# Spatial Registry Model : Towards a Grounded Account for Executive Attention

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## Abstract

Mental tasks that feature algorithmic processing with symbolic items are shown to rely on brain regions known for visual-spatial functions. Yet, exactly how these functions may help execution of amodal tasks remains an open question. Here we propose a hypothesis for manipulation of items in working memory, which relies on registering items in a spatially-organized short-term memory store. Switching executive attention to items that need processing may then be embodied through shifting spatial attention towards those registry locations. We studied gaze shifts of human subjects during memory tasks as a proxy for shifts in spatial attention. Analysis of gaze shifts during sorting random sequences of five decimal digits indicates that sorting in memory elicits gaze shifts that correlate with sorting procedure. Our proposal establishes a functional relationship between general-purpose production mechanisms that support algorithmic memory tasks with amodal items, and modal systems for perception and action.

**Keywords:** Cognitive Architecture; Algorithmic Information Processing; Visuospatial Attention; Executive Attention; Working Memory; Spatial Registry Model.

## Introduction

Cognition by means of amodal symbolic concepts in an algorithmic manner is a unique trait of the human species. Identifying the relationship between this newly emerged symbolic machinery and evolutionarily older systems for perception and action is a fundamental question about the nature of human cognition that has motivated numerous studies during recent decades. The focus of a host of these studies has been grounding representation of symbolic concepts in perception and action (Barsalou, 2008; Dehaene & Cohen, 2007; Wood, Willmes, Nuerk, & Fischer, 2008).

However, this mode of human cognition is equally dependent on a general purpose machinery that can support robust execution of algorithms. Such a machinery should provide basic functions such as temporary maintenance of relevant items and applying selective processing to the maintained items. For example think of an instance of a mental subtraction problem (let's say 412 - 78) which normally needs to be done in a controlled and algorithmic way rather than an automatic way or direct recall from the long term memory. In this case a feasible algorithm for the mental operation should fulfill the constraints of this machinery such as capacity limitations in working memory. Given the limited capacity of the working memory, one might argue that an efficient algorithm for mental subtraction might be different from formal algorithms for subtracting Arabic decimal numbers (which usually do not take the notion of working memory into account). These operations usually require maintenance of several symbols each one subject to a specific process in each stage.

Recent behavioral studies conducted with concurrent tasks paradigm have identified that memory tasks involved with symbolic concepts that feature memory manipulation, interfere with visual processing to a larger extent as compared to passive maintaining of similar items (Akyürek, Hommel, & Jolicœur, 2007; Fougnie & Marois, 2007; Han & Kim, 2004; Peterson, Beck, & Wong, 2008; Spinks, Zhang, Fox, Gao, & Tan, 2004). These findings suggest that visual perception and parts of this machinery in charge of memory manipulation draw on common resources crucial for both processes.

Meanwhile among all regions that are actively involved in executive memory tasks, recently the role of a parietal region with strong visual-spatial characteristics has been highlighted. More specifically in a patient study, (Koenigs, Barbey, Postle, & Grafman, 2009) showed that damage to the superior parietal lobule (SPL) is reliably associated with deficits on tests involving the manipulation and rearrangement of information in working memory. This brain region is known for its contributions to a variety of visuospatial functions such as saccadic eye movements(Quintana & Fuster, 1993), visuospatial attention (Kanwisher & Wojciulik, 2000; Griffin & Nobre, 2003), visuospatial short-term memory (D'Esposito et al., 1998) and visuomotor functions (Ferraina, Battaglia-Mayer, Genovesio, Archambault, & Caminiti, 2009).

Significance of Koenigs et al. 's findings is partly related to showing that dependency of the symbolic machinery to perceptual system is not limited to representation and is also related to the processes that support execution of dynamic or active memory tasks.

Tasks featuring memory manipulation are also known to be attention-demanding and thus some researchers have suggested that involvement of SPL in these tasks is related to focusing executive attention (Osaka, Komori, Morishita, & Osaka, 2007). Yet existing theoretical frameworks have not elucidated how visual-spatial characteristics of this region are exploited for either memory manipulation or focusing attention. To provide a theoretical account for involvement of visuospatial systems in memory manipulation we propose the Spatial Registry Model (SPM).

## Spatial Registry Model

Our proposal assumes a functional role for brain regions with visual-spatial encoding features in registering memory items in a spatially-organized short-term memory. We assume that an item in working memory may register with a corresponding visuospatial short-term memory. This registry may occur when selective access to memory items is required.

We assume that binding of items to spatial locations is not random and is guided by biological/behavioral preferences that fulfill the task requirements. For example a linear layout with a particular direction for a registry provides the advantage of encoding the sequential order of items in a natural way and might be critical for tasks that need explicit information about the sequential order of items. In this case a linear spatial registry with an arbitrary orientation might satisfy this requirement, however, the choice of orientation and direction for a particular subject might be determined by other biological preferences set by dominant trends in the environment or previous experiences.

These spatial registries may then be used as a handle to activated items in working memory for further processing such as memory retrieval or selective deletion of memory items. In fact Griffin and Nobre (Griffin & Nobre, 2003) have shown that orienting spatial attention towards locations represented in working memory is possible and results to similar behavioral advantages of orienting spatial attention to perceptual space.

For instance, imagine double counting as a mental task in which two signals are be counted separately. In this case two numbers are actively maintained in working memory and upon receiving each of signals, its associated number should be incremented by one. Our framework suggests that registering these two numbers with spatial locations in turn might help proper handling of incrementing operation. So if number $n_1$ associated to signal $s_1$ is registered with location $l_1$, upon receiving $s_1$ spatial attention will be shifted to $l_1$ to retrieve $n_1$ for incrementing. Associating counters to spatial locations in this case facilitates retrieving corresponding counters.

Our hypothesis implies that those tasks that require selective processing on several concurrently maintained items in working memory, impose an extra load on systems for spatial encoding. This condition applies to a variety of tasks referred to as executive memory tasks or active memory tasks which have been shown to engage SPL (as a region with spatial encoding characteristics) (D'Esposito et al., 1998). More specifically Osaka et al. (2007) in a study of group differences showed that performance in an instance of these tasks is correlated with activation of SPL, so that low performance subjects show little activation at this site.

Given the close relationship between visuospatial attention and eye movements (Hoffman & Subramaniam, 1995; Kowler, Anderson, Dosher, & Blaser, 1995), to test this framework we studied eye movement behavior of human subjects during an abstract mental task, as a proxy for deciphering shifts in spatial attention during mental algorithmic processing. It has been previously shown that tasks such as mental multiplications increase the rate of eye movements (Lorensjr & Darrow, 1962). We hypothesize that additional eye movements during mental multiplication is related to shifting spatial attention, driven by corresponding shifts of executive attention to different items kept in working memory during the operation. Thus, we expect that at least some aspects of eye movements during memory tasks should be memory-bound, and hence should be systematically bound to algorithmic features of the background process.

We tried a simple task with algorithmic features that can easily be manipulated to study how such manipulation may impact eye movement patterns. Our task was sorting five digits into ascending order in memory. Stimuli were initially presented visually, however we instructed and monitored subjects to perform the task from memory and in front of a blank screen (Figure 1).

To capture a dense spatial gist of eye movement data, which can also capture possible shifts in spatial attention we formed normalized distributions of gaze shifts. We processed eye movements made during the course of task execution and when no visual stimulus was present on the presentation screen.

Our first experiment demonstrates that unlike passive maintaining of items, initial binding of memory items to spatial locations significantly modulates eye movement activities during the sorting task even though the stimulus is not visually present. To manipulate spatial binding of items we primed two different orientations by initial visual presentation of items along two different orientations (horizontal and vertical). The idea is that priming an orientation might guide spatial binding of items into space along the primed direction. We then tested whether eye movements respond to this spatial priming during active processing (task 1) versus passive maintaining (task 2). Dependency of each task on spatial access to memory items through shift in spatial attention may then result to modulation of eye movements along the primed direction.

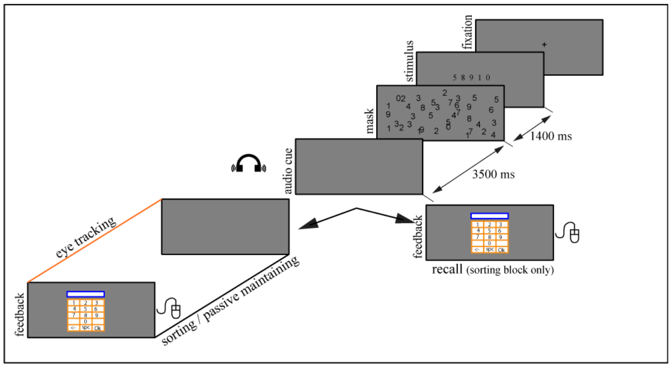

Figure 1: *Schematic view of the experimental paradigm.*

Our second experiment is designed to show that modulated eye movements during the sorting task are indeed correlated with the sorting procedure. To do so, we categorized the stimuli for the sorting task into subsets that presumably require similar processing sequences in a generic order-sensitive sorting algorithm. Significant differences between gaze shift patterns for different categories of sequences then would show that shifts in spatial attention are correlated with the process of sorting. We compared the eye movements for two categories of stimuli with that of their reverse stimulus type (mirrored sequences). The idea is that reversing the order of items of mental stimulus will lead to symmetric binding of items to spatial locations. Thus, a process controlled by shifting spatial attention to registry locations of items would be expected to induce symmetric shifts in spatial attention and, accordingly symmetric memory-bound gaze shifts.

## Experiment1

### Aparatus

Stimuli were displayed on a 46-inch LCD monitor (Sony Bravia XBR-III, 1,016 × 571.5 mm), 97.8 cm in front of participants (corresponding field of view is $54.7^\circ \times 32.65^\circ$). A fixed chin rest was used to position the eyes in front of the screen and the height of the seat was adjusted. Eye position was tracked by an ISCAN RK-464 (ISCAN) in pupil-CR mode (240 Hz) to right eye.

### Procedure

All items were presented completely for 1400 ms on the screen, $3^\circ$ wide on a gray background in black font size 24pts. Stimulus presentation was followed by a visual mask consisting of random digits scattered all across the screen for 100 ms to flush the iconic memory traces of the stimulus. A delay period of 3500 ms was imposed after the visual mask. The delay period was ended with an audio signal.

During the blocks of sorting task the signal was either a cue for sorting (two thirds of trials) or for unsorted recall (one third of trials). Because subjects did not know in advance whether they would have to answer with the sorted or unsorted digit sequences, we reasoned that they would be forced to wait until the end of the delay period – after the stimulus had been long removed from the screen – before they started any sorting.

Subjects were informed about monitoring their performance on the recall task and were notified that in case of a performance below 90%, their result would be discarded. All subject could meet the 90% performance level for the recall task. Responses were collected manually and through a two-button computer mouse operated by the right hand. For reporting the items a virtual keypad was presented on the screen. Items were selected from a $3 \times 4$ graphical table with ten cells designated to ten decimal digits, one cell designated to backspacing and one cell to white space.

Subjects were instructed to repeat the sorted string once and before clicking for reporting the sorted string. During sorting trials eye movements were recorded after the audio cue for starting the sorting process and mouse click for reporting the sorted string. During the sorting task, total trial duration was unlimited and subjects would click a mouse button once they finished the sorting task. During the passive maintaining, the duration of trials were randomly chosen from a normal distribution of duration times for sorting.

### Participants

Six female and three male university undergraduate students with normal or corrected to normal vision, participated for course credit. Participants' ages ranged from 18 to 24 (M=22.3 years, SD=1.8). Eight subjects reported to be right handed and one subject reported to be left handed.

### Stimulus

We tried two different visual presentation methods (horizontal and vertical) to establish different spatial associations between locations and memory items. Stimulus for each trial was a random string of five non-repeating decimal digits. The experiment was administered in four blocks for different combinations of tasks and presentation methods. Subjects performed the sorting task in first two blocks. Each block contained 15 recorded sessions.

### Results

We analyzed the normalized distribution of gaze-shift directions (GSD) to measure eye movement responses to presentation method during each of tasks. The value of the normalized distribution of gaze shift direction (GSD) along a specific direction conceptually represents the probability of making a gaze shift in that direction, so the difference between normalized GSDs along a certain direction represents the difference between probabilities of gaze shift under two compared conditions.

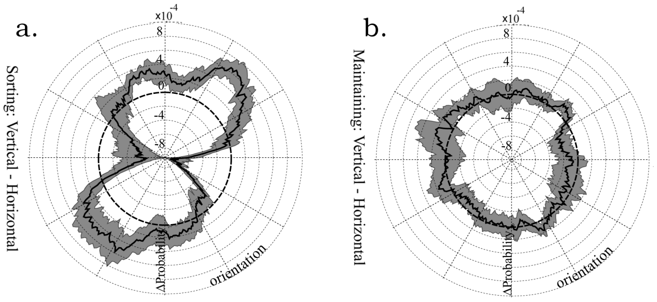

Figure 2: *Difference between probability distribution of gaze shifts orientation. Difference of probability values is shown radially, dashed bold circle marks zero. The graph on the left panel is related to the sorting task, the one on the right panel is related to the passive maintaining task.*

If memory items are accessed through shifts in spatial attention, we expected to see significant impact of initial priming onto eye movements during active processing. In contrast, since passive maintaining is believed to rely only on articulatory rehearsing in the phonological loop(Baddeley, 1992), we expected to see little or no impact during passive maintaining.

Inspecting the data validates our hypothesis (Figure 2). Indeed during the sorting task, GSD for the horizontal presentation method on average is biased along the horizontal direction compared to the normalized GSD for the vertical presentation method (Figure 2.a). This bias can be measured by disparity between GSDs along the horizontal direction (gaze shifts within ±45° from horizontal) or along the vertical direction (gaze shifts within ±45° from vertical). When the task is sorting, the difference in GSD along the horizontal direction, for horizontal relative to vertical presentation, on average is $+4.41\% \pm 1.51\%$ (mean± SE) which is significantly above the chance $(ttest, n = 9, p < 0.0192)$. However, when the task is passive maintaining (Figures 2.b) the difference in GSD along the horizontal direction on average is $1.3\% \pm 1.76\%$ (mean ±SE), n.s. $(ttest, n = 9, p \geq 0.9288)$.

This result shows that unlike passive maintaining of abstract items, during active processing, gaze shifts notably respond to the orientation along which the memory items are spatially associated. However, the significance of this result is related to demonstrating that the shifts in spatial attention (measured by gaze shifts) are indeed independent of the representation of memory items proposed by some researchers(Wood et al., 2008; Dehaene & Cohen, 2007).

## Experiment 2

In this experiment we tested whether string of digits that require different steps for sorting induce significantly different gaze shift patterns. Our metric for difference in the sorting procedures maps onto the cost of sorting using a generic order-sensitive algorithm.

### Participants

Seven female and three male university undergraduate students with normal or corrected to normal vision, participated for course credit. Participants' ages ranged from 18 to 23 (M=21.9 years, SD=1.6). Eight subjects reported to be right handed and two subjects reported to be left handed.

### Stimulus

We hypothesized that sequences of items that can be sorted with the same set of permutations call for similar algorithmic processes. We did not make any explicit assumption about the underlying algorithm for sorting a string of ordinals. However we assumed that the algorithm is not sensitive to actual values of the items; instead, only the relative order of the items determines the sequence of processing steps. For example 2013 and 7249 require the same processing steps for sorting (shifting the first item to a position after the third item). In fact all common efficient algorithms for sorting, process these two sequences (and every two sequences with similar condition) similarly (Cormen, Leiserson, Rivest, & Stein, 2009).

Thus for our experiment we chose four categories of 5 digits (categories 1,2,3 and 4), identified by these canonical strings (respectively): 34012, 21043, 41230 and 03214. Exemplars for each category were generated by using different digit values while preserving relative ordering – for instance, 78156 belongs to category 1.

We randomly generated strings of five digits belonging to these four categories as the stimuli for the sorting task and presented them horizontally on the screen. Note that categories 1 and 3 are respectively symmetric to categories 2 and 4 in their order of items in the sequence. We administered this experiment in four blocks each block including 20 sorting trials. 5 exemplars of each of stimulus types used for sorting trials plus 10 trials of recall challenge. We used the same hardware setup and same procedure as the sorting blocks of the previous experiment however items were presented only along the horizontal orientation.

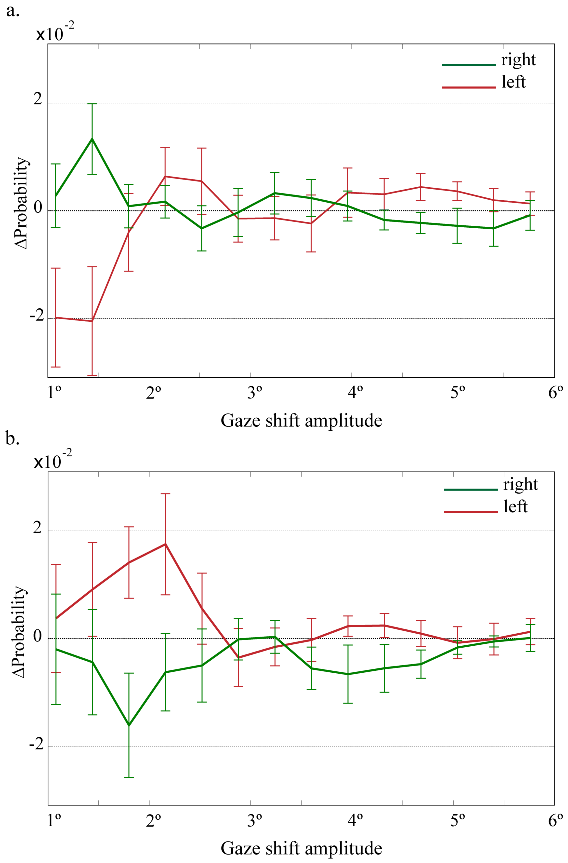

Figure 3: *Sequences of items which are symmetric induce symmetric gaze shifts during the sorting task. Each graph shows the difference between averages of normalized amplitude distributions of gazes for two symmetric sets of stimuli. On the top panel, the result for stimuli of type 1 – stimuli of type 2 (canonically represented by 34012 and 21043) is shown. The bottom panel shows the result for stimuli of type 3– stimuli of type 4 (canonically represented by 41230 and 03214).*

### Results

To investigate the possible symmetry in gaze shifts we used distributions of gaze-shift amplitudes towards right and left. All gaze shifts with direction towards the right within ±45° around the horizontal direction were counted as rightward gaze shifts, and similarly for leftward gaze shifts.

To quantify symmetry of gaze shift distributions we subtracted the normalized distributions of gaze shifts associated with symmetric stimulus types. Doing so, the effect of the background noise in gaze shifts was notably reduced. Meanwhile, in the case of a symmetric relationship between distributions, we would expect a non-zero antisymmetric relationship between the right side and the left side difference distributions.

However note that since we project the gaze locations on the stimulus presentation screen, in the case that gazes reside on a plane different from projection screen the right side and the left side of the difference distributions might appear in different scales. A linear adjustment of scale for the left side is applied to compensate for projection of the gaze locations onto the presentation screen. The result of this adjustment is that the expected values for gaze shift amplitude for the left side and the right side of the graph match. For the pair of stimuli of type 1 and stimuli of type 2, the left side is scaled by 0.8 for the pair of stimuli of type 3 and stimuli of type 4, the left side is scaled by 0.67.

Figures 3.a and 3.b show the average of the right side versus the left side of the difference distributions respectively associated with pairs 1-2 and 3-4. In each figure, the scale of amplitudes on the left side is linearly adjusted by a constant factor so that the expected amplitudes on the left side and the right side match (see Figure 3). The result for both pairs of stimuli is significantly different from statistical estimation of zero sampled out of random permutations of gaze shifts data (for pair 1-2, unpaired $ttest$, $N1 = 10, N2 = 1000, p < 0.0001$ and for pair 3-4 unpaired $ttest$, $N1 = 10, N2 = 1000, p < 0.0001$ ). To measure antisymmetric relationship, we used linear correlation between data points of the right side with data points on the left side. For the pair 1-2 this correlation is -0.69 and for the pair 3-4 the correlation is -0.78. Both these (anti-)correlations are significant (for pair 1-2 $t(-0.69) = -3.302, df = 12, p < 0.0032$, for pair 3-4 , $t(-0.78) = -4.318, df = 12, p < 0.0005$). This result shows that initial symmetry in the order of items in the sorting stimuli results in later symmetric gaze shifts (and presumably shifts in spatial attention) during the sorting process. This finding lends empirical support to this idea that working memory items are bound to spatial locations and spatial binding of memory items is systematically used for the algorithmic processing of abstract items.

## Discussion

From an evolutionary standpoint, it has been argued that the capability of working with abstract concepts might have been made possible by co-opting modal systems for perception and action (Barsalou, 1999, 2008; Dehaene & Cohen, 2007; Knops, Thirion, Hubbard, Michel, & Dehaene, 2009; Hubbard, Piazza, Pinel, & Dehaene, 2005). We are extending this argument to production systems that support controlled algorithmic information processing by assuming that systems with visual-spatial characteristics provide a registry mechanisms which is used for directing executive process to the item of interest in working memory.

The role of visuospatial short-term memory as a peripheral storage unit has been argued in working memory literature (Baddeley, 1992; Repovs & Baddeley, 2006). Standard models of working memory consider a domain specific role for such storage systems and give their control to a domain independent functional unit namely central executive (CE). Hence it is implicitly assumed the role of visuospatial short-term memory is limited to tasks that feature visual-spatial characteristics (Repovs & Baddeley, 2006).

Our proposal adds a domain independent and executive role to systems with primary role of visuospatial encoding. This assumption is consistent with other studies that have emphasized on the role of systems with primary visuospatial functions in the deployment of executive attention (Osaka et al., 2007).

Our proposed model fills this gap by suggesting that SPL may embody the spatial registry, thus establishing a link between shifts of executive and spatial attention. This assumption is also consistent with Koenigs et al's finding that showed the same site that has been previously known for storing visuospatial short-term information is also critical in all memory tasks that feature memory manipulation. Moreover, Nobre et al. (Nobre et al., 2004) have shown that this particular region is involved in orienting spatial attention towards both internally represented locations and external physical locations.

Furthermore, our assumption might help explain the notable impact of executive memory tasks on visual processing (Han & Kim, 2004; Peterson et al., 2008; Fougnie & Marois, 2007). In fact the need for memory manipulation is the common feature of all executive memory tasks that have been shown to have notable impact on visual processing. Although this may not always have been noted by the experimenters, our proposal pinpoints the visuospatial system as the common resource needed for both visual processing and mental executive tasks.

In contrast to our process-related hypothesis, a number of other researchers have proposed a representation-related hypothesis for the role of visuospatial systems in mnemonic tasks(Wood et al., 2008; Dehaene & Cohen, 2007). For example, in a recent

fMRI study, Knops et al. (2009) showed that activation patterns in SPL during mental addition and subtraction are similar to those elicited by saccadic eye movements towards right and left. They argue that, from an evolutionarily standpoint, numbers are very recent in our history and thus it is not likely that we have specific regions dedicated to representing numbers in our brain; hence, they hypothesized that involvement of SPL is related to related to role of spatial resources in representation of numbers.

However this assumption about the role of visuospatial systems in representing numerals falls prey to its limitation in scope of concerned items, and cannot be generalized to abundant evidence of their involvement in a wide range of memory tasks with other types of (non-numeric) items, such as the the word-span tests of Osaka et al. Yet, since mental mathematical operations (including mental arithmetic) require manipulation of memory items, a process-related hypothesis can address Knops et al.'s observations.

Hence our hypothesis provides a more parsimonious account for the role of visuospatial systems of the brain in executive memory tasks. While we do not rule out the possibility for a role of the brain's spatial encoding resources in representation of numeral concepts, we propose that cortical changes parallel with mastering manual skills and tool making were key evolutionary changes that paved the way to mnemonic algorithmic controlled information processing (which is also crucial for mathematical processing). These changes include dramatic development in prefrontal and parietal association cortices, including SPL: According to Paillard (Paillard, 2000), development of SPL is concerned with attentional anchoring of gaze by coding the direction of the optic axis relative to the head, which is crucial for manipulating physical objects. We propose that this change characterizes the involvement of visuospatial systems in abstract mental tasks, and the same functionality of shifting attention towards items of interest (Ballard, Hayhoe, Pook, & Rao, 1997) is being simulated for manipulating memory items.

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