSs were not as efficient as HSs. This was evident in both retrieval success and retrieval speed measures. Quantitative modeling of the SAT functions indicated that LS individuals were slower (reflected in the intercept parameter of the SAT function) in initiating the successive serial memory search operations that access temporal order information from working memory. This is in contrast to previous investigations assessing the relationship between WMC and item recognition (Öztekin & McElree, 2010), which indicate that LS individuals exhibit similar retrieval speed measures when accessing item information from working memory, in the absence of interference. Speed differences were only prominent when resolving interference, during which LSs were slower. Taken together, these data suggest that group differences with respect to retrieval speed measures emerge when controlled processing is required, either due to the presence of interference in the retrieval context or depending on the type of information (i.e., item versus relational) that needs to be accessed from memory. In the following sections, we discuss the observed group differences in more detail.

4.3.1. WMC effects on availability of temporal order memory

For successful retrieval, memory representations need to be available in memory. Availability of the memory representations may depend on representations being encoded effectively, and maintained in an active state until the time of retrieval. If the memory representations are not available for retrieval, this might be due to representations not being actively maintained in working memory or they become unavailable due to loss of strength or interference of task-irrelevant items. The asymptote measurements in our study reflect the availability of the target information required for the task. When given enough time, if participants cannot recover the temporal order information this can be presumably interpreted as a lack of availability of the temporal representations of the study items in memory. Our findings showed that LSs had lower accuracy than HSs, measured by empirical asymptotic accuracy and SAT asymptote estimates. This finding, complementing other studies in the literature (Kane & Engle, 2002, 2003; Kane et al., 2001; see Unsworth & Engle, 2007 for a review), might indicate that LSs are worse than HSs at maintaining representations in an active state. In JOR paradigm, participants need to protect the contents of their memory while switching between multiple active representations, in order to reach the required information (the temporal position of the items) for the recency judgment. The present data offer two possible explanations to the lower availability of the temporal order information for the LS group. It is possible that LSs were not able to encode the study materials well in the first place. Encoding temporal order information may require more elaborative encoding, and HSs might better adjust themselves for efficiently encoding the temporal order of the study material. Alternatively, the two groups may not differ at sufficient encoding, however accuracy differences might arise solely due to the inefficiency of the memory search for the LS group. Previous research suggests that LSs are not as good as HSs at filtering out the irrelevant information and allocating their attention on the relevant material (Kane et al., 2001; Unsworth, Schrock, & Engle, 2004; Öztekin & McElree, 2010), and that they are prone to internal and external distraction. LSs' being less effective while they are allocating their attention is a well-studied phenomenon. Therefore, we believe the latter explanation is more likely.

4.3.2. WMC effects on accessibility of temporal order memory

One salient advantage provided by the SAT procedure is that it enables independent assessments of retrieval success and processing speed. This allowed us to differentiate the dynamics of the retrieval operations engaged to access temporal order memory, independent of differences in terminal accuracy. Our data showed that in addition to the lower availability of the temporal order information, LSs were slower in engaging in the successive serial memory search operations that access temporal order information. Retrieval dynamics measures obtained from the SAT procedure enable separately assessing both the time point in which information first becomes available (the intercept parameter) and the rate of the accumulation of information in memory (the rate parameter). Previous investigations of the time course of JOR (McElree & Dosher, 1993) have indicated serial memory search operations to reflect on the intercept parameter. In other words, each successive retrieval operation that accesses study items in their temporal order takes time, and delays the intercept parameter. In line with these previous findings, our data specifically pinpointed group differences to occur on the intercept parameter of the SAT function, implicating that the LS group is less efficient in deploying these serial memory search operations that access temporal order information. This slower retrieval of temporal order information could stem from (a) delayed initiation of the serial scan process, (b) slower scanning through the memory representations, or a combination of both. Indeed, our data implicates a combination of both (a) and (b). Below, we discuss these explanations in more length.

4.3.2.1. Delayed initiation of the serial scan. Successfully judging the recency of the items requires activating representations outside the focus of attention, execution of the serial memory search, and switching attention to the successively retrieved representations during this controlled memory search. For this entire process to be successful, the activated item representations should be ordered by their position in the study list. If WMC reflects the ability to maintain context binding (Oberauer, 2005), one possibility is that LSs might not have maintained temporal context bindings as well as the HS group. This would slow down correctly reinstating the temporal positions of the studied items.

Studies examining the controlled search differences between HSs and LSs found similar findings, showing that LSs were not as efficient as HSs in the search process (e.g., Spillers & Unsworth, 2011; Unsworth, Spillers, & Brewer, 2012). It is possible that LSs are not as good as HSs when setting up an overall retrieval plan (Unsworth, Brewer, & Spillers, 2013). In JOR task, the retrieval plan might be to strongly associate the items with their positions that would make reinstating the context faster. That said, previous research suggested that that the groups differ in generating efficient retrieval cues to search memory with (Spillers & Unsworth, 2011). Setting up a plan and generating cues to use during retrieval are important and LSs might be doing both of these but what affects their efficiency? For instance, they might also have a cue present at retrieval, but whether this cue leads them to the specified relevant item or not is an important component that would affect successful retrieval of the item.

WMC is measured by complex span tasks, which intrudes processing of the memoranda by presenting additional operations. Participants have to maintain the recently encountered representations in a state to retrieve them later. When the pattern of errors to this task was examined (Unsworth & Engle, 2006), it has been shown that LSs could not retrieve the items from earlier positions of the lists as much as the items that were presented later in the lists. LSs also had higher output transpositions (an item recalled correctly but in an incorrect position) than HSs. Accordingly, it has been suggested (see Chow & Conway, 2015; Unsworth & Engle, 2006) that, LSs employ less efficient memory cues that disallows them to remember the items' positions correctly. The output transpositions occurred mostly for the items from middle positions in the lists, which suggests that temporal-contextual cues for these items were not diagnostic enough. Additionally, Spillers and Unsworth (2011) employed a delayed free recall paradigm to investigate how WMC impacted the use of internally generated temporal-contextual cues. They showed that, although LSs and HSs initiated the recall process similarly, LSs were not as efficient as HSs. While HSs benefited from using the recalled items as a cue to recall other items, LSs were unable to do this. These findings suggest that LSs are less efficient in using temporal-contextual cues during retrieval, which could explain the delay in initiating the serial memory search. However, the observed differences in the linear trends on the intercept parameters cannot be explained by just the delay in initiating the serial memory search. This latter finding further implicates that LSs were also less efficient in executing the serial scan operations after they had been initiated.

4.3.2.2. Slower memory search. After the participants initiated the serial scan, what is left is to scan through the memory representations until the later probe matches one of the successively retrieved representations. In order to do this, participants need to carry out multiple retrieval operations, and compare the test probes with the elements in memory. Comparing activated memory representations with the probes, and judging whether they match or not might affect the retrieval speed. However, in a previous study that investigated time-course of WMC related effects in item recognition (Öztekin & McElree, 2010), there were no speed differences between the HS and LS groups when they judged whether the probe belonged to the study list or not. Therefore, this explanation is less likely. Consistent with this finding, our results showed that there were no differences between groups in the speed of information accumulation, reflected in the rate parameter. On the other hand, the difference between the groups in the linear trend in which the intercept parameter further slows as a function of the study position of the later probe might arise from differences in the speed of scanning through memory representations. This process requires switching the focus of attention from one representation to another at each successive retrieval operation, which would require controlled attention resources. We suggest that LSs serial memory search operations might be further delayed due to the necessity of attentional control at each successive retrieval operation during the serial scan. Accordingly, our findings implicate both that (a) LSs were delayed in initiating the serial scan and (b) were further less efficient in carrying out this controlled serial memory search.

5. Conclusion

In this study we evaluated the impact of working memory capacity on the recovery of temporal order information in retrieval accuracy and retrieval speed measures. Our results suggest that WMC predicts the ability to search through items in memory by slowing the serial search operation employed to access temporal order information. Although both groups applied the same strategy to recover temporal order information, namely a self-terminating backwards serial scan, low WMC group was slower and impaired in this search process. A serial search through items in memory is an exhaustive controlled search process that requires cognitive control. We showed that initiation of the serial memory search operations was delayed for individuals with low WMC compared to high WMC. Low WMC group was also less efficient in completing the serial scan. Accordingly, the data implicate that retrieval of temporal order information from working memory was slower for low WMC group due to both a delay in initiation of a backwards serial scan strategy, and a less efficient/slower serial memory search after the scan had started. These findings are consistent with the previously observed delayed controlled processes for low WMC in the face of interference/distractors, and extends this notion to other contexts that require controlled processing, such as recovery of relational information.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cognition.2016.04.007.

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