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Working memory capacity and controlled serial memory search

Eda Mızrak *, Ilke Öztekin

Department of Psychology, Koç University, Rumelifeneri Yolu, Sarıyer 34450, Istanbul, Turkey

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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

* Corresponding author.
E-mail addresses: emizrak@ku.edu.tr (E. Mızrak), ioztekin@ku.edu.tr (I. Öztekin).

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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.