Title
Traces of Intellectual Working Memory Tasks on Visuospatial Short-Term Memory

Journal
Proceedings of the Annual Meeting of the Cognitive Science Society, 35(35)

ISSN
1069-7977

Authors
Noori, Nader
Itti, Laurent

Publication Date
2013

Peer reviewed

Traces of Intellectual Working Memory Tasks on Visual-Spatial Short-Term Memory

Nader Noori (nnoori@usc.edu), Laurent Itti (itti@usc.edu)
Department of Computer Science, University of Southern California
Los Angeles, CA 90089 USA

Abstract

We measured the sensitivity in detecting a change in the location of one of two visual targets over a short period of time to investigate the impact of a secondary intellectual symbolic WM task on the visuospatial short-term memory, in a dual-task paradigm. We observed that engaging in a WM task that involves manipulation of symbolic information impacts the ability to detect a location change, and this impact does not change when more time is allocated to the WM task. Furthermore, we observed that the impact of a mental sorting task on the ability to detect location changes is spatially selective to the horizontal orientation. Our results suggest a possible role for sensory-motor working memory, which supports perception-action schemas in manipulation of information during the intellectual symbolic working memory tasks.

Keywords: Perception-Action Schema; Symbolic Working Memory; Sensory-Motor Working Memory; Working Memory Manipulation; Visuospatial Short-Term Memory.

Introduction

The quality of our modern life has become so dependent on the ability to perform intellectual tasks with symbols (e.g. addition or subtraction) that we force our children to spend a big chunk of their life on learning them at school and home. Effective assessment of individuals' ability in performing these tasks has become a constant occupation of mind for some cognitive psychologists among which some have suggested that the ability of management of working memory (WM) is an indicator and the key to understanding individuals' ability in performing these tasks (Conway, Kane, & Engle, 2003). Suggestions such as this, have created a motivation for understanding mechanisms of WM management.

Better understanding the human ability for maintaining and manipulating symbolic content poses the question of which brain mechanisms may be recruited by these tasks. From an evolutionary standpoint it is not easy to entertain the idea that our brain has evolved a dedicated system for maintaining and manipulating symbolic concepts in mental schemas, which are indeed very recent cultural inventions (e.g., numbers in mental arithmetic). Meanwhile, humans often perform daily sensory-motor routines that require temporary maintaining and manipulating of information gathered from the environment and relevant to the task. Robust maintaining of task-relevant information for performing perception-action schemas provides an adaptive value, which might have led to evolution of sensory-motor working memory. For instance think of the adaptive advantage of the ability to temporarily maintain the location of a targeted prey which is momentarily out of sight until the right moment for attack.

As suggested by some researchers, it is conceivable that evolutionary older systems for encoding, maintaining and manipulating of information for rudimentary tasks are coopted or reused for the intellectual tasks with newly invented concepts (Paillard, 2000; Dehaene & Cohen, 2007). For example, some researchers have entertained the idea of using space in the representation of numbers (Knops, Thirion, Hubbard, Michel, & Dehaene, 2009; Wood, Willmes, Nuerk, & Fischer, 2008).

However, studying capacities for maintaining and manipulating of information in the intellectual domain and in the sensory-motor domain are traditionally pursued in different research communities, with not much of cross-talk. Hence, studying the possibility of reusing sensory-motor working memory in intellectual symbolic tasks has not been fully explored yet.

The goal of the present study is to investigate the possibility of involvement of visual-spatial short-term memory in manipulation of information during intellectual symbolic working memory tasks. Short-term memory of the location of a visual target is a component of sensory-motor working memory and is crucial for performing a range of visual-motor tasks. We measured the impact of two different intellectual symbolic tasks on the ability to maintain the spatial information of the location of visual targets.

Similar attempts with an opposite goal have been made to pinpoint the role of the central executive (CE) as the supplier of executive attention (Repovs & Baddeley, 2006) during maintaining visuospatial short-term memories (Phillips, 1983; Logie, Zucco, & Baddeley, 1990). In those studies, spatial span – the maximum size of a matrix of symbols which can be recalled better than a threshold performance – is used as a measure for the capacity spatial memory. Any change in the memory span as the result of engagement of the CE would be interpreted as evidence for a role for executive resources in maintaining spatial information. Meanwhile, engaging CE is mostly achieved by engaging subjects in intellectual symbolic working memory tasks, known as executive working memory tasks.

These studies have been equivocal in their conclusions about the role of executive resources in maintaining spatial memory. Phillips has reported that performing a mental arithmetic task reduces the visual/spatial span (Phillips, 1983). He concluded that maintaining spatial information is facilitated through an active mental imagery process which is inhibited by the load of the mental arithmetic. Logie, Zucco and Baddeley (Logie et al., 1990) compared the effect of both a mental arithmetic and a mental imagery task, on both visual and word spans, and showed that the the mental imagery task impairs the visual span to a greater extent, while mental arithmetic impairs the word span to a greater extent. However, they still observed an impact of mental arithmetic on visuospatial span and stated that "*the impairment in short-term visual memory* *resulting from secondary arithmetic reflects a small general processing load*".

However, later on, Baddeley and Repovs summarized the results of many dual-task studies, pinpointing the role of CE in maintaining and manipulating information in components of Baddeley's multi-component model of working memory. They concluded that simple representation and maintenance of information may be independent from the CE (Repovs & Baddeley, 2006). This conclusion includes maintaining spatial information tested in measuring spatial span which is contrary to Baddeley's previous note on the impact of mental arithmetic on spatial span.

In the present study, we use the sensitivity of subjects in detecting a change in location of two dots to measure the ability of retaining visual-spatial information. This requires retaining an amount of spatial information which is below the capacity of normal subjects (Luck & Vogel, 1997). In other words, instead of using a fixed threshold for performance in measuring the span of short-term memory, we used a fixed amount of information load below the normal capacity of our subjects, to measure the effect of a secondary intellectual working memory task. Although this paradigm does not measure the spatial working memory capacity in its conventional definition yet, it reflects the general capacity of maintaining spatial information over a short period of time. Moreover, this measure tests the spatial short-term memory in a way that is closer to the use of spatial information in daily perception-action routines. Finally, this paradigm can be easily used to test the spatial selectivity of any potential impact on the spatial short-term memory. This paradigm can be deployed in fixed-length blocks which eliminates the influence of the training factor.

Using this sensitivity measurement paradigm, we inspected the influence of two different symbolic working memory tasks on the short-term spatial information retention. In our first experiment, we used a dual-counting task in which two running counts need to be maintained and updated upon presentation of two distinguishable audio signals. We use the rate of signal presentation as a parametric feature to change the amount of time that is allocated to this task. This allows us detect any impact onto spatial short-term memory caused by decaying information as the result of performing the symbolic working memory (SWM) task.

In our second experiment, we used mental reordering versus retaining of four random alphabetical characters (presented auditorily) as our symbolic working memory tasks. We compared their impact onto retaining spatial information along either the horizontal or vertical orientation. This allowed us to test the spatial selectivity of the impact of mental reordering of characters compared to maintaining them.

Experiment 1

We asked our subjects to perform a mental dual counting task of two audio signals, while they were also retaining visual-spatial information. The goal was to test whether this symbolic working memory task could interfere with retaining visual-spatial information as simple as the spatial locations of two visual targets. We also aimed to test whether a possible interference is due to competition over scarce executive resources that might be needed for both the manipulation of working memory content and the retention of visual-spatial information.

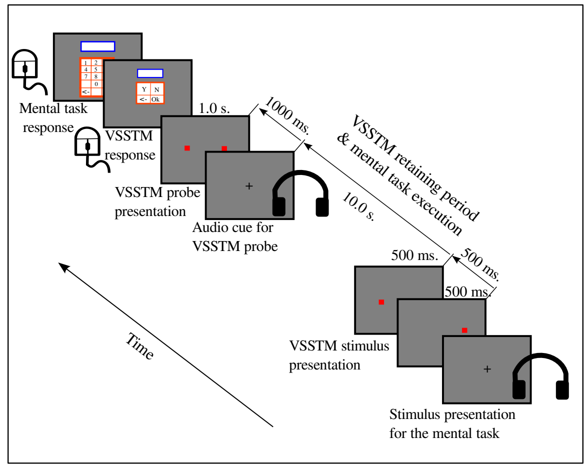

Figure 1: Schematic view of the experimental paradigm.

Mental dual counting involves maintaining two running counters, associated with two signals, in working memory, and, each time a new signal is perceived, incrementing the associated counter. The rate of updating of the internal counters can be adjusted by the rate at which audio signals are presented. This allows manipulation of the total amount of time that putative executive resources may be free and available for other tasks (e.g., active retaining of spatial short-term memory), which in turn may affect the sensitivity measure. We chose two different rates for presenting audio signals for the dual counting task. In separate blocks, we asked subjects to ignore versus count the signals while retaining the visual-spatial information.

Method

Apparatus Visual-spatial 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 $54.7° \times 32.65°$). To control the viewing distance, subjects used a chin rest to maintain their head position during the experiment. A gray background (0.62 cd/m2) was displayed during the experiment. A headphone was used for presenting audio stimuli. Our stimulus presentation program was developed using iLab Neuromorphic Toolkit (iNT) and operated on a Linux 64bit machine.

Subjects Fourteen female and one male undergraduate students with normal or corrected to normal vision, participated for course credit. Participants' ages ranged from 18 to 23 years ($M = 20.9$, $SD = 1.6$).

Procedure Figure 1 displays a schematic view of the experimental paradigm. Visual-spatial stimuli consist of two separately displayed red dots, each one placed randomly on an imaginary circle at center of screen with a diameter of 3.125° angle of view. Each dot stayed on the screen for 500 ms and a 500 ms blank screen separated the display of red dots. On the virtual circle, dots were at least 90° and at most 120° apart. Subjects had to retain the location of red dots for about 10 seconds during which they were supposed to engage in a symbolic working memory task.

During a 10 second period after the removal of the second dot, audio signals of two easily distinguishable types were played in a random order either in a slow tempo or a fast tempo. We used two 250 ms long, 50 Hz tones as audio signals; a soft tone (sine wave) and a rough tone (square wave). For the slow tempo condition, four signals were played with a random ISI of 3000 ms to 3600 ms, and for the fast tempo condition 8 signals were played with ISI of 1330 ms to to 2000 ms.

In all trials, subjects were given an initial set of 3 separate digits (each could have initial value between 0 and 3). In half of the blocks, subjects were asked to ignore audio signals and to keep repeating three random digits played before the onset of visual targets. We refer to this task condition as the ignore condition (IC). Under this condition, subjects had to report these same three digits at the end of the trial. In the counting condition, subjects were asked to increment the first digit upon hearing the soft tone, to increment the last digit upon hearing the rough tone, and to remember the middle digit unchanged. All three digits were reported at the end of trial. We refer to this condition as the engage condition (EC).

The memory of the location of targets was probed at the end of a 10 second retaining period by presenting two probe targets simultaneously. Probe targets were presented either on the exact same location as the initial targets (with 50% chance), or the location of one of the probe targets was shifted along the imaginary circle at least by 45° and at most 60° away from the location of the initial target. Subjects were supposed to respond whether both probe targets appeared at the same locations as the original stimuli. During the retaining period, a fixation cross remained at the center of the screen. Subjects fixated the fixation cross during the SWM task execution period. Subjects reported their three digits by mouse clicks on a virtual keypad after responding to the visuospatial probe.

We administered the experiment in separate blocks of 20 trials for the engage and ignore conditions. Each block contained equal numbers of trials with each possible tempo. Each subject performed two blocks of trials for each engagement condition.

Results Sensitivity of subjects in detecting matching probes was used to measure the impact of the symbolic working memory (SWM) task onto the visual-spatial short-term memory (VSSTM) task. Figure 2 demonstrates the mean value of sensitivity (d') in identifying matching visuosptial probes, for different conditions. To determine the significance of the impact of task and tempo factors, d' values were submitted to a two-way ANOVA with repeated measures on both factors.

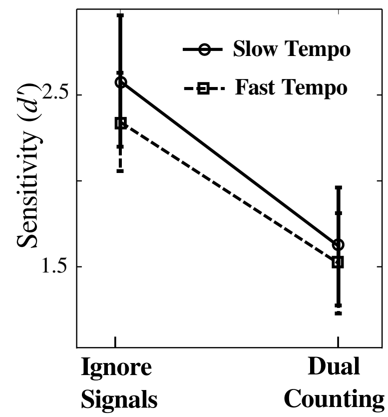

Figure 2: Impacts of task condition and audio signal rates on the sensitivity measure (experiment 1).

The analysis revealed a main effect of task at significance level $p < 0.0001$ $[F(1,14) = 37.69]$. The tempo of audio signals did not show a significant main effect $[F(1,14) = 0.504, p = 0.49]$. No significant interaction between factors was observed $[F(1,14) = 0.11, p = 0.74]$.

Further analysis revealed that sensitivity was higher in identifying identical probe targets when subjects ignored audio signals $(M = 2.46, SD = 1.29)$, compared to when subjects were engaged in dual counting of audio signals $(M = 1.57, SD = 1.21)$. Moreover, increasing the tempo of audio signals decreased the mean value of d' for both task conditions; however, this change did not reach a significant level.

To measure the engagement of subjects in the counting task we compared the number of counted signals for both tempos. The difference between the sum of reported counters and the sum of initial counters was used as the measure of counted signals. The average counted signals for fast tempo was $6.7 \pm 1.2 (M \pm SEM)$ and the average counted signals during the slow tempo was $3.8 \pm 0.2 (M \pm SEM)$, which was significantly less than the counted signals for the fast tempo $[F(1,14) = 131.04, p < 0.0001]$.

Discussion Our results indicates that, first, the sensitivity measure is sufficiently sensitive for detecting the impact of a secondary working memory task such as the dual counting, even though the load on the VSSTM appears to be half of the capacity of visual-spatial short-term memory in normal subjects (Luck & Vogel, 1997). Second, the double counting task can impair the retention of visual-spatial information over a short period of time. A significant impact on the sensitivity measure with such a low amount of spatial information suggests that the dual counting task, independent of the tempo, can potentially impact the spatial span too.

One may maintain that this effect is caused by engaging

CE in the dual counting task. However, on the basis of the sensitivity measure, increasing the rate of dual counting neither showed a main effect nor an interaction with the VSSTM task. Based on this result, one may come to the conclusion that increasing the tempo indeed does not change the complexity of the task, and thus does not add to the load on the central executive.

In this sense, the double counting might use a specific amount of executive resources in lapses associated to each signal presentation event. Garavan has proposed a model for a self-paced version of dual counting task which consists of five steps (Garavan, 1998): 1. stimulus identification, 2. orientation of attention to the associated counter, 3. updating the count, 4. rehearsing the other count, 5. key-press. The first four steps can be used as a model for our version of the dual counting task. Previous research suggests that executive attention does not play a direct role in the first step (He & McCarley, 2010). Also, verbal rehearsing in step 4 is suggested not to be dependent on executive resources (Repovs & Baddeley, 2006). Additionally one may maintain that rescheduling the sequence of rehearsing in the case of switching between different counters (Garavan, 1998) may also draw on executive resources.

Involvement of executive resources in updating counters may result to unavailability of necessary resources for retaining visuospatial information over a refractory period (Pashler et al., 1994). Hence, a higher rate of signal presentation in fast tempo trials hypothetically would occupy a larger fraction of retaining period with a refractory condition.

Yet, one needs to establish how executive resources may play a role in retaining location of two visual targets to leverage a refractory explanation for the impact of dual counting on the sensitivity in location change detection. One may propose that retention of VSSTM requires active maintenance through a rehearsing process (Awh, Jonides, & Reuter-Lorenz, 1998; Awh et al., 1999), which according to Jonides is a "*controlled sequence of retrievals and re-encoding of items into the focus of attention*" (Jonides et al., 2008). This may also draw on general executive resources needed for manipulation of information in symbolic working memory tasks. This argument hinges on this assumption that rehearsing prevents VSSTM traces from decay, so that interrupting the rehearsal process results in decaying traces of spatial short-term memory. Yet, this would imply that the more the rehearsing is interrupted, the more the effect of decay is pronounced. This in turn suggests that adding to the rate of dual counting may affect the performance on the visual-spatial task, which is not supported by our results.

Without CE as the shared scarce commodity between the SWM task and spatial information maintaining process, one should consider another source of conflict between manipulation of information in the SWM task and retaining spatial information. One source of conflict could be that visuospatial short-term memory is indeed used during the SWM task.

The use of space for the manipulation of information has been previously discussed for specific SWM tasks such as immediate reverse recall (Rudel & Denckla, 1974) and mental sorting of numbers (Noori & Itti, 2011). One may imagine a use of space as natural addressing system for the content of SWM, which can be used as a handle to shift processing to different items of working memory (Noori & Itti, 2011).

Our next experiment explores this matter in the case of a mental sorting task by measuring the sensitivity in detecting a location change along the horizontal versus the vertical directions. An account based on a bottleneck in executive resources for the impact of SWM on retention of spatial information maintains that interrupting the CE would affect VSSTM independently of the spatial location of visual targets. Hence, our second experiment provides us with another opportunity for testing the role of CE in retaining visual-spatial information.

Experiment 2

To test whether the observed influence of the SWM task on VSSTM is due to utilization of space for active manipulation of symbolic working memory content, we examined the selectivity of the impact of a mental sorting task on VSSTM. In particular, we used two visual-spatial targets either along the horizontal orientation or the vertical orientation. Subjects performed a sorting task on a random list of English letters during the visual-spatial information retaining period.

Subjects Eleven female and three male native English speaking undergraduate students with normal or corrected to normal vision participated for course credit. Participants' ages ranged from 19 to 22 years ($M = 20.39, SD = 1.4$).

Procedure The procedure for this experiment is similar to experiment 1, except for the location of visual targets and the symbolic working memory task (see Figure 1). Visual targets were two red dots presented either along a horizontal line or a vertical line passing through the center of screen, each dot on one side of the center, and between $1^{\circ}...4.9^{\circ}$ angle of view away from the center. Visuospatial probe targets were presented simultaneously in the same locations as target stimuli with 50% chance, otherwise, one of probe targets was displaced by 1.4°, either inward or outward along original presentation direction so that two probe targets remained on two sides of the center cross along the direction of initial presentation.

Before the onset of the red dots, four randomly selected English letters were presented aurally to be maintained in the same presentation order (during maintaining trials), or sorted in alphabetical order (during sorting trials), within a 10 second period. At the end of the delay period, subjects first responded to the visuospatial query, followed by reporting four characters by mouse clicks on a virtual keypad displayed on the screen.

We administered the experiment in separate blocks of 20 trials for the maintaining and sorting conditions, but each block contained equal number of trials for each different direction for the presentation of visual targets. Each subject performed two blocks of trials for each task condition.

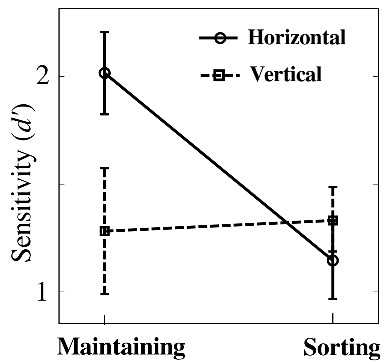

Figure 3: Average sensitivity measure for two tasks and two target orientations (experiment 2).

Results Figure 3 demonstrates the mean value of sensitivity (d') in identifying matching visuosptial probe targets for different conditions of SWM task (Maintaining vs. Sorting) and visual target orientations (Horizontal vs. Vertical). To determine the significance of the impact of task and target orientation factors d' values were submitted to a two-way ANOVA with repeated measures on both factors.

The analysis revealed a main effect of the task $[F(1,13) = 8.43, p = 0.012]$. No significant main effect of target orientation was determined $[F(1,13) = 3.12, p = 0.10]$ while the interaction was marginally significant $[F(1,13) = 4.3, p = 0.058]$. A post-hoc correlated-samples one-way ANOVA revealed a simple effect of the task, only for horizontal targets $[F(1,13) = 15.26, p = 0.0018]$, and no simple effect of the task condition at the level of vertical visual targets was observed $[F(1,13) = 0.03, p = 0.86]$.

Moreover, further analysis for exploring simple effects of orientation at different task levels showed that under the maintaining condition subjects demonstrated a higher sensitivity in detecting identical horizontal probe targets ($M = 2.02, SE = 0.19$) compared to identical vertical probe targets ($M = 1.28, SE = 0.29$). A correlated-samples one-way ANOVA revealed that the simple effect of orientation during the maintaining task is significant $[F(1,13) = 5.11, p = 0.041]$.

Discussion As the analysis revealed, compared to maintaining of four characters in their original order for a later recall, sorting them into an alphabetical order could significantly influence the sensitivity measure. This result again demonstrates the capacity of the sensitivity measure in registering the impact of a secondary SWM task on temporary retention of spatial information. Given our significant results under the low amount of load on VSSTM in our location change detection, one would also expect an impact on spatial span tasks (higher load) due to engaging in a mental sorting task.

However the striking result was that the impact of the sorting task on the sensitivity measure is only significant for visual targets that are spanned along the horizontal direction. Switching task condition did not change the average sensitivity to shift in location of targets along the vertical direction.

The sensitivity to change of location for vertically spanned visual targets was significantly above chance and, unlike the horizontally spanned targets, switching to the sorting task did not decrease sensitivity. This is consistent with the finding of the previous experiment, in that the influence of SWM task on the retention of spatial information is not caused by involvement of executive resources in spatial information retention; otherwise, one would expect an influence on the sensitivity for vertically distributed visual targets too. The initial sensitivity along vertical orientation was lower than along the horizontal orientation, hence one may raise the point that there was less room for decreasing the sensitivity along the vertical direction, and detecting a change would need more space. Controlling for the influence of this initial difference on the sensitivity in location change detection remains to be tested in a separate experiment, with a setup that can balance the sensitivities for detecting target locations along the vertical and horizontal directions during the list maintaining task.

General Discussion

The goal of this study was to explore the influence of intellectual working memory tasks devoid of visual and spatial features on the ability of retaining visuospatial information over a short period of time. We used a measure which is different from the actual capacity of spatial memory for holding spatial information. Instead we used the ability to detect a change in spatial location of one of two simple visual targets. In both experiments we observed that engaging in active manipulation of working memory content results to a decrease in the sensitivity of subjects in detecting a change in location of targets which needs to be explained.

Theories of working memory in the realm of cognitive psychology —independent of what they assume about the nature of representation in WM — usually assume a specific execution model based on separation of storage and execution. As such, a conflict between two tasks is either associated with sharing storage or with drawing on limited executive resources. Given that the WM tasks in our study are devoid of immediate visual features, one may conclude that the source of conflict is the the dependency of the retention of visual-spatial information and WM task on the CE. Yet, one should be clear as to how CE explains this conflict rather than — as Baddeley and Repovs have stated (Repovs & Baddeley, 2006) — using CE as a homunculus which has an undisclosed role in everything.

As we discussed in our introduction Baddeley's latest account assumes no role for the CE in retention of spatial information as simple as we tested in our experiment.

We also discussed that the proposal of Awh and his colleagues for engagement of a rehearsing mechanism in maintaining visuospatial information (Awh et al., 1998, 1999), and Jonides' account for the dynamic of rehearsing process (Jonides et al., 2008), may suggest a role for the CE in retention of visuospatial information. Our experiments were able to test this hypothetical role and our results did not support it.

Another view of working memory, proposed by Cowan (Cowan, 2001), has recently gained popularity in the cognitive psychology community. According to Cowan, working memory content is a part of long-term memory in a heightened state and under attention (Cowan, 2001). He explains the limitation in the capacity of working memory by the limitation of the internal attention in covering only four items at a time. The role of CE in this schema is to dynamically dispatch attention between representations in the long term memory, to make them available for processing. Accordingly, one might say that attention might be shared between information about the locations of two dots and the identities of four characters of the sorting task, which would exceed the capacity limit of 4 items proposed by Cowan. Yet, this explanation lacks sufficient detail to explain why adding to the rate of double counting and fastening this juggling of content of working memory under the watch of attention has no impact, or, in our second experiment, the effect of sorting characters in memory is limited to the sensitivity in detecting changes along the horizontal orientation.

Finally, there is another explanation, previously proposed by Noori and Itti (Noori & Itti, 2013, 2011), which falls out of the realm of models of working memory that assume separation of execution and storage. According to Noori and Itti, manipulation of information during symbolic intellectual working memory tasks (e.g., mental sorting or mental arithmetic) is made possible by re-using those sensory-motor working memory systems that evolutionarily have been developed to support perception-action routines (such as the occulomotor system). They argue that the capacity of maintaining information about locations of objects in space, in preparation for action on these objects, may provide a capacity for an internal binding of working memory task items for further manipulation. They assume that the management of working memory is made possible through an operational schema. In a way that was specified by Arbib's schema theory, operational schemas eliminate the need for a general-purpose CE in charge of management of working memory content, by instead defining explicit mechanisms that range from simple action-perception routines in catching a prey (Arbib & Liaw, 1995) to high-level language production (Arbib, 2005).

According to this account, one may assume that visuospatial short-term memory which maintains information about the whereabouts of real objects (e.g., locations of dots in our experiments), is also being utilized for the manipulation of working memory for the intellectual symbolic task (e.g., keeping two running counts separate and yet accessible) by binding symbolic items to space. This assumption may explain the observed effects as the result of a retroactive interference which masks memory of stored information about the location of dots.

Acknowledgments

This work was supported by the National Science Foundation (CRCNS Grant No. BCS-0827764), the Army Research Office (W911NF-11-1-0046), and the U.S. Army (W81XWH-10-2-0076).

References

Arbib, M. (2005). From monkey-like action recognition to human language: An evolutionary framework for neurolinguistics. *Behavioral and brain sciences*, *28*(02), 105–124.

Arbib, M., & Liaw, J. (1995). Sensorimotor transformations in the worlds of frogs and robots. *Artificial Intelligence*, *72*(1), 53–79.

Awh, E., Jonides, J., & Reuter-Lorenz, P. A. (1998, June). Rehearsal in spatial working memory. *Journal of Experimental Psychology. Human Perception and Performance*, *24*(3), 780–790. (PMID: 9627416)

Awh, E., Jonides, J., Smith, E. E., Buxton, R. B., Frank, L. R., Love, T., et al. (1999). Rehearsal in Spatial Working Memory: Evidence From Neuroimaging. *Psychological Science*, *10*(5), 433–437.

Conway, A., Kane, M., & Engle, R. (2003). Working memory capacity and its relation to general intelligence. *Trends in cognitive sciences*, *7*(12), 547–552.

Cowan, N. (2001). The Magical Number 4 in Short-Term Memory: A Reconsideration of Mental Storage Capacity. *Behavioral and Brain Sciences*, *24*(01), 87–114.

Dehaene, S., & Cohen, L. (2007). Cultural Recycling of Cortical Maps. *Neuron*, *56*(2), 384–398.

Garavan, H. (1998, March). Serial attention within working memory. *Memory & Cognition*, *26*(2), 263–276.

He, J., & McCarley, J. S. (2010). Executive working memory load does not compromise perceptual processing during visual search: Evidence from additive factors analysis. *Attention, Perception, & Psychophysics*, *72*(2), 308–316.

Jonides, J., Lewis, R. L., Nee, D. E., Lustig, C. A., Berman, M. G., & Moore, K. S. (2008, January). The Mind and Brain of Short-Term Memory. *Annual Review of Psychology*, *59*(1), 193–224.

Knops, A., Thirion, B., Hubbard, E. M., Michel, V., & Dehaene, S. (2009). Recruitment of an Area Involved in Eye Movements During Mental Arithmetic. *Science*, *324*(5934), 1583–1585.

Logie, R. H., Zucco, G. M., & Baddeley, A. (1990, October). Interference with visual short-term memory. *Acta Psychologica*, *75*(1), 55–74.

Luck, S. J., & Vogel, E. K. (1997, November). The capacity of visual working memory for features and conjunctions. *Nature*, *390*, 279–281.

Noori, N., & Itti, L. (2011). Spatial Registry Model: Towards a Grounded Account for Executive Attention. *Proceedings of the 33rd Annual Conference of the Cognitive Science Society*, 3187–3192.

Noori, N., & Itti, L. (2013). Schema-driven, space-supported random accessible memory systems for manipulation of symbolic working memory. In *Proceedings of the 35th annual conference of the cognitive science society.*

Paillard, J. (2000). Neurobiological roots of rational thinking. In *Prerational Intelligence: Adaptative Behavior and Intelligent Systems Without Symbols and Logic* (pp. 343–355). Kluwer Academic Publisher.

Pashler, H., et al. (1994). Dual-task interference in simple tasks: Data and theory. *Psychological bulletin*, *116*, 220–220.

Phillips, W. A. (1983, August). Short-Term Visual Memory. *Royal Society of London Philosophical Transactions Series B*, *302*, 295–308.

Repovs, G., & Baddeley, A. (2006, April). The multi-component model of working memory: Explorations in experimental cognitive psychology. *Neuroscience*, *139*(1), 5–21.

Rudel, R., & Denckla, M. (1974). Relation of forward and backward digit repetition to neurological impairment in children with learning disabilities. *Neuropsychologia*, *12*(1), 109–118.

Wood, G., Willmes, K., Nuerk, H., & Fischer, M. H. (2008). *On the cognitive link between space and number: a meta-analysis of the SNARC effect.* Pabst Science Publishers.