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Where What You Count is What Really Counts

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Where What You Count is What Really Counts

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Abstract

We noticed that human subjects were notably faster and more accurate in concurrent counting of three location-based events while they ignored the identity of targets, compared to concurrent counting of three identity-based events while they ignored the locations. In a control experiment, subjects performed a location-based triple counting task, while now also paying attention to the target identity. This did not incur any additional cost, compared to the cost of the location-based counting. Performing each of these tasks relies on maintaining three running numerical counters, and on switching between them to increase each one. Our results suggest that switching between these counters has lower cost when they are associated to spatial locations, compared to when they are associated to identities. This difference is not affected when additionally processing the identity of items. We argue that this might be related to the advantage of the space in switching attention between internal representations.

Keywords: Symbolic Working Memory; Working Memory; Spatial Strategies; Spatial Registry; Visuospatial Short-Term Memory; Concurrent Counting; Triple Counting; Focus of Attention.

Introduction

The challenge of many non-trivial intellectual symbolic working memory tasks lies in the difficulty of juggling several residents of working memory at the same time; there are one or two items that are being acted upon while a few others are actively maintained and kept apart for future steps of the process. For example think of adding 34 to 89 mentally while looking away from the paper or the screen. During early mathematics education, students are taught to perform this task in a sequential way, and by several calls on the addition table for single-digit numbers. In this example, while 3 and 8 (or 30 and 80?) are maintained for the next step of the operation, 9 and 4 are the ones that are acted upon first.

Due to the increasing role of abstract representations in solving difficult problems, intellectual symbolic tasks such as this example have become increasingly important as a part of necessary mental skills for a civilized individual in modern time. Understanding our limitations in maintaining and manipulating mental concepts that are needed for intellectual tasks is key to understanding our cognitive limitations, and to possibly improving individuals' performance. This in turn poses the question of how we manage to keep some items in our working memory, and how we can handle selecting them for the right operation at the right time.

The common metaphor among cognitive psychologists, which captures the selectivity of operations on several actively maintained items, is the shiftable spotlight or focus of attention. Attention in this sense refers to the special treatment that a few representations receive, which in turn makes it possible to be acted upon (or processed) with more agility (in terms of response time or accuracy).

Cowan goes even further and uses the concept of attention to directly relate working memory representations to long-term memory representations. In his view, residents of working memory are those representations in long-term memory which have received attention. He states that this attention may apply to only four items at a time, and hence the number of representations in working memory is limited to four (Cowan, 1999). Some other researchers have mentioned that indeed the spotlight of attention is even narrower than four items, and there is room for only one representation (Garavan, 1998; McElree, 2001). Experimental support for this claim comes from the observation that the most recently attended resident of working memory is privileged in terms of processing speed (McElree & Dosher, 1989; Mcelree, 2006; Garavan, 1998; Voigt & Hagendorf, 2002). For example Garavan studied the execution time of human subjects in a self-paced dual counting task where subjects had to keep count of how many of two possible visual shapes (triangles versus squares) had been presented. The sequence of switching between internally maintained counters is dictated by the stimulus sequence of triangles and squares. Garavan noticed that updating a recently updated counter (e.g., when two squares or two triangles are presented consecutively) is significantly faster than updating alternative counters (e.g., when a square is presented after a triangle or vice-versa). Garavan showed that this speedy update of a recently updated internal counter is not related to the perceptual priming in detecting the associate signal. He posited that the execution time difference between updating one counter twice and updating two different counters is related to the cost of shifting the focus of attention from one counter to the other one.

Oberauer has tried to reconcile Cowan's concept of attention with the single spotlight focus of attention, to establish a framework that explains storage and processing as two features of working memory (Oberauer, 2002). While the concept of shifting the focus of attention seems to capture the dynamics of working memory during mental processing, one question remains to be answered: what is the underlying mechanism for switching between two working memory representations? In particular, is there a unitary system for switching attention between items of working memory, either in space or in other dimensions?

For this matter, some researchers have looked at brain activities of human subjects during tasks that involve reconfiguration of cognitive resources by switching between different representations. Yantis and his colleagues, in a series of fMRI studies, have compared BOLD signals during switching attention in the visual-spatial domain or in other representation domains. They have identified a fronto-parietal network which is common among different tasks (Shomstein & Yantis, 2006; Tamber-Rosenau, Esterman, Chiu, & Yantis, 2011; Greenberg, Esterman, Wilson, Serences, & Yantis, 2010; Chiu & Yantis, 2009). Among these regions, the superior parietal lobule (SPL) of the posterior parietal cortex (PPC), which is also known for its role in shifting visual attention and eyes in space, is shown to be engaged in all of the studied switching tasks. Based on this evidence, Yantis proposes a general-domain switching mechanism (Chiu & Yantis, 2009).

Yet, an important question is whether such a switching mechanism is indeed a domain-independent machinery, or is in fact a part of an evolutionary older system that is lent or co-opted for use in different domains. It is important to distinguish between these two alternative views as they propose two different views of the evolution of human cognition. On the one hand, the domain-independent machinery may sound more appealing to some researchers in terms simpler description of the functioning mind. On the other hand, the idea of co-opting evolutionary older systems (e.g., sensory-motor systems) for switching is more plausible from an evolutionary perspective (Dehaene & Cohen, 2007; Paillard, 2000) and provides an opportunity to ground working memory machinery in perceptual-motor systems in line with more recent trend in grounded and embodied cognition (Lakoff & Núñez, 2000; Barsalou, Simmons, Barbey, & Wilson, 2003; Damasio & Damasio, 2006; Dehaene & Cohen, 2007).

As an example of a grounded model for working memory processing mechanisms, Noori and Itti (Noori & Itti, 2013a, 2013b, 2011) propose a framework for management of working memory items which relies on the role of sensory-motor working memory systems for manipulation of working memory items, even in the context of symbolic and abstract items. They assume that manipulation of memory items is facilitated by a registry of memory items to spatial locations, accessible to visuospatial attention mechanisms. Switching spatial attention between those locations, is then based on operational schemas, similar to what Arbib has proposed in the perception-action domain (Arbib, 1992). Their proposal suggests the performance on mental operations that need memory manipulation, even in the case of abstract and symbolic representations, would depend on how those sensory-motor systems are utilized.

To test the dependency of switching between working memory representations on utilization of space, we studied speed and accuracy of our subjects in performing a modified version of Garavan's task (Garavan, 1998). We arranged two versions of a triple counting task: identity-based counting (counting appearances of three possible symbols) and location-based counting (counting any symbols appearing in three possible locations). A domain-independent account predicts that the switching time between internal counters should be independent of our counting paradigms. Our results do not favour this prediction.

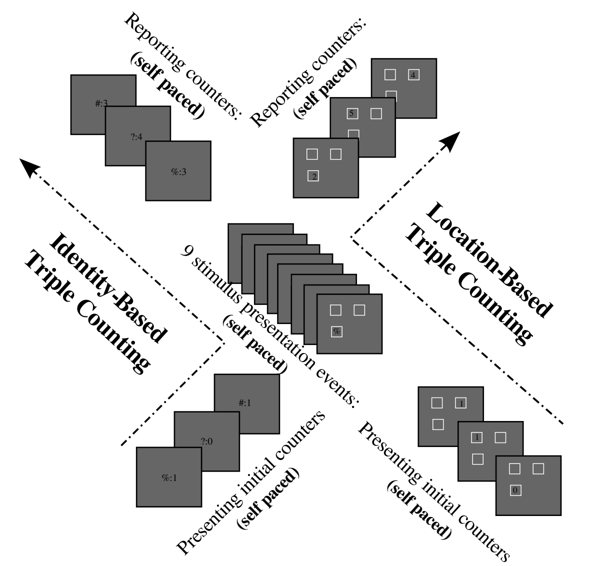

Figure 1: Schematic view of both triple-counting paradigms. Nine target presentation events (at the center of the diagram) is similar for both paradigms.

Experiment 1

The first experiment compares the cost of switching between different running counters in a concurrent triple counting task for an identity-based and a location-based mental counting. Subjects in both versions of the task maintain three running counters in their memory. These counters are associated to three different events.

In both versions of the task, an event is a subject-initiated brief visual presentation of a keyboard character in a box on the screen. In the case of location-based counting, the difference between events is defined based upon the location of the character, while the identity is irrelevant. In contrast, in the identity-based counting version, the difference between counting events is defined based on the identity of characters, and the location is irrelevant. Counters should be updated upon perceiving their associated signal. Since a signal presentation is initiated by the subject, the task progresses with a pace determined by the subject, which allows us to measure execution times.

We measured the time between two consecutive signal initiations and analysed them based on similarity or dissimilarity of counting-relevant and counting-irrelevant features of two consecutive events, to explore the effect of type of counter-event binding. Moreover, we analysed the error rates in counting using different measures, to explore possible effects of counter-event binding on the accuracy of counting.

Method

Apparatus Stimuli were displayed on a 46-inch LCD monitor (Sony Bravia XBR-III, 89cm $\times$ 50cm), 97.8 cm in front of participants (corresponding field of view is $54.7^\circ \times 32.65^\circ$). 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.

Subjects Seven female and four male undergraduate students with normal or corrected to normal vision, participated for course credit. Subjects' ages ranged between 19 to 21 ($M = 19.7, SD = 0.78$).

Procedure Figure 1 depicts a schematic view of the triple counting paradigm for both identity and location based concurrent counting. Events for both types of counting paradigm presented in a similar way: one of three keyboard characters $, # or ? would be selected to appear in one of three fixed boxes located in three of four main quadrants randomly and upon subject's press of any of keys on the keyboard. In each trial boxes centered at vertices of a virtual square with sides that would appear 3.5° wide from subject's view point. In each trial three out of four possible boxes were selected randomly and remained on screen throughout the counting process. In trials of location-based counting boxes appeared on the screen from the beginning of the trial and during presentation of the initial counters.

Each trial started by presenting three initial counters. Initial counters were either 0 or 1 which were selected randomly. During trials of counting identity-based events each item was presented next to its initial counter at the center of screen and during trials of location-based counting initial counters appeared at the center of boxes. Each trial included nine counting events. The pace of counting was determined by subjects. At the end of ninth counting event subjects reported the counters using the keyboard and in the same order of initial counter presentation.

Independent of the type of the counting task the identity and the location of target character changed randomly and independently. The identity of two consecutive characters changed with 50% of the chance and the location of two consecutive character presentation changed with 50% of the chance. This arrangement roughly balanced the change in counting-relevant and counting-irrelevant features.

Five trials of each counting paradigm defined a block. The type of counting paradigm change in two consecutive blocks. Each subject performed between 20 to 30 blocks which left us between 50 to 75 trials of each counting paradigm. At most 10 blocks were performed in each session. A five minute break administered between each two consecutive sessions.

Results Tables 1 and 2 summarize the results of experiment 1. Table 1 shows the average execution time for four possible combinations of changing the location or the identity of two consecutive signals separated based on the type of concurrent counting paradigms.

The effect of three factors on execution times were examined: a. the type of concurrent counting (with LBTC and IBTC as its two levels), b. change in the counting-relevant feature (the location in LBTC and the identity in IBTC) for two consecutive signals (changed or same as two levels) and c. change in the counting-irrelevant feature (the identity in LBTC and the location in IBTC) for two consecutive signals (changed or same as two levels). The execution time data with these three factors was submitted to a $2 \times 2 \times 2$ within-subjects ANOVA.

Location Based Counting		
	Same Location	Changed Location
Same Id	0.834 ± 0.077	1.552 ± 0.136
Changed Id	0.889 ± 0.102	1.564 ± 0.116
Identity Based Counting		
	Same Location	Changed Location
Same Id	1.126 ± 0.135	1.198 ± 0.143
Changed Id	2.122 ± 0.190	2.120 ± 0.205

Table 1: Mean ± SE of the execution times (experiment 1).

The analysis revealed a significant main effect of the type of counting task [$F(1,10) = 16.4, p = 0.0151$], with a faster response time for the location-based triple counting ($M = 1.2100s, SE = 0.055$) compared to the identity-based triple counting ($M = 1.6415s, SE = 0.0819$). The main effect of change in the counting-relevant feature also proved to be significant [$F(1,10) = 171, p = 0.0009$]. A change in counting-relevant feature requires switching between the counters, and the average execution time for this case was higher than when two consecutive signals shared the same counting-relevant feature (i.e., the same counter is updated twice in a row). However, for the counting-irrelevant feature whose change does not require switching between counters, no significant impact was observed [$F(1,10) = 1.9237, p = 0.1956$].

The analysis also revealed a significant interaction between the type of the double counting task and the change in counting-relevant feature with $F(1,10) = 24.1, p = 0.0006$. A further analysis showed that indeed the change in counting-relevant feature resulted in a larger difference in execution times for IBTC compared to LBTC. All three other possible interactions were non-significant.

We quantified counting errors using four different measures: a. the proportion of trials that had at least one mistake in the reported counters (Incorrect Trials), b. the absolute difference between the reported values and the actual values (Counter Error), c. the absolute difference between reported values and actual values, after sorting both the counters and the reported values (Sorted Counter Error) and d. the absolute difference between the sum of reported values and the sum of actual counters (Sum Error). Among these four measures, a. and b. are the most sensitive measures, while c. discounts any error in incorrectly reporting the order of counters, and d. is the least sensitive measure as it does not account for any error in adding to the right counter or in reporting the counters in the correct order.

Table 2 shows mean ± standard error values for each of these error measures for two types of concurrent triple counting. To assess the significance of the effect of the type

Error Type	LBTC	IBTC	Sig.
Trials with Error	$20.5\% \pm 5.4\%$	$39.3\% \pm 7.1\%$	**
Value Error	0.11 ± 0.03	0.31 ± 0.07	**
Sorted Value Error	0.10 ± 0.03	0.22 ± 0.04	**
Sum Error	0.24 ± 0.08	0.40 ± 0.09	*

Table 2: Mean ± SE of error measures (experiment 1). ** means $p < 0.01$, * means $p < 0.05$

of the counting task on each of these four measures, the data of each error measure was submitted to a separate one-way within-subject ANOVA. A significant main effect of the counting type on the error rates was revealed, for all four measures of error. The significance of this impact on the first measure is quantified by $[F(1,10) = 20, p = 0.0012]$; for the absolute difference, this significance is quantified by $F(1,10) = 15.4, p = 0.0028$; for the absolute difference in sorted sequence of counters and reported values, the significance is quantified by $[F(1,10) = 17.2, p = 0.00197]$; and finally for the absolute difference between the sum of counters and the sum of reported values, the significance of the main effect is quantified by $[F(1,10) = 9.11, p = 0.0129]$.

Discussion Changing the counting-relevant feature in two consecutive events for both counting paradigms requires increasing a counter which is different from the previously increased counter, and thus involves switching to a different counter. We observed that, independent of what defines the counting-relevant feature (location or identity of items), switching between counters results in a significantly lower speed for counting. Thus, we could replicate what Garavan had previously reported in the case of an identity-based dual-counting task (Garavan, 1998). However, compared to Garavan's study, our subjects were slower than his (both in updating one counter in a row or switching between counters and updating). This difference might be related to the fact that we had three counters, which might have had an extra load for maintaining the items. Moreover, our subjects needed to switch between two different counting paradigms frequently, and this might have had some impact on the execution time. Finally, we did not impose a delay between blocks of different counting paradigms, and subjects were only notified about the change in the counting paradigm by displaying a message on the screen.

However, the striking result of this experiment is related to the significant difference in execution time and counting errors of our two paradigms. Compared to the identity-based paradigm, the location-based paradigm proved to be both faster and more accurate. Even when the sums of reported counters were compared to the sums of actual counts, subjects were significantly more accurate in the location-based counting. Note that this measure for counting error is not even sensitive to the counting-relevant feature, and yet identity-based counting is significantly slower and less accurate with respect to this measure. This reveals that the slower execution time in identity-based triple counting is not the result of a trade-off between accuracy and speed.

Another striking result was related to the fact that not only the overall execution time during LBTC was less than the execution time during IBTC but also the switching cost was significantly less for LBTC. This is related to the fact that in our analysis we observed a significant interaction between switching condition and the counting paradigm. While updating the same counter during LBTC was about 300 milliseconds faster than IBTC, updating a different counter, which involves switching between counters, was about 560 milliseconds faster. This result suggests that using location as the counting-relevant feature has saved on the switching cost rather than a cost associated to maintaining or updating counters. We discuss the significance of this result in the general discussion.

Experiment 2

In our second experiment, we test whether the higher cost for both counting and switching in the identity-based concurrent counting is indeed the result of differences in character versus location perception. It is known that processing visual forms and locations engages two different pathways; the ventral pathway specialized in identifying visual forms, which serves object perception, and the dorsal pathway specialized in identifying spatial locations, which serves action (Goodale & Milner, 1992). One may argue that the observed differences between execution times in two concurrent counting paradigms is indeed related the processing of the visual input, and before the processing of the counters. To test the effect of identity recognition on the counting cost, we replaced the Identity-Based Triple Counting task with a modified version of the Location-Based Triple Counting task which involves identification of characters. In this paradigm, the running counters are still associated to locations; however, an occasional appearance of a dummy target can change the counter values and the rule of the concurrent counting thereafter. Thus, every time a valid target appears at a location, its identity should be checked before updating the counter associated to the target presentation location. We call this task Id-Controlled Location-Based Triple Counting or IC-LBTC for short.

Method

Subjects Seven female and four male undergraduate students with normal or corrected to normal vision, participated for course credit. Subjects' ages ranged between 19 to 24 $(M = 20.1, SD = 1.4)$.

Procedure In this experiment # and ? were targets for incrementing a counter and % was used as the dummy character. Subject were instructed that trials were arranged in two type of blocks, no-dummy blocks and dummy-possible blocks. In no-dummy blocks which contained 5 trials, only # and ? could appear in boxes and all events had to be counted. However, in 50% of the dummy-possible blocks, at some ran-

Location Based Counting		
	Same Location	Changed Location
Same Id	0.719 ± 0.068	1.214 ± 0.105
Changed Id	0.716 ± 0.071	1.285 ± 0.105
Id-Controlled Location Based Counting		
	Same Location	Changed Location
Same Id	0.724 ± 0.071	1.205 ± 0.113
Changed Id	0.710 ± 0.060	1.285 ± 0.104

Table 3: Mean ± SE of the execution times (experiment 2).

dom time the character % would appear only once in a box; in this case, the counter for that box had to be reported as 0 (i.e., reset and ignored during subsequent stimulus presentations). In the beginning of each block, subjects were notified about the type of block by a written message appearing on the screen.

Thus each trial of a IC-LBTC block could be similar to trials of the LBTC or could have the dummy character appearing only once in one of the boxes. Choosing to include the dummy character in a IC-LBTC trial was decided randomly and with 50% of the chance.

Given that blocks of different counting paradigms were similar in every sense we imposed a 10 second delay with a message on the screen informing the subject about whether in the next block there will be dummy characters or not.

Results Table 3 shows the average execution time for four possible combinations of changing the location or the identity of two consecutive signals, separated based on the type of concurrent counting paradigms. For the controlled location-based counting, only those trials without dummy characters were included in the analysis.

To assess the significance of the effect of controlling for the identity of characters during the triple concurrent task, switching locations and switching identities, execution times were submitted to a $2 \times 2 \times 2$ within-subject analysis of variance with type of counting, switching location and switching identity as three factors. The analysis showed no effect of attending to the identity of characters on the execution times $[F(1,10) = 0.011, p = 0.92]$. A significant effect of changing the location of target in two consecutive events on the execution times was observed $[F(1,10) = 53.9, p = 0.00557]$ and marginally-significant effect of switching the identities was observed $[F(1,10) = 4.13, p = 0.07]$.

The data for all measures of error were separately submitted to within-subject one-way ANOVAs with type of counting as the main factor to assess the impact of attending to the identity of characters on the error rates. None of the analyses returned a significant main effect of the counting paradigm on the error rates.

Except for one subject, all subjects correctly reported the incidence of appearance of the dummy character with 100% accuracy.

Error Type	LBTC	IC-LBTC	Sig.
Trials with Error	$19.1\% \pm 3.9\%$	$18.1\% \pm 4.1\%$	*n.s.*
Value Error	0.11 ± 0.02	0.10 ± 0.03	*n.s.*
Sorted Value Error	0.08 ± 0.02	0.07 ± 0.02	*n.s.*
Sum Error	0.21 ± 0.05	0.17 ± 0.04	*n.s.*

Table 4: Mean ± SE of error measures (experiment 2). n.s. : non-significant

Discussion The analysis of both execution times and error measures showed that compared to LBTC, attending to the identity of characters during IC-LBTC incurred no extra cost. This suggests that attending to the identity of the items in IBTC does not seem to be the source of extra cost of IBTC counting paradigm relative to LBTC.

However compared to the LBTC in experiment 1, subjects were significantly faster in LBTC trials of the second experiment. Given that subjects had to switch between LBTC and IBTC in the first experiment and LBTC and IC-LBTC in the second experiment, the faster execution time in the second experiment might have been related to a lower cost for switching between the two tasks in the second experiment. This difference might be related to either the 10 second imposed delay between blocks of experiment 2, or the fact that both tasks in the second experiment are indeed two versions of the same counting paradigm, and thus switching between blocks of experiment 2 is less costly. Furthermore, since there was no significant interaction between the identity of experiments and changing counting-relevant factor in both LBTC trials, the effect of switching between blocks of tasks seems to have had equal effects on both updating the same counter in a sequence or updating two different consecutive counters. This suggests that the extra cost on switching between counters during IBTC counting is not likely related to the cost of switching between blocks of experiment 1.

General Discussion

The goal of this study was to test the dependency of putative switching mechanisms for managing working memory in the internal domain and in a seemingly abstract and symbolic context, on the explicit utilization of space. We analysed our subjects' execution time in two concurrent counting tasks that differed in their reference to spatial locations. In one version of the task, where counting events were associated to spatial locations on the screen, subjects were faster and more accurate than when the identity of visual targets was the basis for the counting events. More importantly, not only the speed of counting in the location-based counting paradigm was generally faster, but also this speed was significantly faster when subjects had to switch between internal counters. Below, we argue that a faster switching between internal counters indicates that the source of speedup indeed is not related to a verbal shortening effect in rehearsing.

In Garavan's process model for a dual-counting task, each counting event consists of a sequence of five steps: 1. stimulus identification, 2. orientation of attention, 3. updating the associated count, 4. rehearsing the other count, 5. key-press. He suggests that the source of a 300 to 400 msec difference in updating the same counter subsequently versus updating two different counters is related to the cost of the second step: a recently attended resident of the working memory is privileged in terms of processing speed or accuracy (Garavan, 1998), and thus updating a counter which was just updated saves on the cost of bringing the item of working memory into the focus.

This model could be adopted for the triple-counting task by considering a third counter which needs to be included in the switching and the rehearsing steps. This model does not assume that the second step of this process, which accounts for the extra switching cost between two different counts, is dependent on perceptual aspects of the counting tasks. Likewise, no other model of working memory, to our knowledge, in which the focus of attention plays a critical functional role in regulating the process, assumes that the second and the third steps of this process are relevant to the perceptual aspects of the counting task. Hence, according to this process model, steps 2, 3 and 5 should be independent of the type of counting events. Our second experiment controlled for the influence of potential effects of perceptual differences, and showed that the source of speed difference in two paradigms cannot be attributed to the perception of events. Consequently, according to this model, the only source of difference in counting speed might be in rehearsing other counts (step 4). However, this effect would affect the speed of counting in a similar way for both updating the same counter or updating counters alternatively. Moreover, the analysis of errors adds another dimension to our argument: even when misplaced counters and signals are discounted in the error calculation, the location-based counting is still significantly more accurate. In sum, we argue that a model that confers a special role to space (unlike Garavan's process model), may be necessary to fully explain our findings.

Noori and Itti's spatial registry framework for manipulation of information in working memory is an example of a model where space plays a special role. According to this model, which assumes that working memory items are bound to spatial locations, accessing items in the internal domain draws on shifting spatial attention to different locations. In the case of location-based counting, counters can be directly bound to the location of boxes, and thus attending to the visual stimulus will automatically draw attention to the location of counters for accessing the counter value. In contrast, during the identity-based triple counting, each signal will draw spatial attention, but the signal location is not correlated with its identity and thus with the associated counter, thus likely a second shift of attention is required to point attention to the correct counter. When items need an update, two shifts in spatial attention may thus be required. The extra shift of attention may account for the slower response time during the identity-based triple counting.

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References

Arbib, M. (1992). Schema theory. *Encyclopedia of artificial intelligence*, *2*, 1427–1443.

Barsalou, L. W., Simmons, W. K., Barbey, A. K., & Wilson, C. D. (2003). Grounding conceptual knowledge in modality-specific systems. *Trends in Cognitive Sciences*, *7*(2), 84–91.

Chiu, Y., & Yantis, S. (2009, March). A Domain-Independent Source of Cognitive Control for Task Sets: Shifting Spatial Attention and Switching Categorization Rules. *The Journal of Neuroscience*, *29*(12), 3930 –3938.

Cowan, N. (1999). An embedded-processes model of working memory. *Models of working memory: Mechanisms of active maintenance and executive control*, 62–101.

Damasio, A., & Damasio, H. (2006). Minding the body. *Daedalus*, *135*(3), 15–22.

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.

Goodale, M., & Milner, A. (1992). Separate visual pathways for perception and action. *Trends in neurosciences*, *15*(1), 20–25.

Greenberg, A. S., Esterman, M., Wilson, D., Serences, J. T., & Yantis, S. (2010, October). Control of Spatial and Feature-Based Attention in Frontoparietal Cortex. *The Journal of Neuroscience*, *30*(43), 14330 –14339.

Lakoff, G., & Núñez, R. (2000). *Where Mathematics Comes From: How the Embodied Mind Brings Mathematics into Being* (1st ed.). Basic Books.

McElree, B. (2001). Working memory and focal attention. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *27*(3), 817–835.

Mcelree, B. (2006). Accessing Recent Events. In *Psychology of Learning and Motivation* (Vol. 46, pp. 155–200). Elsevier.

McElree, B., & Dosher, B. (1989). Serial position and set size in short-term memory: The time course of recognition. *Journal of Experimental Psychology: General*, *118*(4), 346.

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. (2013a). 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.*

Noori, N., & Itti, L. (2013b). Traces of intellectual working memory tasks on visual-spatial short-term memory. In *Proceedings of the 35th annual conference of the cognitive science society.*

Oberauer, K. (2002, May). Access to information in working memory: exploring the focus of attention. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *28*(3), 411–421. (PMID: 12018494)

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.

Shomstein, S., & Yantis, S. (2006, January). Parietal Cortex Mediates Voluntary Control of Spatial and Nonspatial Auditory Attention. *The Journal of Neuroscience*, *26*(2), 435 –439.

Tamber-Rosenau, B. J., Esterman, M., Chiu, Y., & Yantis, S. (2011, October). Cortical Mechanisms of Cognitive Control for Shifting Attention in Vision and Working Memory. *Journal of Cognitive Neuroscience*, *23*(10), 2905–2919.

Voigt, S., & Hagendorf, H. (2002). The role of task context for component processes in focus switching. *Psychologische Beitrage*.