

## Eye-Movement Signatures of Abstract Mental Tasks

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### Abstract

Brain regions with visual-spatial characteristics are known to be recruited in mental tasks featuring algorithmic information processing with symbolic concepts. Yet, exactly how they contribute to such processing remains an open question. Here we propose a framework for manipulation of items in memory, which relies on registering memory items in a spatially-organized short-term memory store. Switching executive attention to memory items that need processing may then be embodied through shifting spatial attention towards those registry locations. We studied gaze shifts during memory tasks as a proxy for shifts in spatial attention. Analysis of gaze shifts during sorting semi-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 those general-purpose production mechanisms that support algorithmic memory tasks with amodal symbolic information and modal systems for perception and action.

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

### 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; Barsalou, Simmons, Barbey, & Wilson, 2003; Dehaene & Cohen, 2007).

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 maintained items. For example think of an instance of a subtraction problem (let's say 42 - 18) which is less likely to be done by recalling from memory. A regular algorithm for subtracting numbers in decimal forms is done in several steps each step involving only particular items.

Recent behavioral studies conducted with concurrent-task paradigms have identified that memory tasks involved with symbolic concepts that feature memory manipulation interfere with visual processing to a larger extent than passive maintaining of similar items (Akyürek, Hommel, & Jolicoeur,

2007; Fougne & Marois, 2007; Han & Kim, 2004; He & McCarley, 2010; 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, Keoings et al. (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. SPL is known for its contributions to a variety of visuospatial functions such as saccadic eye movements (Quintana & Fuster, 1993), visuospatial attention (Kanwisher & Wojciulik, 2000), visuospatial short-term memory (D'Esposito et al., 1998) and visuomotor functions (Ferraina, Battaglia-Mayer, Genovesio, Archambault, & Caminiti, 2009). Significance of this result is partly related to showing that dependency of this symbolic machinery to the perceptual system is not limited to representation of symbolic information and is also related to the processes that support execution of dynamic memory tasks.

Tasks featuring memory manipulation are also known to be attention-demanding and thus some researchers have suggested that the 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 regions with visuospatial characteristics in memory manipulation we propose the Spatial Registry Model (SPM) that relies on spatial binding of items for memory manipulation.

### 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 store. We assume that an item in working memory, independent of the nature of its representation, may register with a corresponding location which with visuospatial representation. This registry may occur when selective access to a memory item is required.

We assume that binding of items to spatial locations is not

random and is guided by biological/behavioral preferences that fulfill 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 experience.

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. Such a mechanism is specially useful when several items are activated in short-term memory and the integrity of the process depends on switching the process to the right item at each stage. For instance, imagine double counting as a mental task in which two signals are to be counted separately. In this case two numbers are actively maintained in working memory and upon receiving each of the 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 the 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, Doshier, & 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 multiplication 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,

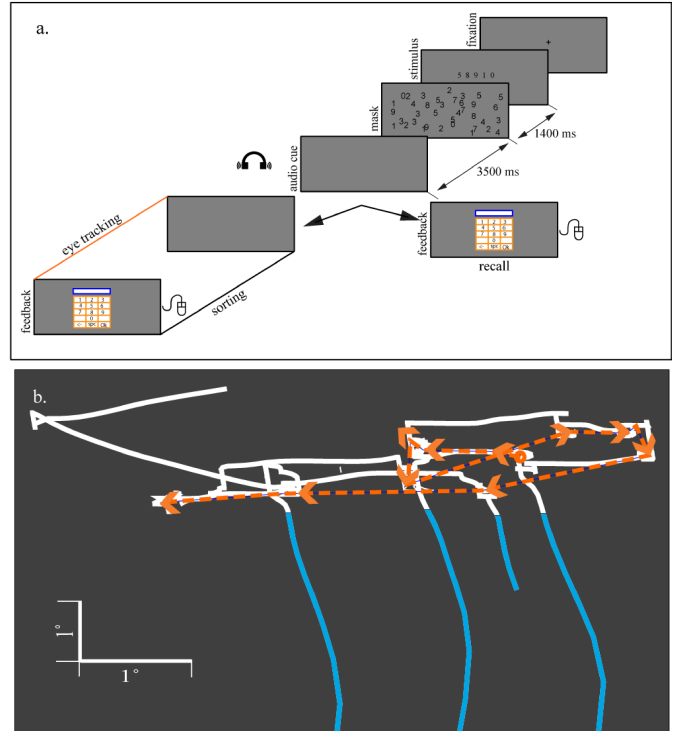


Figure 1: a. Schematic view of the experimental paradigm. Tasks were performed in front of a blank gray screen after visual presentation of the stimulus. b. Sample eye trace during mental sorting in front of a blank screen. Downward blue trajectories correspond to blinking during the task execution.

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.a.).

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 (Figure 1b).

Our 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 our memory task stimuli 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 in the 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.

## Experiment

### 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 items. 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 a 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.

### Participants

Seven female and three male 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.

### Procedure

All items were presented completely for 1400 ms on the screen,  $3^\circ$  wide on a gray background in black font size 24 point. 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. 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. Indeed, if they started sorting

early, it would be very difficult for them to also recall the original sequence order and that could affect their performance in recall trials. Hence the performance for the recall task was monitored. Subjects were informed about monitoring their performance on the recall task and were notified that in case of performance below 90% their result would be discarded. All subject could meet the 90% performance level for the recall task. The average performance for the recall task was 96.5%.

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. At most five items could be selected by moving the mouse pointer over the designated area and clicking on the left button.

During the sorting task, total trial duration was unlimited and subjects would click a mouse button once they finished the sorting task. Subjects were instructed to repeat the sorted string once and before clicking for reporting the sorted string. During sorting trials eye movements were recorded between the audio cue for starting the sorting process and mouse click for reporting the sorted string.

### Apparatus

Stimuli were displayed on a 46-inch LCD monitor (Sony Bravia XBR-III,  $1,016 \times 571.5$  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. Stimuli presentation and eye tracking were operated by two different machines (Stimulus presentation machine with Intel(R) Xeon(TM) CPU 3.20GHz processor, with Linux version 2.6.24.7-desktop-1mnb operating system; eye-tracker machine with MS Windows 98 operating system).

### Data processing

Fifteen-point display calibration was used to compute the affine transform from the eye-tracker coordinates to the stimulus coordinates in the least-square sense. We ran a RANSAC algorithm to find the best 9 calibration points which gave us the smallest residuals on the affine transformation. Small nonlinear residual errors in the transformation were corrected by a thin-plate-spline warping algorithm (Bookstein, 1989). The eye position data then was transformed into the stimulus presentation coordinates.

Transformed data was processed for detecting gaze events. To classify a point as gaze-point, the ratio of eigenvalues of the covariance matrix of x-positions and y-positions of eye locations within a specific time window was used. A value close to one means that data is scattered more locally, while very small or very large values mean that the data is scattered more peripherally. We used four different time win-

dows: 40ms, 60ms, 80ms and 100ms. The threshold for ratio of minimum to maximum of eigenvalues for these four windows was respectively equal to 0.75, 0.65, 0.55 and 0.45. Upon pre-processing of data for each of the four time windows, each point with local scattering, was marked by 1 in contrast to data points with peripheral scattering which were marked by 0. The result of this process was four binary vectors each corresponding to one of the time windows. A median filter then was applied on each vector with median values respectively equal to 11, 13, 15 and 17. Data points which had scored 1 in all of these processed vectors were selected as 'potential gaze-point' marked by 1 versus 0 for the rest of points. A min filter of 70 ms length then was applied on the vector of potential gaze points to remove isolated potential gaze points. As the result gaze events were at least 70 ms long with relatively local scattering.

## 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  $\pm 45^\circ$  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 stimuli. Doing so, the effect of background noise in gaze shifts was notably reduced. Meanwhile, in the case of symmetric relationship between distributions, we would expect a non-zero antisymmetric relationship between right side and left side difference distributions.

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

Figures 2.a and 2.b show the average of the right side versus 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 right side match (see figure 2).

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 t-test,  $N1 = 10, N2 = 1000, p < 0.0001$  and for pair 3-4 unpaired t-test,  $N1 = 10, N2 = 1000, p < 0.0001$ ).

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 the 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.

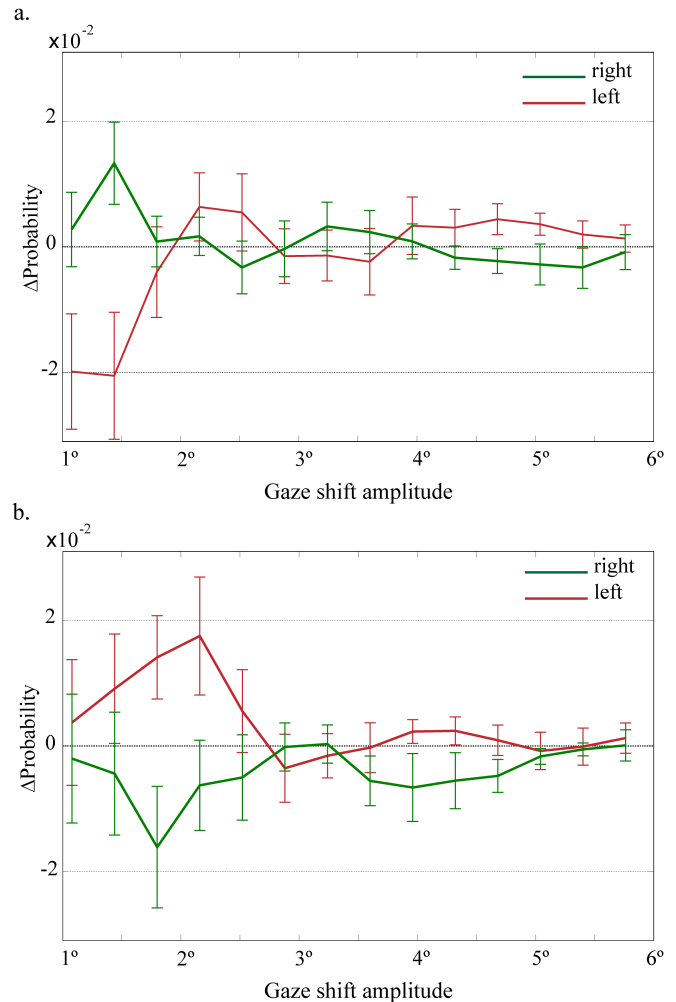


Figure 2: Sequences of items which are symmetric induce symmetric gaze shifts during the sorting task. Each graph shows the difference between averages of normalized amplitude distributions of gazes for two symmetric sets of stimuli. On the top panel, the result for stimuli of type 1 – stimuli of type 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).

## Discussion

From an evolutionarily standpoint, it has been argued that the capability of working with abstract and symbolic concepts might have been achieved by co-opting modal systems for

perception and action (Barsalou, 1999; Barsalou et al., 2003; Barsalou, 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 mechanism which is used for directing the 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 the working memory literature (Baddeley, 1992). 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 the 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 the role of SPL in the deployment of executive attention (Osaka et al., 2007). However, previous studies did not elucidate exactly how this region contributes to executive attention allocation. 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 that 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.

Furthermore, our assumption might help explain the notable impact of executive memory tasks on visual processing (Han & Kim, 2004; Peterson et al., 2008; Fougny & 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 involvement of visuospatial systems of the brain in mnemonic tasks. 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 the contribution of SPL in these tasks is related to representation of numeral items. However, this assumption about the role of SPL in

representing numerals falls prey to its limitation in scope of concerned items, and cannot be generalized to abundant evidence of involvement of visual-spatial systems (e.g. SPL) 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.(2007). Yet, since mental mathematical operations (including mental arithmetic) require manipulation of memory items, a process-related hypothesis can address Knops et al.'s (2009) 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 the involvement of parts of visual-spatial systems in dynamic memory tasks with these symbolic and abstract concepts might be related to co-opting brain resources that support visually guided actions in the space.

In the context of the natural tasks, Ballard et al. (Ballard, Hayhoe, Pook, & Rao, 1997) have suggested a deictic coding mechanism to link external sensory data with internal cognitive programs and motor actions. They mention that working memory can related to moment-by-moment disposition of body features such as eye movements and hand movements.

Paillard (Paillard, 2000), from a neurobiological perspective, argues that cortical changes parallel with mastering manual skills and tool making were key evolutionary changes that paved the way to rational thinking. These changes include dramatic development in prefrontal and parietal association cortices. According to Paillard, development of parietal association cortex in human is particularly 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 these changes characterize the involvement of the visual-spatial systems supporting abstract mental tasks, and the same functionality of shifting attention towards items of interest is being simulated for manipulating memory items.

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