Schema-Driven, Space-Supported Random Accessible Memory Systems for Manipulation of Symbolic Working Memory

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Abstract

We present an execution model for manipulation of working memory content during intellectual symbolic working memory tasks, which allows random access of WM content through a schema-operated sensory-motor spatial working memory. The core concept of this framework is binding symbolic items to spatial locations which are accessible *via* selective mechanisms of attention in space. An operational schema implements basic WM management operations such as insertion, deletion and fetching through sequences of shifts in spatial attention towards registry locations. We apply the model to a serial recall task (both forward and backward orders). We show that the model provides a better fit to human data in backward recall compared to forward recall, which conforms with the evidence for leveraging spatial strategies for backward recall and phonological strategies for forward recall in normal subjects. We discuss additional possible implications of our model and its assumption of spatial organization of WM content and access through shifts of attention.

Keywords: Memory Manipulation; Operational Schema; Forward Recall; Reverse Recall; Computational Modelling; Intellectual Tasks; Working Memory.

Introduction

Cognitive psychologists use the term *working memory* (WM) to emphasize on the use of temporarily stored information in connection with cognitive tasks that involve processing information (Baddeley, 1992). However, a review of the literature shows that the information processing aspect of cognitive tasks mostly applies to and have been explored using intellectual tasks with symbols. Tasks such as random digit generation, forward and backward digit or word span, mental arithmetic, *n*-back recall, double counting and sorting are prevalent in the context of cognitive psychology to explore the ability for manipulation and maintenance of information in working memory (see Repov and Baddely's review paper (Repovs & Baddeley, 2006)).

Although the credit for popularizing the term *working memory* goes to cognitive psychologists, the concept of *working memory* as the ability of temporarily storing information for the use in the upcoming task has been applied in other domains and to tasks that lack symbolic or intellectual features. For example, working memory which is of the interest in the perception community is related to maintenance and manipulation of information for sensory tasks such as visual search (Oh & Kim, 2004), or in action-perception domain for performing action routines (Arbib, 1987).

However what distinguishes WM in different domains is beyond differences in particular instances of *information* and indeed is mostly related to their execution models: the functional principles for management or manipulation of information. In particular what different models of working memory in the domain of cognitive psychology (CP) share is a meta-concept for their execution models which can be referred to as the dichotomy of process-storage. Applying this meta-concept to management of information for human working memory was one the most important contributions of Alan Baddeley and Graham Hitch to cognitive psychology which was originally presented in their seminal work (Baddeley & Hitch, 1974), and ever since has become the common denominator of all models of WM in CP. In this dichotomy which was inspired by Von Neumann's architectural design for modern digital computers (Von Neumann, 1982), the role of execution and processing is given to a central processing unit —namely the Central Executive (CE)—which controls the flow of information between and within storage slave units. However, a long debate over the nature of storage in CP community (Jonides et al., 2008) has restricted elaborations on functional mechanisms of CE.

The concept of CE in WM management did not prove as successful as its counterpart in Von Neumann's proposal in achieving a working memory management schema which helps information processing. What distinguishes the central processing unit (CPU) in Von Neumann's architecture from CE in Baddeley's proposal is that the CPU had all mechanisms for control of storage units built in, while Baddeley and Hitch use the central executive as a metaphor for a central and powerful executive unit with no specific detail as to how CE controls slave storage units (Baddeley, 1992). As Baddeley himself has stated in several occasions because of this lack of specificity, CE has become *the rag bag of unanswered questions*(Repovs & Baddeley, 2006) or a *homunculus* (Repovs & Baddeley, 2006; Baddeley, 1996). What is known about the executive role of the central executive, for the most part, is postulated by Baddeley and colleagues. Inspired by Norman and Schallice's idea of the Supervisiory Attentional System (SAS) (Norman & Shallice, 1986), Baddeley has proposed that CE plays a role in controlling limited resources of executive attention (Repovs & Baddeley, 2006; Baddeley, 1996). However, adding the function of controlling executive attentional resources has not been able to fill the void of a paradigm for an executive model for manipulation of information and to yield a model that explains how executive paradigm are encoded.

To give an example of an alternative meta-concept for manipulation of information we can refer to Arbib's work on information processing in perception-action loops. Arbib in his neuroethologic studies used the concept of information processing in a mechanistic fashion (Arbib, 1980) which was informed by Norbert Wiener's theory of control and the concept of interplay between information and action in controlling biological organisms (Wiener, 1948). The term *'Schema'* was the key concept in Arbib's terminology for describing how neural systems interplay to exchange information to achieve a biological goal (Arbib, 1992). In his later work on modeling visually-guided actions, he included the concept of working memory as a mechanism for sustaining information representations relevant to upcoming actions, as long as they remain relevant (Arbib, 1987).

While we share our target of study with contemporary cognitive psychologists, in devising an execution model for manipulation of information in the intellectual and symbolic domain, we are influenced by Wiener's system-theoretic and biologically-plausible concept of flow of information, and by Arbib's schema-theoretic approach (Arbib, 1992). We also have one specific additional assumption for our execution model for memory manipulation, which is the use of space-supported sensory-motor systems in manipulation of information. We argue that, from an evolutionary standpoint, it is plausible that the capacity of performing intellectual symbolic tasks, which are very recent in our evolutionary history, might have emerged by re-using or co-opting rudementary systems for action and perception. Thus, we try to re-use sensory-motor systems as the building blocks of our approach to a model of working memory for intellectual working memory tasks.

We refer to this schema-driven and space-supported sensory-motor system which provides a random-accessible memory system for manipulation of information as the spatial registry system (SRS). The following section of this paper explains the general concepts of SRS. To demonstrate the power of this paradigm, we present a simple SRS model for immediate forward and backward recall. We show that the model explains the human patterns of errors in backward recall, which has been argued to utilize space for memory organization. Finally, we discuss what we learned from this simulation effort.

The Spatial Registry System (SRS)

The focus of this section is description of a system for random access of symbolic content of working memory during intellectual mental tasks. Random-accessible working memories are the critical components for dynamic manipulation of information. Yet, they are not the only working memory systems in the context of intellectual working memory tasks. We later discuss a serially-accessible memory as an additional utility memory which collaborates with SRS systems for achieving a complete functioning working memory system.

We propose that symbolic items of the working memory can register with spatial locations in a grounded sensory-motor system which is supported by a spatial representation. Examples of such system –as we presented elsewhere (Noori & Itti, 2011) – can be occulomotor system, or a kinesthetic system that helps proper configuration of body parts in space using proprioception and muscle movements (think of a profoundly blind individual's ability for performing tasks in space without any visual reference).

This registry mechanism provides spatial addressing for random access to items of working memory. What is critical is how this addressing is used in the process of memory manipulation. The critical component is spatial selective attention (SSA) as a means to shift between items that are registered with space. An operational schema (OS) defines the sequence of shifts between registry locations.

For example, imagine the case of a concurrent mental head-counting of adults and children in a party. As your gaze shifts to a person in the living room, first your visual system becomes engaged in identifying whether the person at focus is an adult or a child. In the next step, one of two running counts that matches the identified category should be increased by one. The challenge is keeping track of two numbers and associating them to categories. A spatial registry strategy is associating the existing count of adults n_a to location l_a (e.g., left side in visual field or under pinky finger of the left hand) and the existing count of children n_c to location l_c (e.g., right side of visual field or under index finger of the left hand). Identifying the next child will trigger a shift of spatial attention to l_c, to fetch the current count of children. Once the increment operation is applied on the current count the result will replace (by first deletion and then insertion) the old count. Note how attention shifts might be used both for perception of the external world and for selection of WM items, which, under the SRS hypothesis, might give rise to conflicts in some situations, which in turn provides ways to test the hypothesis (see Noori and Itti's paper in this proceedings (Noori & Itti, 2013) where they report the effect of congruency of shift of spatial attention for target detection and shift of selective attention in internal domain during triple-counting of visual targets).

The operational schema can be conceptualized as a list of mappings of the current state onto the next action. Here is a formal representation of an alternative OS for our head-counting scenario.

$\mathcal{OS}_1 : \{child \Rightarrow shift\ to\ l_c\ ;\ adult \Rightarrow shift\ to\ l_a\}$
$\mathcal{OS}_2 : \{at\ l_c \Rightarrow fetch\ n_c\ ;\ at\ l_a \Rightarrow fetch\ n_a\ \}$
$\mathcal{OS}_3 : \{\ at\ l_c\ \&\ n_c\ is\ retrieved \Rightarrow n_c \rightarrow n_c + 1$
$;\ at\ l_a\ \&\ n_a\ is\ retrieved \Rightarrow n_a \rightarrow n_a + 1\}$
$\mathcal{OS}_4 : \{shift\ the\ gaze\ to\ next\ person\ \&\ identify\ the\ category\}$

Each of these schemas may include other sub-schemas. For example $n_c \rightarrow n_c + 1$ in $\mathcal{OS}_3$ may include a sequence of operations over internal representation such as deletion and insertion (binding to space).

We have discussed the neural evidence for this hypothesis elsewhere (Noori & Itti, 2011). Here we only mention one neuropsychological study which provides a critical evidence for our proposed model(Koenigs, Barbey, Postle, & Grafman, 2009). Koenig *et al.* showed that patients who have sustained damage to their superior parietal lobule (SPL) generally lose their capacity for mental operations that need rearrangement of information and thus they concluded that SPL is *critical* for manipulation of information in working memory. Interestingly, SPL is a part of the association cortex in the posterior parietal cortex (PPC) and sits at the junction of several sensory processing regions, with projections to motor area of the brain. SPL is shown to be critical for a wide range of routines that need sensory-motor integration, such as navigation, visual search, etc (Rizzolatti, Fogassi, & Gallese, 1997).

We need to add that the spatial registry system is not a unitary system and several SRS systems might collaborate in running the executive machinery of working memory. However, what all SRS instances have in common is, first, their build-in internal space representation, second, a mechanism to shift the attention to those locations, and, third, a binding mechanism which can associate locations with symbolic representations.

In our view, spatial registry systems are complemented by other systems that mimic a serially-accessible memory, to provide a layer of working memory for intellectual symbolic tasks. An example of such system can be the sensory-motor system that supports speech perception-vocalization (Wilson, 2001) which is believed to be critical for spoken language acquisition (Baddeley, Gathercole, & Papagno, 1998).

A Spatial Registry System for Serial Recall

Here we present an SRS model for the immediate serial recall task for both forward and backward recall directions. As we will discuss later in our review of the literature, experimental evidence suggest that forward and backward recall draw on different brain systems. Forward recall seem to take impact from phonological characteristics of the list items (Bireta et al., 2010), suggesting that forward recall relies on phonological resources of the brain. On the other hand, backward recall is disrupted in individuals with deficit in spatial cognition (Rudel & Denckla, 1974), suggesting that backward recall relies on spatial encoding. We used a spatial registry model applied to both directions of recall; however, as we will discuss, we learned that our SRS model provides a better fit for human behaviour, which conforms with what is assumed about involvement of different systems of working memory in two immediate recall directions.

A brief review of the literature

Serial digit span tasks are common in both clinical assessment and neuropsychological studies (Rudel & Denckla, 1974). However, forward recall, disproportionately, has received more attention in modeling attempts. This is mainly related to the importance of temporal serial order in everyday tasks (Glasspool, 2005). As the result, there are many neural models, behavioural models, and mathematical models dedicated to describing forward recall. In contrast, for backward recall, theoretical efforts mostly have focused on augmenting or reusing models of forward recall. In the face of abundant behavioural and neural evidence that serial recall in forward and backward directions draw on different brain mechanisms, it is not surprising that models of backward recall have obtained remarkably less success in describing human behaviour compared to forward recall (Bireta et al., 2010). Only flexible mathematical models with enough degrees of freedom ,such as the Temporal Ratio Model (Brown, Neath, & Chater, 2007), have been able to successfully model both recall tasks in one shot (Bireta et al., 2010).

In terms of similarity, recalling in both orders shows recency and primacy effect (Henson, 1996; Li & Lewandowsky, 1995). Yet ,in forward recall a stronger primacy effect is observed (Henson, 1996), while in backward recall a stronger recency effect is observed (Li & Lewandowsky, 1995). Several studies have revealed the difference between recalling in two directions. Bireta *et al.* tested four benchmark effects that demonstrate the role of phonological resources in immediate forward recall tasks – the *word length effect*, the *irrelevant speech effect*, the *acoustic confusion effect* and the *concurrent articulation effect*– for both directions of recall. They reported that the benchmark effect *'was either absent or greatly attenuated with backward recall despite being present with forward recall'*. On the other hand, Li and Lewandowsky observed that altering visual-spatial characteristics of the recall list affected backward recall and not forward recall (Li & Lewandowsky, 1995).

Neuropsychological evidence also supports that neurological damage to phonological resources of the brain impairs forward digit span while damage to spatial resources of the brain impairs backward digit span (Rudel & Denckla, 1974). Consistent with these observations, neuroimaging studies also have revealed differences in cortical regions which are active during the two different recall orders (Sun et al., 2005; Hoshi et al., 2000). In particular, these studies have revealed significant activation of cortical areas with spatial processing characteristics in backward recall compared to forward recall.

In terms of modling efforts, Bietra *et al.* have briefly reviewed existing models. Their review indicated that those models that take the phonological aspect of forward serial recall are not successful in modeling backward recall, and only models that are agnostic to the difference in underlying mechanisms of serial recalls in two different directions are relatively successful in modeling both tasks.

In sum, available evidence suggests that a model that confers a special role to space may be necessary for a mechanistic model for the backward recall. In the following section we detail such a model, built based on the specifications of the SRS model for visuospatial working memory as the spatial registry.

Simulation

A population coding of a one dimensional space in the form of an array of neurons was used as the registry space. Population coding of neurons has been extensively explored (Pouget, Dayan, & Zemel, 2000) in the literature and is popular for neural modeling of visuospatial working memory (Constantinidis & Wang, 2004). This array of neurons encoded a parametric space spanning the range of -1 to 1. The tuning curve for neurons in this array was characterized by $\sigma_0 + x_n \times \kappa$ where σ_0 is the tuning band parameter of the neuron at the center of space, x_n is neuron's peak response location, and κ a constant which controls the variability of tuning band in the array of neurons.

Registering with a specific location would trigger noisy activation in the population around the target memory field. The share of a registry at x_r in activation amplitude of a neuron at x_n is determined by $A_0 e^{-\frac{(x_r-x_n)^2}{2\times\sigma_n{}^2}}$. In case of registering several items in the activation of a neuron is defined as the sum of evoked signals of all registries as long as the sum of signals is less than a saturation value $\mathcal{S}$. So the base response amplitude of neuron n is defined as follow:

$$max(\mathcal{S}, \sum_{i=1}^{N} A_i(t) \times e^{-\frac{(x_{r_i}-x_n)^2}{2\times\sigma_n{}^2}}) \qquad (1)$$

where i is the index for registered items, x_{r_i} is the registry location of the item i and $A_i(t)$ denotes the effective amplitude of the ith registry at time t which is defined by:

$$A_0 \times e^{-\frac{t-t_i}{\tau_d}} \qquad (2)$$

where t_i is the registry time of item i and τ_d , the damping factor, controls the decay rate of registry effects.

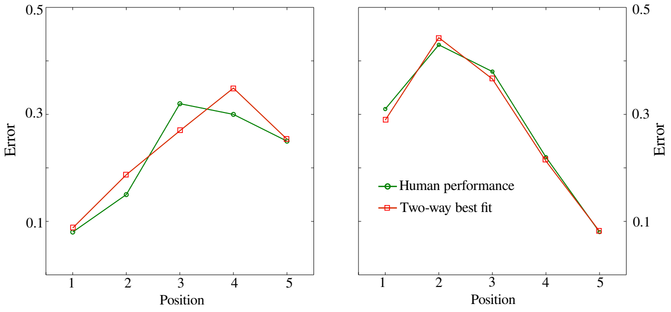
The schema for the immediate recall task includes two phases: binding and recall. During the binding phase, independent of the recall order, items of the list orderly register with locations from left to right so that each item in the list registers on the right side of previously registered item (except the first item). The exact times and locations of registries are perturbed by different random distributions. The distances between registry locations are determined by a Weibull distribution with two parameters (shape factor and scale factor). Duration of registry and recall processes are defined by two separate Gaussian distributions, which adds four more parameters to our model.

In the recall phase, a part of the schema is independent of recall direction, which is the condition for identifying the most active neuron, and for selecting the next item (until all items are removed from the registry space). Neurons in the array compete for gaining control of a registry recalling unit. The item at the closest registry location to the selected neuron will be recalled. Recalling memory items from registry involves inhibiting neurons in the array associated with registration of the recalled item.

Another part of the recall schema which is sensitive to the direction of recall is characterized by a bias. The bias is applied by a multiplicative exponential factor of the position which acts as a biased modulation of neural activities. For forward recall, this bias will enhance the activity of neurons on the left side of the space, and during the backward recall this bias enhances activities of neurons on the right side of the space. So, a part of the schema for recall is selecting the bias direction; however, once the bias direction is selected items will be selected only based the order of most active neurons.

Par	*Description*	*Par*	*Description*
σ_0	Spatial tuning at the center	κ	Tuning band var factor
β	Bias factor	ν	Noise factor
τ_d	Damping factor	K	Binding shape factor
λ	Binding scale factor	$\mathcal{S}$	Saturation factor
μ_b	Mean for binding duration	σ_b	STD for binding duration
μ_r	Mean for fetching duration	σ_r	STD for fetching duration

Table 1
Parameters of the SRS model for serial recall



(a) Forward Recall (b) Backward recall

Figure 1: Positional error for the best two-way fit for both directions of recall compared to the human performance.

This implementation only accommodates positional or movement errors in which items are recalled in the wrong order. This type of error is the most prevalent error among adults (McCormack, Brown, Vousden, & Henson, 2000) in recall tasks. However there are other types of errors such as omissions, intrusions and repetitions with less significant effect. Table 1 summarizes all parameters of this implementation.

Results and Discussion

To explore tuning parameters we used serial position error for a list of five items from Li and Lewandowsky's study (Li & Lewandowsky, 1995). An evolutionary algorithm was used to optimize the parameters based on the sum of absolute distance of predicted positional error over the ground truth data for both directions. So optimization of parameters was performed with regard to ground truth data for both directions simultaneously and forward and backward error data played equal roles in the evaluation function. However a closer inspection of the result revealed that the final parameters shifted in favour of the backward data. The best fitting parameters among 2857 independently generated solutions yielded a prediction for backward recall with 5.6% absolute distance to the human data (out of 500% maximum possible distance) while the same set of parameters yielded a prediction for the forward recall with 14.8% absolute distance to the human data (see Figure 1). Further analysis of best first 100 independent solutions of the optimization process showed that the quality of predicted solution for backward recall was significantly better than forward recall ($t(198) = 47.93, p < 0.0001$), where the difference between mean of fitness qualities was 6.6% in favour of the backward recall.

Moreover, a closer inspection of all generated parameter sets during during optimization process revealed two highly distinguishable modes for σ_0, the first order tuning curve parameter. A population of solutions with narrow tuning curve at the center peaked around $\sigma_0 = 0.04$ which included 847 solutions all with $\sigma_0 < 0.1$. Another population of wide tuning curve at the center peaked around $\sigma_0 = 0.57$ all with $\sigma_0 > 0.38$ included 2010 solutions. Later analysis of the fitness values of these solutions showed that the population of wide tuning curve (WTC) on average scored better fitness value than the population of narrow tuning curve (NTC). The wide tuning curve population (WTC) generally scored better in each of recall types compared with the narrow tuning curve population. Moreover, WTC and NTC populations were also highly separable with regard to other parameters including the bias factor, and temporal characteristics of binding and recall of item. In particular the for WTC the average duration of the task was correlated with the damping factor of neural activity while the duration of the task was independent of the damping factor of neural activities. In sum, WTC population provided both better solutions and more plausibility.

To test the predicting power of the model we used the parameter of the best solution discovered in the optimization of the previous phase to simulate the movement errors (the distance between order of an incorrectly recalled item, and its true order; e.g., if item 3 is recalled as item 2, the movement error is 1) in forward recall data for six items, from another study (McCormack et al., 2000). Note that number of items for training was different than for testing. Moreover, positional error data, which is used for optimization of parameters, is independent of movement errors (which we confirmed through simulation, not shown here).

Figure 2 shows the result of our simulation in the same graph with the data of two adult human subject groups, tested in two different experiments with different settings for a forward recall task (McCormack et al., 2000). Our simulation result sits in between the data points for two different results for adult human subject groups, which demonstrates that our prediction is in the range of the variability of the performance of human subjects, and clearly demonstrates the predictive power of the model.

In sum, the result of our simulation shows that SRS for immediate serial recall can account for human behaviour. However, as it was explained, the quality of our solution for backward recall is significantly better than the quality of our result for forward recall once both recall orders played the same role in optimization of parameters. This may be related to the fact that normal subjects leverage their phonological resources for forward recall (Bireta et al., 2010).

This does not mean that visual-spatial resources cannot be used for forward recall. In fact previous studies have shown that articulatory suppression during working memory task with written verbal material can eliminate the effect of other signature effects such as word length effect or acoustic confusion effect without diminishing subjects' capacity for remembering the serial order (Wilson, 2001). These evidences suggest that once the speech recognition-vocalization system as the primary source of encoding serial recall is no longer accessible (by articulatory suppression) and working material are presented in visual format, another mechanism is utilized for encoding serial recall which does not rely on phonological resources. We argue that one could use a visual-spatial strategy for forward recall too. In this case, the prediction of our SRS model is that the overall performance would not be significantly better (see Figure 1a). However, using phonological resources for the forward recall has at least one advantage, which is freeing visual-spatial resources for other tasks. In contrast the ability to perform a backward recall task with impaired spatial resources is restricted (Rudel & Denckla, 1974), in agreement with our finding that visual-spatial resources are used for backward recall.

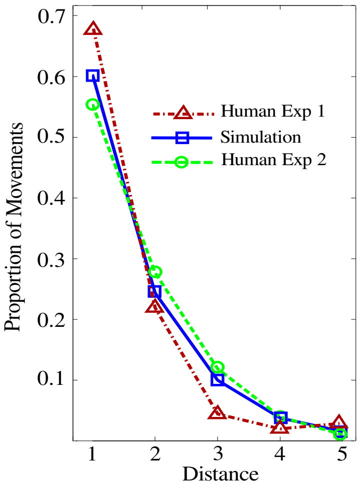


Figure 2: Prediction of SRS model along experimental data for movement errors during serial recall of six items.

General Discussion

In this paper we presented the idea of a space-supported, schema-driven, random-accessible memory system in the domain of intellectual working memory tasks of cognitive psychology. Our proposal included a strong evolutionary assumption about what would constitute an executive model for a working memory system in the intellectual domain, which can be built atop sensory-motor systems that support perception-action routines. Perception-action routines, such as prey catching, evolutionarily, preceded the intellectual routines, such as mental subtraction, and thus we suggest that sensory-motor working memory systems for regulating the former routines might have been reused for maintaining and manipulation of information needed by the evolutionary more recent latter routines.

The presented model provides a randomly-accessible working memory, yet to get a full-function working memory model that explains human behaviour across different domains, one may need to take a serially-accessible working memory subsystem into consideration too. A speech perception-vocalization subsystem –which resembles the phonological loop in Baddeley and Hitch's three-component model of working memory (Baddeley & Hitch, 1974)– may be considered as an alternative serial component of working memory machinery in the domain of symbolic tasks. However, we argue that a serial system is not sufficient to explain humans' flexible memory manipulation of symbolic information in the intellectual domain, and one may need to include a faster and more flexible working memory system for random access to its content.

Finally one may argue that the visuospatial sketchpad in Baddeley and Hitch's model (Baddeley & Hitch, 1974) can achieve the same function of our proposed SRS system. We can summarize the differences or our spatial registry system and the visuospatial sketchpad as follow.

First, while visuospatial sketchpad is merely a visual-spatial system our SRS is a generic schema-driven system and as previously suggested several instances of sensory-motor working memory systems (e.g. occulomotor or kinesthetic system) may fulfil the characteristics of SRS.

Second, our SRS comes with a built-in executive system in the form of the operational schema (OS), while the visuospatial sketchpad outsources the execution functions to the CE, with no specifications of how this executive functions are exerted. In this sense, SRS provides a mechanistic model of manipulation of WM items while the sketchpad is a passive storage resource.

Third, in Baddley's model visuospatial sketchpad is a domain-specific storage slave unit which stores task-relevant visual-spatial information, while in our proposal an SRS system may play a general role in manipulation of symbolic information with no immediate visual or spatial features.

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