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Schematic Processing in Working Memory Tasks Relies on Learning and Long-Term Memory Resources

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Abstract

This paper presents an evidence for involvement of long-term memory (LTM) resources along volatile memory (VM) resources in active management of information in a working memory (WM) task that features schematic processing of WM content. It was observed that in rehearsing frequently changing WM items in a self-paced concurrent-counting task when subjects learn and use a fixed rehearsing order across different episodes of the task they make significantly less error compared to when they adopt different rehearsing order for different episodes. This finding suggests that while retaining information in this task practically draws on volatile resources such as the phonological loop (PL), access to the corresponding item in WM relies on learning and retaining data structures in LTM. It is discussed that in this role learning and LTM resources help render schematic access to episodic information stored in less structured storage units such as PL. In this role LTM and learning plays a crucial role in execution of WM tasks that employ complex process schemas.

Keywords: Working Memory; Symbolic Working Memory; Volatile Memory; Long-term Memory; Concurrent-counting; Schematic Access

Introduction

The concept of working memory (WM) originally started as an offshoot of the concept of short-term storage (STS) (Atkinson & Shiffrin, 1968), a concept which in dual-store views of memory is in contrast with the long-term store. As a result, for more than two decades WM discourse was dominated by those models which assume that retention of information in WM is entirely separated from long-term memory (Baddeley & Hitch, 1974; Baddeley, 1992, 2000). A key supporting evidence for this view came from neuropsychological reports of bilateral hippocampal lesion that had left subjects with a dense impairment in their ability of forming episodic memories yet, without a notable deficit in temporary information retention for regulating daily tasks (Scoville & Milner, 1957). Reports of a reverse effect and spared long-term memory in the face of sever deficit in short-term information retention (Shallice & Warrington, 1970) established the idea of a double dissociation between STM and LTM.

However, from the turn of the century a growing body of experimental evidence as well as theoretical interests have started casting doubt on the idea of a complete dissociation between LTM and temporary retention of information in WM. Apart from those theoretical efforts which seek to explain WM as an entirely LTM-embedded construct (Cowan, 1999; Ruchkin, Grafman, Cameron, & Berndt, 2003; Oberauer, 2009) some evidences have emerged that suggest a role for LTM resources along volatile and short-term memory resources in supporting WM tasks (Jonides et al., 2008).

Apparently, some researchers have been able to isolate WM task conditions under which the dependency of WM on hippocampal region of the brain becomes markedly evident. Neuroimaging studies consistent with study of patients with hippocampal damage (Ranganath & Blumenfeld, 2005; Olson, Page, Moore, Chatterjee, & Verfaellie, 2006) have revealed that in the case of engaging in novel working memory tasks or when tasks involve creating association between task-relevant information the medial temporal lobe (MTL) and Hippocampus become inevitably implicated. Conforming evidence has emerged from study of individual differences in working memory capacity (WMC) tasks. Unsworth and Engle (Unsworth & Engle, 2007) have mentioned that the nature of individual differences in working memory capacity (WMC) can be better explained by considering a primary (short-term) memory responsible for active maintenance and a secondary (long-term) memory responsible for active search. Their conclusion is consistent with Davelaar *et al*'s proposal based on behavioral evidences and computational modeling of free recall task in suggesting collaboration of LTM and STM resources in retention of information (Davelaar, Goshen-Gottstein, Ashkenazi, Haarmann, & Usher, 2005). These evidences have invited theoretical efforts for modeling involvement of multiple storage resources with different temporal retention characteristics.

Some authors have proposed that LTM and STM resources alternatively can be used for storage of information in WM tasks depending on their relative operational cost. In this paradigm a trade-off between cost of utilizing each of resources determines the preferred choice for storage of information. It is postulated that the cost of using STM resources is related to their sever limited capacity while the cost of LTM resources is related to interference-prone retrieval and speed of learning. There have been theoretical efforts such as Ericsson and Knitsch's long-term working memory framework (Ericsson & Kintsch, 1995) or O'Reily, Braver and Cohen's distributed model of WM (O'Reilly, Braver, & Cohen, n.d.) that explain this trade-off. These models basically accept the same functional role for LTM and STM in retention of episodic information. Although these models generally explain involvement of LTM resources in WM tasks they do not explain why and how contribution of hippocampal region becomes necessary in performing novel working memory tasks (Ranganath & Blumenfeld, 2005).

In a recent theoretical proposal Noori has proposed a role for LTM in management of access to episodic information stored in short-term resources of WM which can explain this effect (Noori, 2015). This role is different from direct involvement in storage of episodic task-relevant information and is rather related to retaining structural information needed for schematic execution of some tasks. He describes this role in the framework of Symbolic Working Memory (SWM), a model of a functional mode for WM in high-order cognitive tasks for which a volatile storage system for retention of symbolic codes of human language is engaged. This symbolic storage system in essence is an extension of sensorimotor systems that are responsible for perception and articulation of symbolic codes of human language. This symbolic storage system is capable of retaining symbolic code segments in exchanges of sensory and motor codes between systems respectively engaged in perception and articulation of language. This volatile symbolic serial storage (VSSS) that resembles the phonological loop of Baddeley and Hitch's model (Baddeley & Hitch, 1974) lacks an internal mechanism for addressing stored segment codes and thus is not suitable for selective operations needed for schematic processing of information in many complex WM tasks that rely on symbolic representations.

However, this limitation can be overcome by accessorizing first, a registry system with addressable and schematically reachable states and second, learning and LTM systems. A state registry system (SRS) typically is a system capable of location-based encoding (e.g. a motor system with spatial encoding capability) that is subject to address-based and voluntarily shift between its states. Furthermore, the process of switching between states can by synchronized with the process of iteration of items during rehearsing or serial monitoring of items in the symbolic storage system. The key role of LTM here is retaining information about associations between the current state of the task and processing programs that take segments of the symbolic codes from the symbolic storage. The current state of the state registry system can be used as the cue for locating a particular segment which encodes relevant and needed information at a specific stage of the task. In this role LTM retains mappings between possible states of the system and execution programs. These mappings are rather stable during the course of the task execution and needed to be learned in the beginning of the task and can be used in later occasions. This is where learning actively takes place when execution of a novel task is required. This information can be shared across different episodes for mapping active state of the task encoded partly in the state registry system (SRS) and other instance of volatile memories. This gives LTM and learning systems a crucial role in rendering selective access to the content of serially encoded information in the phonological loop or other instance of symbolic storage which is necessary in many complicated task that are often categorized as executive memory tasks. In a sense, LTM practically becomes an essential part of memory management in those tasks that draw on selective and schematic access to the information retained in the symbolic serial storage. This is also consistent with reports of deficit in performing executive WM tasks in AD[1] patients (Baddeley, 1996; Baddeley & Wilson, 2002). This hypothesis has non-trivial implications for understanding the nature of deficit in functioning of WM especially with respect to what traditionally attributed to the function of central execution (Baddeley, 1996; Baddeley & Wilson, 2002). This paper aims at testing this hypothesis. In the next section a paradigm for testing engagement of learning and LTM systems in WM tasks is devised. The results along qualitative observation of body movements which suggest systematic engagement of motor system in execution of a WM task are consistent with what is described by Noori (Noori, 2015).

Experiments

Self-paced WM tasks in which selective processing on a few items of WM are cued fulfil those conditions that SWM model prescribes for engaging learning and LTM resources. For this purpose in this study a self-paced triple counting (TC) task is adopted. The task requires retaining three numbers form which only one is processed at each counting event. The schema here is finding the number which matches the most recently presented target to be processed and used for producing a new value and replacing this new value with the old value. Retaining three one-digit numbers very well falls in range of verbal memory span of normal subjects. However, what renders the difficulty of such tasks is arranging a reliable way for accessing to the matching WM item at each stage of the task. This is where SWM model suggests that a registry system can help tag items in their rehearsing sequence by synchronizing the rehearsing process with iteration in state registry system. The predicted role of learning system is learning the association between states of the registry system and programs for processing number words in verbal short-term memory system. This creates a condition in which items in the rehearsal loop are associated to targets of counting during an episode of the task in a learned order. An efficient regime is learning these associations once and using them for different episodes. This means that subject follows a fixed rehearing regime (FRR) with respect to targets of counting. A less efficient yet plausible regime is learning a different association or a different rehearsing order in different episodes of the task. I refer to this regime as mixed rehearsing regime or MRR. The immediate cost of employing MRR compared to FRR is a higher chance of between-episode interference. This interference affects the order in which items should be retrieved from the PL. This will translate to higher error rates for MRR condition compared to FRR condition. Resolving interference between different traces of previously learned associations might also incur additional cost in terms of processing time.

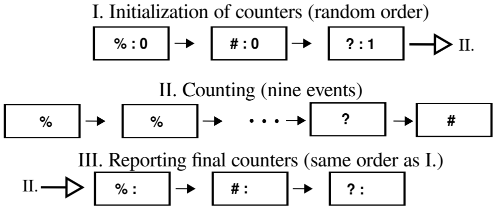

Figure 1: Sequence of events in a trial of TC task.

To create a condition in which adopting a MRR strategy is induced each trial of the task started with presentation of initial counters (0 or 1) to targets of counting in a random order (see Figure 1). The idea is that subjects may opt for learning association between cues and initial numbers in the order of initial target presentation which changes between dif-

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[1] Alzheimer's Disease

ferent episodes, a condition which is apt to MRR condition. Subjects may also be instructed to ignore the order in which initial counters are presented and rehears numbers in a fixed order across different episodes of the task, a strategy which is apt to FRR condition.

The error in counting targets was measured by two different measures a. the distance between the sum of counted values and the sum of true values (*SumError*) b. the average distance between counted values and real values after sorting both sequences in order (*SoError*). Both measures of error are insensitive to reporting items in a wrong order in the last stage of the trial and moreover, *SumError* is even insensitive to any error as a result of misidentification of visual targets. Also the delay between issuing two target presentation events were used as a measure of reaction time (RT).

Each trial of the task involves a fixed number of target presentation (nine) and the identity of targets may change between two consecutive target presentations with 50% of the chance. Targets are three keyboard characters (#,% and ?) which are presented visually and remain on the screen for only 600 milliseconds. At the end of each trial subjects report their counted values in the same order in which initial counters are presented. By adopting MRR subjects may save on the cost of reordering counters for reporting items at the final stage. This will decrease the difference between the cost of MRR and FRR which in turn may help induce adopting MRR as the preferred strategy for performance of the tasks when no explicit instruction is provided.

Experiment 1

Twenty two subjects (seventeen female) received verbal instruction about the task without any reference to a particular strategy. Subjects performed a training session including four to six trials and succeeded to performing the task only when they successfully carried out two trials of the task with no error. One subject who could not satisfy this condition was left out from the study. Subjects then were instructed to perform their first block with the same strategy of their last training trial. After finishing a block of twenty five trials of the task subjects were asked to verbally report their strategy. All subjects reported that they relied on rehearsing three counters throughout the trial and at least once for every target presentation. Except five subjects who reported a fixed rehearsing order the rest of subjects reported that they adopted the order of rehearsing based on the order of presentation of initial targets. Only those sixteen subjects who reported a mixed rehearsing strategy (MRR condition) continued to performing the second block for which they were instructed to use a fixed order for rehearsing (FRR condition). After two additional training trials subjects performed a block of twenty five trials of the task under FRR condition.

Results Figure 2 depicts a summary of the results of experiment 1. The left panel compares the average and standard error of mean (SEM) for *SoError* and *SumError* for two consecutive blocks/conditions. The right panel compares the average and STE of reaction times (RT) for two blocks/conditions.

The average of *SoError* was reduced from 0.358 (SEM=0.062) in the first block to 0.168 (SEM=0.044) in the second block. The difference in average of *SoError*s between two blocks proved statistically significant as a result of carrying out a one-way ANOVA for correlated measurements $[F(1,15) = 15.5; p = 0.0013]$.

Similarly the average of *SumError* was reduced from 0.726 (SEM=0.132) in the first block to 0.326 (SEM=0.093) in the second block. To test the statistical significance of this change in average of *SumError* the data from two consecutive blocks was submitted to a one-way ANOVA for correlated measurements which indicated a significant difference $[F(1,15) = 15.6; p = 0.0012]$.

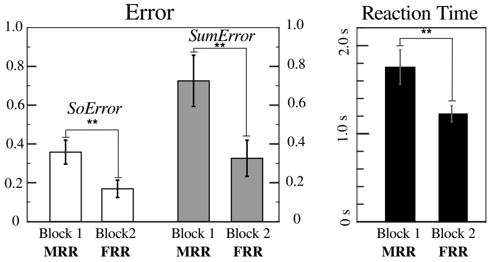


Figure 2: Results of experiment 1.

To test whether the impact of *SumError* is a result of systematic counting error the distribution of displacement of sum of counters (relative to the sum of real values) was closely inspected. Note that the value of *SumError* is absolute value this latter measure. The average of displacement of the sum of reported counters for the first block was -0.072 (SEM=0.168) and for the second block this value was 0.086 (SEM=0.095). A one-way ANOVA for correlated measurements was carried out to test the significance of the difference between average values which indicated a statistically insignificant difference $[F(1,15) = 0.1, p = 0.92]$. Moreover the average of displacement of sum of reported counters for each block was compared with zero as the null hypothesis in a one-sample t-test. A significant difference from zero would indicate a systematic over counting or under counting (e.g. as a result of skipping the counting process to reduce the load of the task). The null hypothesis was not rejected for both cases indicating that the sum of reported counters is not shifted away from the sum of real counters in a specific direction. The t-test for the case of MRR block returned $t(15) = -0.4284; p = 0.67$ and for the case of FRR returned $t(15) = -0.9013; p = 0.38$. Furthermore inspecting distribution of the displacement of the sum of reported counters revealed a symmetric distribution around zero with a strong peak at zero. The difference between distributions was a larger variance for distribution of displacement values for the case of MRR compared to FRR and stretching the distribution to larger displacements on both sides of zero. This result is consistent with Garavan's analyses on displacement of individual reported counters relative to their true values in a dual-counting task. In Garavan's experiment the length of trial was random and often longer than this experiment. Garavan noticed that reported counters were generally close to their real value and their displacement were symmetrically distributed around zero. He came to this conclusion that the error in the case of dual-counting tasks is not related to a systematic under counting or over counting however he did not go further in suggesting a model for possible source of error in this task.

In terms of reaction time measures the average RT reduced from 1755 ms ± 197 ms (mean±STE) in the first block to 1225 ± 91 ms (mean±STE) in the second block. A one-way ANOVA for correlated measures was carried out which yielded a significance difference between average of RTs in two blocks (F(1,15)=10.27; p= 0.006). Reaction times were analyzed in more detail by separating the data for counting events related to counting a repeated target (when a target is the same as the previous target) and the data for counting non-repeated targets. The result was submitted to a 2×2 ANOVA for repeated measures on both measurements with repeating condition as a factor and the block identity as the second factor. The analysis revealed a highly significant main effect of repeating condition $[F(1,15) = 172.6; p < 0.0001]$ and a significant main effect of the block identity $[F(1,15) = 10.4966; p = 0.0055]$. The analysis did not detect a significant interaction between two factors $[F(1,15) = 0.53; p = 0.47]$. The observed significant effect of repeating condition is consistent with findings of previous studies in which processing an immediately past object of working memory is shown to be faster (Garavan, 1998; Oberauer, 2002).

Discussion These results show a clear improvement in performing TC task in two blocks of the experiment. This improvement is reflected in both the average reaction time and accuracy in counting task. However, in order to attribute this difference to the change in rehearsing strategy one needs to eliminate the possibility of improvement in performance of the task as a result of procedural learning. The design of experiment 1 does not allow to rule out the possibility of improvement in performing the task as a result of learning those aspects of task performance that are not related to the rehearsing strategy. All trials of MRR with low performance rate are performed earlier during the task and high performance condition are confound with later trials. Garavan has previously reported an improvement in reaction time as a result of continuous performance during concurrent counting of two targets (Garavan, 1998). The design of a control experiment should take this into consideration that if FRR as a more efficient strategy is employed first it is hard to administer and control for proper execution of MRR a less effective strategy in the second block. Thus in designing a control experiment reversing the order of performance strategies or interleaving blocks of different conditions might not be useful. The second experiment addresses this issue and provides an opportunity to test the effect of learning on performance of the task.

Experiment 2

The second experiment is designed to test possible effects of learning strategy-independent elements of TC task on performance measures in the previous experiment. In this experiment two blocks of TC were performed both under MRR condition. The protocol for the second experiment was similar to that of experiment 1 except that subjects who performed the task under MRR condition were asked to perform a second block with the same MRR strategy. Twenty healthy subjects (14 female) preformed the first block. Three subjects had adopted a fixed order of rehearsal in performing the first block which were eliminated from the study. Seventeen other subjects performed a second block of TC task with MRR condition. Before starting the second block subjects performed two additional trials to balance the number of trials before starting the second block with that of the first experiment. These extra trials between two blocks were not included in the analysis of results.

Results and discussion Figure 3 shows a summary of the results of the second experiment. First, inspecting average $SoError$ values showed that $SoError$ values in two blocks of MRR were very close. The average $SoError$ in the first block was 0.322 (SEM=0.072) and in the second block the average was 0.344 (SEM=0.073). Average $SoError$ values were submitted to a one-way ANOVA for repeated measurements which did not indicate a significant difference between mean of $SoError$ values $[F(1,16) = 0.7; p = 0.41]$.

Inspecting average $SumError$ values showed slight increase in the average of $SumError$s from 0.656 (SEM=0.168) in the first block to 0.751 (SEM=0.187) in the second block. A one-way ANOVA ofr correlated measurements also indicated that this difference is not statistically significant $[F(1,16) = 2.66; p = 0.122]$.

The average RT improved from 1637 ms (SEM=139 ms) in the first block to 1298 ms (SEM=98 ms) in the second block. This improvement proved statistically significant as a result of carrying out a one-way ANOVA for repeated measurements $[F(1,16) = 11.9; p = 0.0033]$. Further analysis revealed that a similar trend holds for both counting repeated targets and counting unrepeated targets. Values of RT for counting repeated events and unrepeated for both blocks were submitted to a a 2×2 ANOVA for correlated samples for both measurements with repeating condition as a factor and the block identity as the second factor. The analysis revealed a highly significant main effect of repeating condition $[F(1,16) = 37.64; p < 0.0001]$ and a significant main effect of the block identity $[F(1,16) = 14.403; p = 0.0.0016]$. The analysis also detect a significant interaction between two factors $[F(1,16) = 6.4085; p = 0.022]$. The average improvement of RT in this experiment was 340 ms (SEM=98 ms) which was less than 530 ms (SEM=160 ms) average improvement in RT between the first block and the second block of the first experiment. However, this difference proved insignificant after a post-hoc one-way ANOVA for non-correlated measurements carried out $[F(1,31) = 1.02; p = 0.32]$.

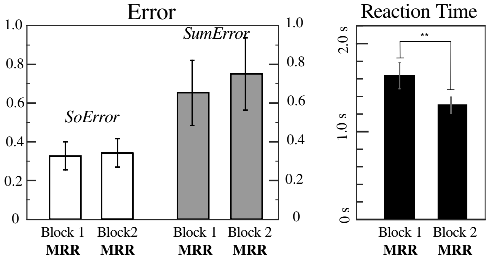
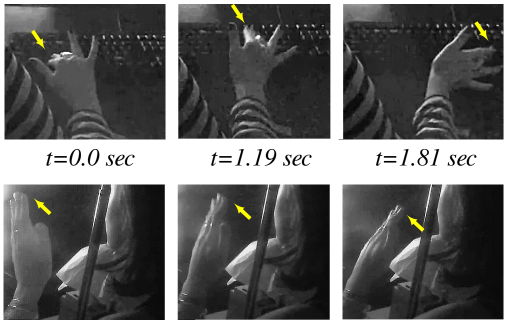


Figure 3: Results of experiment 2.

Results of this experiment first indicate that continued performance of the task affects reaction time and error measures differently. While RT is subject to improvement the average value of both measures of error remained in the same range. As a result, two experiments together did not produce a conclusive result about the effect of rehearsing on improving reaction times. As Garavan had shown for the case of dual-counting task RTs can reach to their asymptotic range after a long period of task execution and thus it seems that evaluating the impact rehearsing strategy on RTs is not reliable unless reaching to the plateau of RTs. In contrast, in terms of measures of error results of this experiment helped rule out an improvement in error rates as a result of procedural learning. This clearly helps establish this conclusion that switching to a fixed order for rehearsal helped reduce errors notably.

Body movements patterns during the counting task

Movement behavior of eighteen subjects from both experiments (eight from the first experiment) was visually monitored by the experimenter during performing the counting tasks for overt body movement. Task-relevant body movements were observed at least at one point during task execution in thirteen subjects. Body movements were repeating and synchronized with the process of rehearsing numbers. The body part, the form of movement and the amplitude of movement varied between subjects. The most prevalent form of body movement was taping or moving three fingers or pressing them against a hard surface in order (n=5). The next prevalent form of body movement was pointing to three locations in space by one finger or hand (n=4) (see Figure 4). Three subjects showed some forms of foot movement. In one case the subject made overt movement of two hands and one leg in association with rehearsing. Most of subjects even those who were aware of their body movement did not mention it as a part of their strategy in performing the task. Those subjects whose movement was not visible were asked about experiencing a spatial arrangement of numbers. Except two subject who rejected experiencing any spatial arrangement of numbers the rest expressed either a visualization or bodily movement such as pressing fingers associated to three numbers in an order from left to right.



t=0.0 sec *t=1.19 sec* *t=1.81 sec*

t=0.0 sec *t=0.48 sec* *t=0.72 sec*

Figure 4: Two examples of rehearsal-synchronized overt hand movement in triple-counting task. Subjects point to three locations.

Some instances of movements which were video recorded during the experiment can be found at the footnote web address[2]. Despite of variation in manifestation of body movements most of these movements can be characterized by a. an arrangement of three locations associated to three counters. b. moving from left to right and then cycling back from the rightmost location to the leftmost location. c. after each target presentation subjects performed at least one cycle of movements.

General discussion

Before further discussion about how different models of WM can explain the present data it is important to develop a deeper understanding of the nature of these measures of error and what they signify. Here I focus on the error in sum of counted values as it is the least sensitive between two measures of error and yet captures the effect of the rehearsal strategy clearly and significantly. Moreover, many factors that might cause error in counting and reporting individual targets can be discounted for the case of sum of counted values. In fact, as long as subjects add 1 to any of three counter values for each target presentation and report them in any order the error in sum of counters should remain zero. Subjects had to update their counter values after each target presentation and then press a key to see the next target and this eliminated the chance of missing any of counting events. The symmetric distribution of displacement of sum of counted values relative to the sum of real values also showed that the source of $SumError$ can not be a systematic missing or performing extra counting. One possibility which is examined in more detail here is that an increased value replaces a wrong target of update. This requires a two stage process in which once a value is retrieved from WM to produce a new value (by adding 1 to it) and then once again the item associated to the old value should be retrieved to be replaced by the new value. Note that replacing the newly produced number with the exact same retrieved value has no effect on $SumError$ as long as subjects add 1 to the retrieved value to produce the new number.

In a computer simulation of this process three variables were selected to be increased in 9 steps. In each step the increased value was misplaces and replaced a wrong value with a probability of p. The simulation for different values of p shows that $SumError$ monotonically increases with increasing p starting from zero. Moreover, the difference between sum of real values and sum of counted values is distributed symmetrically around zero with a variance which increases with the amount of p (see Figure 5). This demonstrates that this model of misplacing recently produced values with the wrong item of WM can capture the trend in present data. Thus I focus the rest of my discussion on explaining what different models can offer as an alternative explanation for possible causes of misplacing values.

Results of two experiments produced clear evidence of the effect of rehearsing strategy on the performance of the triple-counting task measured by $SumError$ and $SoError$ so that adopting a fixed order for rehearsing counter values across different trials significantly reduces the error. Rehearsing numbers in a fixed order throughout each trial was a strategy that all subjects attempted to follow independent of the type of the

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[2] http://tiny.cc/tc-motor

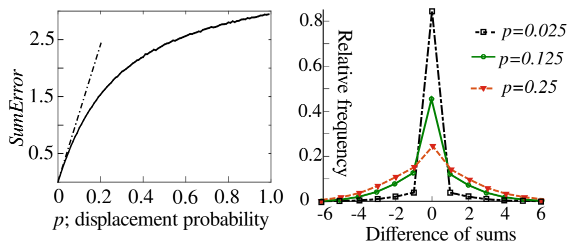

Figure 5: Simulated error of sum after nine counting events.

block. The difference between MRR and FRR blocks was that in MRR condition subjects altered the rehearsing order between trials while FRR condition subjects adhered to one rehearsing order for all trials of the block. When the above model for the source of error is considered, a viable model should be able to explain this effect through explaining how the chance of misplacing newly produced numbers increases as a result of altering rehearsing order between episodes.

What indeed is represented by the order of rehearsing is an internal representation which relates the order of three retained numbers in PL to an order for arranging three targets of counting. This internal representation apparently is an important aspect of performing the task. The disruptive effect of altering order of rehearsing between episodes or equivalently, the constructive effect of using the same order for different episodes suggests that retention of this internal representation is mediated by LTM. Thus a short-term buffer such as the episodic buffer in Baddeley's multi-component model (MC-WM) (Baddeley, 2000) by itself can not account for interference between trials as a result of changing rehearsal order. When the present data is applied to Baddeley's model it would imply that episodic buffer also employs long-term memory elements as well as short-term buffers contrary to Baddeley's own description (Baddeley, 2000).

SWM model accounts for the difference between performance under FRR and MRR conditions by assuming the effect of proactive interference between traces of target-registry state association. Since retrieving items from the rehearsal loop is mediated by retrieving the association between targets and states of registry system, using different associations for different episodes in effect increases the probability of retrieving a wrong item from the rehearsal loop as a result of interference between traces of previous associations.

An important difference between explanation of SWM and LTM-embedded models of working memory is that SWM explicitly assumes that the episodic information including three running numbers and the state registry system are volatile and thus short-term in nature. LTM-embedded models of working memory assume that episodic information are retained in LTM although in active state and under spotlight of executive attention (Cowan, 1999, 2001; Oberauer, 2009). To account for the present data with a fully LTM-grounded model one needs to first establish the relevance of rehearsing order to the mechanism by which items of WM are retrieved. When the same cue-based retrieval mechanism of LTM is assumed for retrieving items in WM as working section of LTM then the present data implies that the rehearsing order in PL encodes some sort of cue to be effective as a factor in performance of the task. However, this also creates a contradiction as one expect to see a disrupting effect for using the same retrieval cue in FRR blocks contrary to what present data suggests. Altogether ability of LTM-grounded models for giving account for this data will depend on the amendment about possible roles of rehearsal order in retention and retrieval of information.

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